DISS. ETH NO. 22165

SHAPE GRAMMARS FOR URBAN NETWORK DESIGN

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES of ETH ZURICH

(Dr. sc. ETH Zurich)

presented by

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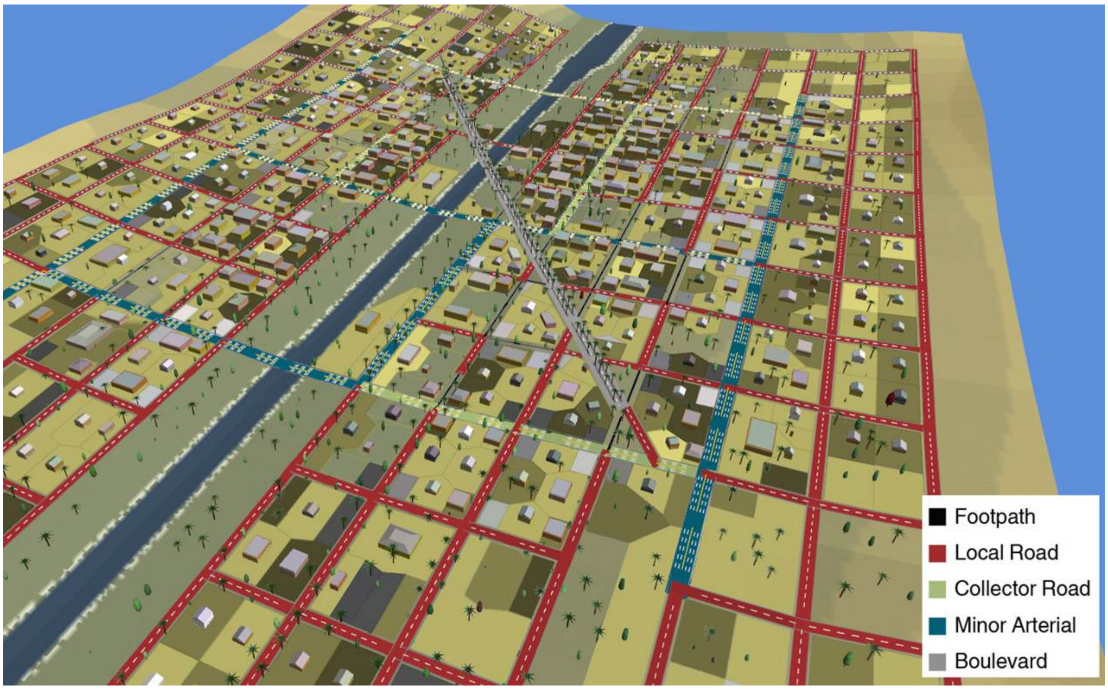
2014



Shape Grammars for Urban Network Design

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PhD-Thesis **No. 22165**

2014

Institut für Verkehrsplanung und Transportsysteme
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Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Source of cover: Vitins et al. (2013) p.16.

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Abbreviations

a Total construction costs ... p. 15

ACO Ant colony optimization ... p. 64

α Parameter of the logit function ... p. 65

$A_{p_k^n}^n$ Set of links of p_k^n ... p. 67

B Budget for infrastructure ... p. 15

β Parameter of the logit function ... p. 65

c generalized user costs ... p. 15

CBA Cost benefit analysis ... p. 92

c_{tt} Monetarized travel time ... p. 118

d Destination ... p. 63

$\Delta d_{\textit{structural data}} \left(\Delta t^{x\%}\right)$ Increase in urban density leading to a maximum travel time increase of $\Delta t^{x\%}$ ... p. 45

δ Evaporation rate ... p. 67

d_F Face density ... p. 94

d_i Intersection density ... p. 102

d_{jobs} Job density ... p. 98

d_{pop} Population density ... p. 98

d_r Road density ... p. 74

ϵ Elasticity ... p. 43

$\mathcal{E}$ Elements of $\mathcal{L}$ ... p. 28

e Element of $\mathcal{E}$ ... p. 17

$\epsilon^{s,A}$ Accessibility elasticities ... p. 83

$\epsilon^{s,E}$ External costs elasticities ... p. 83

$\epsilon^{s,T}$ Monetarized travel time elasticities ... p. 83

F Face ... p. 97

$\mathcal{G}$ Grammar of $\mathcal{L}$ . . . . p. 28

G Graph . . . . p. 32

GA Genetic algorithm . . . . p. 59

$\gamma(l_{od})$ Weighting factor dependent on travel distance l_{od} extrapolated for a year . . . . p. 63

HCM Highway capacity manual . . . . p. 49

$\mathcal{I}$ Initial assertion where design algorithm starts . . . . p. 17

I Investment . . . . p. 43

IACGA Integrated Ant Colony and Genetic Algorithm . . . . p. 64

$\mathcal{L}$ Language . . . . p. 28

l Boulevard length . . . . p. 83

λ Application range . . . . p. 83

l_F Circumferences of a face F . . . . p. 94

$l_{i,j}$ Length of link i–j . . . . p. 15

$L_{Parents}$ Set of links i-j which are present in at least one parent network . . . . p. 65

M Meshedness . . . . p. 97

N Number of nodes . . . . p. 97

$\mathcal{NP}$ Non-deterministic polynomial-time hard . . . . p. 22

ν Number of arms . . . . p. 50

o Origin . . . . p. 63

$\mathcal{O}\big(f(n)\big)$ Calculation cost for function $f(n)$ . . . . p. 22

$\mathcal{P}$ Solvable in polynomial time . . . . p. 22

p Penalty for budget violation . . . . p. 15

$p_{c=n}$ Density of intersections with cardinality n . . . . p. 95

p_{ij}^g Probability of choosing link i-j in iteration g . . . . p. 65

Φ Number of phases at a signal light . . . . p. 52

P_n Population n . . . . p. 67

p_k^n Individual k of P_n . . . . p. 67

q Flow . . . . p. 32

$\mathcal{R}$ Set of rules of $\mathcal{G}$ . . . . p. 28

r Rule $\in \mathcal{R}$ . . . . p. 17

rg Relative gap . . . . p. 166

ϱ Accounts for additional randomness in the logit function . . . . p. 65

$\mathcal{S}$ Semantics of $\mathcal{G}$ . . . . p. 28

Abstract

A variety of network patterns strongly influences the designs of today's cities and agglomerations. The network patterns show considerable topological design variations, which become evident when comparing network patterns of different cities or even within the same city. Numerous urban transport network patterns have been developed in past eras and have been used for transportation purposes. However, changing travel demands, technologies, as well as strong regional and worldwide migration and urbanization make it ever so necessary to adapt and extend urban infrastructure in the future. Therefore, fundamental knowledge about urban and transport network design is necessary to increase general understanding of the effects of today's networks and to improve and adapt general design recommendations for the future development of cities and agglomerations.

Today, recommendations on urban design are available in guidebooks and norms. However, these design recommendations often rely on scarce fundamental research. There is little quantitative research on which to draw upon. Moreover, real world urban plans and patterns vary considerably in topology and size which hampers the definition of general recommendations based on these plans and patterns. Design algorithms are being applied increasingly in urban and transport planning. However, most obtained results are very application specific and can hardly be transformed into general design recommendations. Urban network design thus remains contentious, despite recent theoretical and applied research on this topic.

Shape grammars are increasingly applied in the complex field of transport and urban design and architecture, especially in an increasing number of urban simulations. Grammars are applied to procedurally design infrastructure, e.g. buildings or neighborhoods. Grammar rules govern the fundamental planning elements, e.g. interior walls or street segments. The elements are added to each other according to distinct grammar rules.

Shape grammars are promising tools for designing urban areas. They can be applied directly in urban design methods without cumbersome calculations, are applicable to different planning sites, and are suitable for solving interdisciplinary planning tasks. With shape grammars it might even be possible to overcome complexity in urban designs. And they can be transformed to urban design guidelines for future applications. This thesis explores the usage of

shape grammars in transport and urban design, and in planning applications. Shape grammars, and especially their effects in planning applications are yet poorly understood despite recent advances in network design and urban modeling. Therefore, a theoretical justification is made and three evaluation methods are suggested and applied within this thesis.

Available literature and existing theory on grammars are reviewed to consolidate and enhance theoretical knowledge, and to analyze the corresponding complexity of grammar based approaches in network design. Grammars are defined both as rules describing the design mechanisms, and as application specification describing the underlying assumptions and effects of the rules. In an example, the proposed theoretical concept is successfully applied on the design of a city boulevard.

Three methodologies are proposed in this thesis to define and evaluate grammars and their effects in network design. For shape grammar definitions and evaluations, it is assumed that road network models on featureless planes are specifically suitable compared to empirical real world network evaluations. In this way it is possible to ignore politically and historically driven network design and past construction decisions. And consequently, networks can be designed, modeled and understood in their fundamental principles. A network design algorithm is developed for the design of network topologies which also implements and extracts shape grammars. Modeling results demonstrate the influence of topology and intersection type choice in road networks. High network meshedness correlates with low user costs, also within the proposed reliability analysis. Experiments confirm the importance of turn delay consideration and intersection type choice. Generally, signals have low user costs and high reliability at increasing traffic flows. Moreover, by increasing the capacities at intersections and on roads the reduction of total user costs is higher compared to the alternative of increasing the overall road network length. Specifically, gridirons with medium block size ($\sim$200m) have high meshedness values and are reliable with signals, thus making them efficient in dense urban areas.

There is strong evidence that different transport modes require different network topologies due to their specific characteristics, especially speed, required capacity and average turn delay. It is also known that pedestrians, with very low speeds and turn delays, prefer denser networks with less capacity on their paths. This result is in contrast to the findings above for road networks; however, it is in line with empirical data from literature. In addition, qualitative comparisons with historical network developments support these findings. In conclusion, it is possible to evaluated shape grammars. Apart from rules, application specifications are required for improved and meaningful grammar applications.

Keywords

Shape, grammar, rule, syntax, design, pattern, topology, IACGA, intersection, road, type, optimization, urban, transport, network, design, assessment, boulevard, meshedness.

Preferred citation style

Vitins, B.J. (2014) Shape Grammars for Urban Network Design, *Dissertation*, IVT, ETH Zurich, Zurich.

Zusammenfassung

Eine grosse Vielfalt existierender Verkehrsnetze zeichnen ihre markanten Muster in die heutigen Stadtpläne. Spezifische Eigenschaften wie Formen und absolute Grössen variieren stark zwischen den urbanen Netzen, sichtbar im Vergleich verschiedener Städte oder sogar in derselben Stadt. Die heute bestehenden Netze und Muster wurden in unterschiedlichen Epochen entworfen und umgesetzt, werden jedoch bis heute und auch in Zukunft als Verkehrsnetze genutzt. Sich ändernde Anforderungen an die Infrastruktur sowie regionale und weltweite Urbanisierungs- und Migrationsprozesse erfordern jedoch Anpassungen und Erweiterungen der bestehenden Infrastrukturen. Ein fundiertes Grundlagenwissen über Entwurfsgestaltung und Stadtentwicklungen ist deshalb essentiell für universelle Entwurfsempfehlungen und für zukünftige Entwicklungen von Verkehrsnetzen.

Es bestehen schon heute Empfehlungen für den Entwurf urbaner Räume in Form von Richtlinien und Handbüchern. Diese Richtlinien und Handbücher beinhalten Entwurfsvorschläge für Verkehrsnetze, basieren jedoch auf einer sehr geringen Anzahl quantitativer Forschung. Als Grundlage für Entwurfsvorschläge können auch bestehende Stadtpläne dienen. Die existierenden Stadtpläne und ihre Muster unterscheiden sich jedoch deutlich bezüglich ihrer Topologie und erschweren deshalb generelle Entwurfsempfehlungen für zukünftige Netzerweiterungen wie auch Verbesserungen oder der Ersatz existierenden Netze. Zusätzlich sind historische Entscheidungen für Infrastrukturbauten oft politisch befangen, oder nur unvollständig evaluiert und sind deshalb bedingt geeignet für die Definition zukünftiger Empfehlungen. Zunehmend werden im Entwurf auch Optimierungsalgorithmen angewendet. Deren Resultate sind jedoch sehr ortsspezifisch; die meisten Algorithmen generieren deshalb kaum allgemeingültige Entwurfsempfehlungen. Die effiziente Gestaltung urbaner Verkehrsnetze bleibt kontrovers trotz der existierenden theoretischen und angewandten Forschung.

Entwurfsgrammatiken werden zunehmend als Werkzeuge in der Verkehrs- und Städteplanung angewendet, speziell in Simulationen urbaner Räume. Grammatiken werden in prozeduralen Methoden für den Entwurf von Infrastrukturen eingesetzt, zum Beispiel im Gebäude- oder Wohnquartierentwurf. Grundelemente wie zum Beispiel Innenwände oder Strassensegmente werden inkrementell aufgrund definierten Regeln aneinandergefügt.

Grammatiken können ohne grossen Aufwand im Entwurf und bei interdisziplinären Planungsaufgaben eingesetzt werden. Grammatiken könnten die Komplexität in der Planung urbaner Räume reduzieren. Zusätzlich können sie als Grundlage für zukünftige Empfehlungen in Planungshandbüchern und Normen dienen. Diese Doktorarbeit erforscht die grundlegende Theorie und den optimierten Einsatz von Entwurfsgrammatiken für die Planung von Verkehrsnetzen. Die Grammatiken und speziell die Auswirkungen in den Anwendungen sind kaum bekannt trotz den immensen Fortschritten im Bereich der Modellierung von urbanen Gebieten. Deshalb werden in dieser Doktorarbeit sowohl eine theoretische Grundlage wie auch drei Methoden für die Evaluation von Entwurfsgrammatiken vorgeschlagen.

Der theoretische Teil inklusive Literaturrecherche untersucht das vorhandene theoretische Wissen über Grammatiken und deren Funktionsweise. Schon vorhandene implizit oder explizit formulierte Grammatiken in der Verkehrs- und Raumplanung werden systematisch aufgelistet. Diese Arbeit definiert eine Grammatik als Kombination einer Syntax und einer dazugehörige Semantik. Die Syntax beinhaltet genau definierte Regeln für den inkrementellen Entwurf von Infrastrukturen. Die Semantik definiert die dazugehörigen Anwendungsspezifikationen, welche die Annahmen, Einschränkungen und Auswirkungen der Regeln beschreiben. Weiter wird die Komplexität im Bereich Verkehrsnetze untersucht und in Zusammenhang mit den Grammatiken gesetzt. Die Definition von Grammatiken sowie die Anwendungsspezifikationen werden beispielhaft und erfolgreich am Entwurf eines Boulevards aufgezeigt und überprüft.

Verkehrsmodelle ermöglichen Netzentwürfe und Auswertungen, welche besonders geeignet sind für die Definition und Evaluation von Grammatiken. Eine Grammatikdefinition aufgrund optimierten und evaluierten Modellentwürfen kann politische und historisch bedingte Planungsentscheidungen ignorieren, im Vergleich zu einer empirischen Ableitung von Grammatiken basierend auf existierenden Verkehrsnetzen. Deshalb werden systematisch verschiedene Verkehrsnetze entworfen, modelliert und anhand verschiedener Kriterien ausgewertet, mit einem Fokus auf Strassenverkehrsnetze. Für eine effiziente Bearbeitung wird ein Algorithmus vorgeschlagen, welcher sowohl den Entwurf und die Optimierung von Verkehrsnetzen wie auch die quantitative Evaluation und Extraktion von Grammatiken ermöglicht. Die Resultate zeigen einen deutlichen Zusammenhang zwischen Netztopologie und Knotentypwahl auf. Eine hohe Maschendichte eines Verkehrsnetzes korreliert mit tiefen generalisierten Reisekosten insbesondere in den Auswertungen betreffend der Zuverlässigkeit. Weitere Resultate heben speziell die Bedeutung der Knotentypwahl im motorisierten Individualverkehr hervor. Lichtsignalanlagen haben bei hohem Verkehrsaufkommen relativ tiefe Abbiegewiderstände und sind zuverlässiger. Zusätzliche Kapazitäten an Knoten und Strecken verringern die Reisekosten stärker als eine Erhöhung der absoluten Streckenlänge des Verkehrsnetzes. Speziell Gitternetze haben eine hohen Maschendichte und sind deshalb zuverlässig in Kombination mit Lichtsignalanlagen und bei zunehmenden Verkehrsaufkommen. Gitternetze sind deshalb besonders geeignet in dicht überbauten urbanen Räumen, besonders wenn die Netze mit hohen Knoten- und Streckenkapazitäten versehen sind, und mit mittlerer Maschengrösse (ca. 200m).

Verschiedene Verkehrsmittel erfordern verschiedene Netztopologien und Eigenschaften aufgrund der Ausprägungen der Verkehrsmittel, besonders Geschwindigkeit, Kapazität und Abbiegeverhalten. Fussgänger haben offensichtlich geringere Geschwindigkeiten und Abbiegeverzögerungen und bevorzugen deshalb dichte Verkehrsnetze mit eher geringen Streckenkapazitäten. Diese Planungsstrategie ist gegenläufig zur erwähnten optimierten Netztopologie des motorisierten Individualverkehrs. Die Resultate sind jedoch kongruent mit den empirischen Daten aus der Literatur sowie mit historischen Netzen. Zusammengefasst zeigt die Arbeit Möglichkeiten auf, Entwurfsgrammatiken zu definieren und zu evaluieren. Ebenfalls zentral ist die Definition von Anwendungsspezifikationen, welche gekoppelt sind mit den Grammatiken und welche eine effektive zukünftige Anwendung von Grammatiken in der Planung ermöglichen.

Bevorzugter Zitierstil

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Acknowledgments

I owe my deepest gratitude to Prof. Dr. Kay W. Axhausen for his continuous support and guidance. I have benefited immensely from his vast knowledge and expertise in the wide and interdisciplinary field of transportation. All through this research I could rely on his valuable and insightful advice for which I am very thankful.

I am also very much indebted to Prof. Dr. David Levinson who supported me during this thesis with his expertise and who contributed in multiple meetings and reviews. In addition, I highly appreciate the numerous discussions with Prof. Dr. Martin Fellendorf, who provided significant inputs to complement and enhance this research.

I thank all members of the Transport Planning Group for their help, our discussions at coffee breaks and for their support throughout the intensive gestation of this thesis. I could always rely on their broad and profound expertise in transportation and cognate fields. I especially would like to thank Dr. Nadine Rieser-Schüssler and acknowledge her continuous support and guidance. Highly appreciated are also the multitude of ideas, inputs, expert options and valuable discussions with academic guests at our institute, especially Prof. Shlomo Beckor, Prof. Johan Joubert, and Dr. Hillel Bar-Gera. Special thanks go also to Dr. Allesio Cardillo who provided detailed research data which I could use for comparison (Cardillo et al., 2006).

I am very much indebted to have benefited from outstanding mentors, who have supported me with their profound expertise in the course of my PhD work, during my previous appointment at Rapp Trans AG and during my previous Bachelor and Master studies.

Without solid IT support this work would not have been possible; and for this I extend thanks to Adrian Zaugg, Joerg-Peter Lorch and the entire IT support group.

Last but not least, I am indebted also to my parents, my brother and to all my wonderful friends for their continuous encouragement and interest in my research work.

This research was funded partially by Climate-KIC for which I am very thankful.

Sources

Chapter 1 draws partially on Vitins and Axhausen (2014) and Vitins and Axhausen (forthcoming).

Chapter 2 draws partially on Vitins et al. (2013) and Vitins and Axhausen (2014).

Chapter 3 draws on the following publications: Vitins et al. (2013), Vitins and Axhausen (2013), Vitins and Axhausen (2014), Vitins and Axhausen (forthcoming).

Chapter 4 draws on the following publications: Vitins and Axhausen (2010), Vitins et al. (2011b), Vitins et al. (2011a), Vitins et al. (2012b), Vitins et al. (2013).

Chapter 5 draws on the following publication: Vitins and Axhausen (2014).

Chapter 6 draws partially on Vitins et al. (2013).

Chapter 7 draws partially on Vitins and Axhausen (2013).

Chapter 1

Introduction

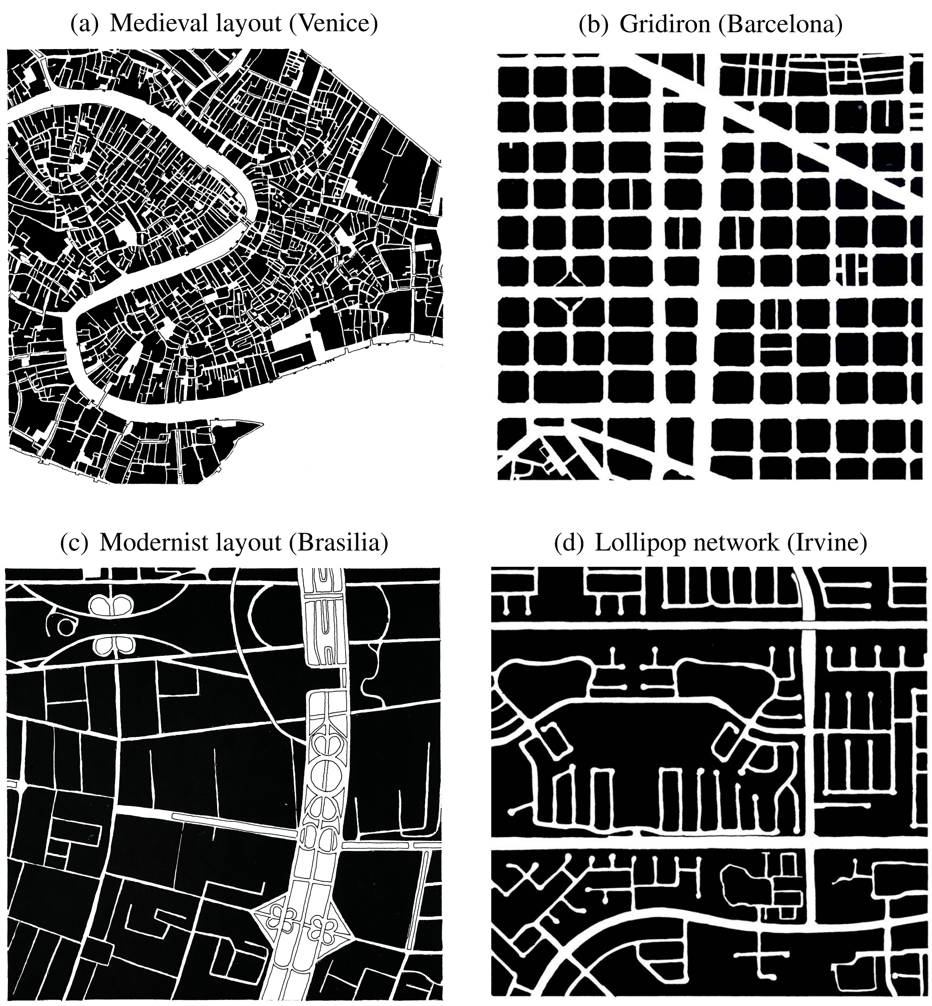
"... what kinds of laws, at how many different levels, are needed, to create a growing whole in a city or a part of a city" (Alexander et al., 1987, p.19).

Chapter 1 narrows the perspective from the broad field of transport and urban design down to a specific grammar based design approach (Sections 1.1 and 1.2). It provides information about the relevance of shape grammars (Section 1.3), applications, and examples of shape grammars (Section 1.4).

1.1 Focus of this Dissertation

Through history each era developed its specific network patterns and characteristics. In each era, network patterns were designed for specific requirements using then available technologies. It can be easily seen that the network patterns of one era replaced these of the prior era, and that many patterns were passed on to following generations. Medieval structures (Figure 1.1(a)) contrast with baroque layouts and gridirons (Figure 1.1(b)), and these differ again from garden cities, modernist layouts (Figure 1.1(c)), as well as lollipop networks (Figure 1.1(d)) which are based on treelike layouts with high dead end densities. Urban networks are considerably different between cities, see e.g. Lampugnani (2010), and can be distinguished in their specific design characteristics (Cardillo et al., 2006). In parallel to the urban patterns, parcel shapes changed considerably over time (Strano et al., 2012). They have converged from a diversity of shapes to mainly oblong and square shapes. It seems that medieval networks grew through a largely self-organized, historical process. Medieval networks therefore contrast to more recent patterns, which have been realized over a short period of time with a specifically designed pattern in a rather top-down approach, e.g. gridirons. All these patterns are of major interest to urban planning.

Figure 1.1: Example network patterns from Jacobs (1993) (1×1 [mile^2]).



Source: Jacobs (1993) p.249, 208, 217, 222.

Obviously, transport modes have changed considerably over time. In Europe, the medieval networks were built mainly for pedestrians and foot carriages. Later, industrialization had an important impact on transportation. Public transportation (trains and tramways for urbanized areas) emerged as a major transport mode at the turn of the century (1900). Regarding the urban design, gridirons were suitable for such modes, and were designed and applied in e.g. the US. Later, automobiles enabled individual transportation. Transport systems around the globe adapted to technological changes. Modernist and lollipop networks were designed, leading to the new car age. And on top, travel costs have decreased, e.g. with low fares in air travel (Widmer, 2002) and low car prices (Frei, 2005).

Current and future technological developments, e.g. automated routing and driving as well as car sharing, allow now more optimized travel in ever more congested and complex networks.

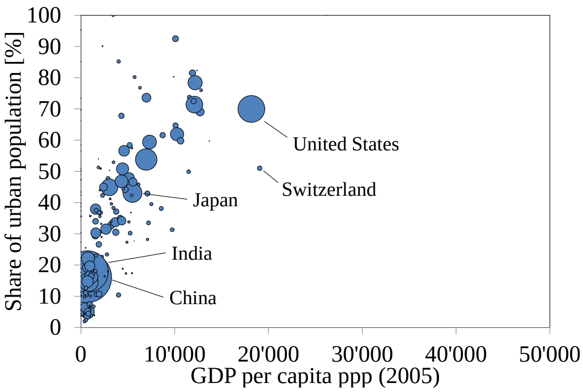
In the future, vehicle assistance may enable a more generic design, which could be detached from the existing network patterns. Moreover, car-independent modes, such as pedestrians, and (electric) bicycles have gained more attention in recent years. Overall, advances in technology will allow to enhance transportation systems also in the future, which will influence spatial development again.

Following the arguments above, it is evident that technology and urban design are interdependent. Advances in technology enable new transport modes, which require new infrastructure, both for transportation and spatial developments. New modes and new infrastructure enable further cost reduction, improved productivity (e.g. Axhausen, 2007), and increasing economic welfare (Venables, 2007). It is expected that urban network design and redesign will prevail in urban planning due to population changes and continuous technological progress.

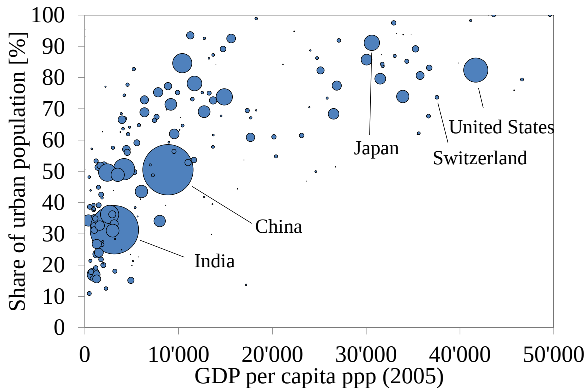
Many reasons drive the design and construction of transport networks. Growth, migration, and therefore densification and sprawl are important causes for urban changes today and in the near future. The driving forces are mainly economic, political, social and technical changes (UN, 2013; Kowald and Axhausen, 2012; World Bank, 2009; Schaefer et al., 2009; Transportation Research Board, 2002; Ewing, 2008). Figure 1.2 shows the explosion of population in urban areas. On the top, it is assumed that travel behavior will continue to change in the future (e.g. MacKay, 2009; Schaefer et al., 2009), as it did in the past (e.g. Axhausen, 2007), including also the choice in travel mode (e.g. car pooling and sharing (Ciari, 2012)).

Figure 1.2: Growing population and share of urban population in the past.

(a) Share of population living in urban areas (1960).



(b) Share of population living in urban areas (2011).



Source: World Bank (2013) online database, and Gapminder (2014).
Bubble size is proportional to population size.

Changes on the travel demand side are ongoing and are difficult to predict in long-term forecast models. Therefore, planners aim at reliable and robust transport systems which allow to absorb variations in travel demand and infrastructure supply. Reliability and robustness of the transport systems has become a priority as there are changing or increasing travel demand, longer trip distance and higher flows and therefore also capacity problems and delays due to the capacity limits on the infrastructure side. One major approach to increase reliability is the adjustment and transformation of infrastructure to absorb changes on the demand side in the short and long term.

Summing up, it can be stated that our transport systems face two major tasks: (1) The systems should be as efficient and productive as possible in the current state, and (2) at the same time reliable and robust to short and long term changes.

Drawing on existing academic literature, four major research strands can be described with examples, each aiming at the overarching goal of network design.

1. Architectural and urban planning perspectives are provided by Alexander et al. (1977), Southworth and Ben-Joseph (2003), Marshall (2005), and others, who presented qualitative urban designs based on profound expertise and knowledge for a functional, livable, and economic city. Stiny and Mitchell (1978) developed and applied grammar rules for the Palladian villa style. Moreover, an increasing number of urban models and simulations have been applied in recent years (ESRI, 2012; UrbanVision, 2012).
2. Transport planning in a wider sense focuses on scenario development and comparison, covering economics (Venables, 2007), risk and resilience (Erath et al., 2009; Helbing, 2013), energy supply in spatial developments (Keirstead and Shah, 2011), and corresponding travel behavioral studies (Bhat and Guo, 2007). Marshall (2005) focuses on streets and patterns and underlying grammar rules, e.g. for road type choice. Van Nes (2003) evaluated and optimized road and public transportation networks and characteristics, such as road spacings, and densities.
3. Graph-based and mathematical analyses evaluate urban networks statistically and from a graph perspective. Evaluations are provided by e.g. Cardillo et al. (2006) and Xie and Levinson (2011), who compared transport network topologies and various network types, and historical developments. Space syntax comprises a set of methods and techniques to analyze spatial arrangements (Hillier et al., 1976).
4. The operations research community has focused on network design and optimization for a long time, and covers multiple network types, e.g. information, water supply, logistics, and transportation (e.g. LeBlanc, 1975; Goldberg, 2002; Hillier and Lieberman, 2005).

Summing up, network design remains contentious despite research achievements, and despite the relatively straightforward underlying definition of networks as (planar) graphs based on nodes and edges (Clark and Holton, 1991).

With the ever increasing relevance of the transportation system, recommendations are required for proper and improved transport system design. Recommendations are essential for planners, organisations and authorities responsible for settlement development. These can be bequeathed to future generations, adapted, and improved for future changes and increased efficiency. To determine recommendations is a relevant research task, requiring interdisciplinary knowledge put also profound knowledge in fields such as transportation, urban planning, architecture, economics.

Norms and design guidelines are well-known platforms for recommendations on network design for both transport, and also urban planning for practitioners and authorities. Road network design guidelines describe only some aspects of urban design and network topology. The "Urban Street Geometry Design Handbook" (ITE, 2008) focuses on road types and hierarchical design, conflict points at intersections, and intersection spacing. "A Policy on Geometric Design of Highways and Streets" (AASHTO, 2004) proposes hierarchical designs, and a focus on technical design and road geometry. The "Planning and Urban Design Standards" (American Planning Association, 2006) elaborates also on hierarchies, and connectivity within network design. High connectivity is recommended for future city design, and is required for multiple urban layouts, such as gridirons, web, radial or curvilinear networks. Both the "Urban Street Geometry Design Handbook" and "Planning and Urban Design Standards" contain elements of the New Urbanism movement (e.g. Dutton, 2000). However, some of the planning recommendations are vague, while others merely rely on past developments and needs. Often, dense or congested urban road network design is not covered in the guidelines, even though networks have higher demands in urbanized areas. Many network design recommendations lack a quantitative research base. The new urbanism movement proposes new design ideas, but mainly relies on qualitative data. Coping with reliability and robustness are often not explicitly tackled.

Despite the various past developments and vast expert knowledge in network design, the consensus on "best practise" on network design remains vague. There is a lack of fundamental knowledge about the effect of different network designs. Norms often rely on qualitative research results. Recommendations often lack detailed verification. There is no methodology to develop and support recommendations and rules, despite the numerous and increasing application in e.g. urban simulations.

This thesis aims at contributing to this fundamental knowledge for improved future network design. First, it focuses on an overall understanding of network design. Second, quantitative evaluations of network designs shed more light on the effect of various network designs and uncovers potential improvements. Third, and more specifically, this thesis aims at an increasing understanding of shape grammars for network design. There is evidence that shape grammar rules are efficient tools for network design. Rules also can be implemented in future norms and design guidelines. They can be applied by network designers and spatial planners without extensive transportation knowledge. They have the potential to overcome the complexity of transport network design. The theory of grammars for network and spatial planning should be congruent with the basic concepts of grammars in cognate fields to combine rules of multiple disciplines such as architecture, urban and transport planning. Overall, a rule based approach seems promising for improved future planning.

This thesis distinguishes between artificially generated networks, network models, and real world networks. Characteristics of real world networks are essential to evaluate past developments (Figure 1.1). E.g. Cardillo et al. (2006) and Strano et al. (2012) evaluated real world networks, and past network developments, e.g. densities and lengths. However, the main focus of this thesis relies on artificially generated networks and network models. Artificial networks enable the investigation and evaluation of specific network designs based on already well-known network and transportation characteristics. Relevant aspects of network designs can be crystalized and explained on artificial networks and their evaluations, while excluding the complexity and size of a real-world network. Artificial networks ignore politically and historically driven network design and construction decisions, which occur in real world networks. Moreover, e.g. topology, road and intersection types can be exchanged for evaluation. And still, the resulting network characteristics remain comparable with characteristics of real world networks due to empirically evaluated models and parameters (e.g. turn delays).

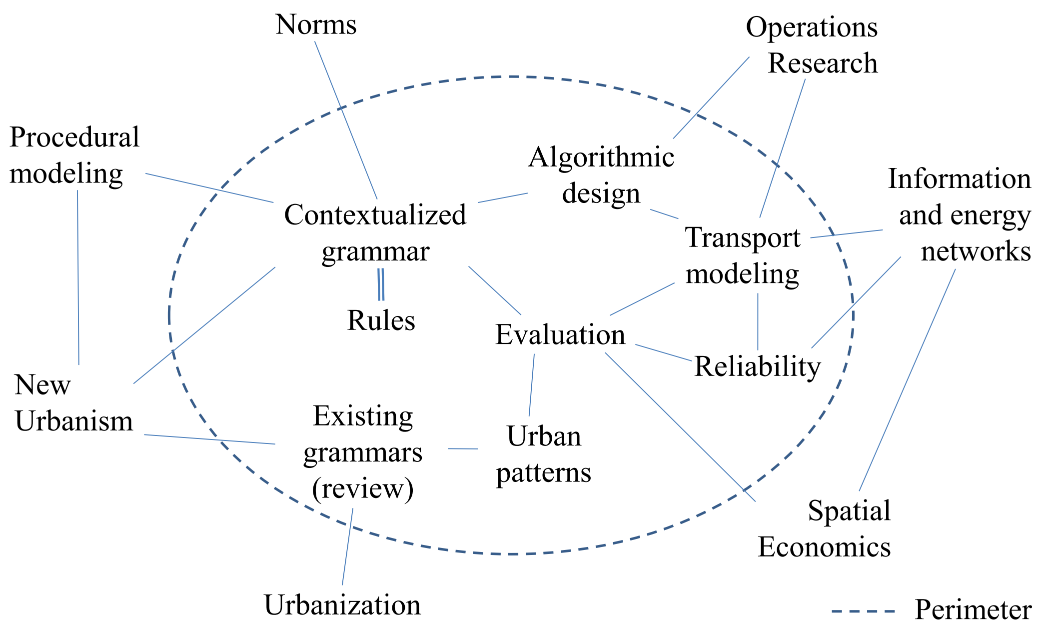
1.2 Structure of the Dissertation

Figure 1.3 shows the topics covered by this thesis, its context and associated fields. The elements outside the perimeter describe fields which are related to the context of the main topic, but which are not further examined in this thesis. The elements inside the perimeter are elaborated and evaluated in detail; however, these elements are complex, and in-depth elaboration of all details was not feasible within this thesis. A strong focus is on shape grammars and on their potential evaluation methods.

The Introduction provides an overview and states the relevance of shape grammars including examples from transport planning and cognate fields. Terminology and a comprehensive literature review are provided in Chapter 2 for the existing research about shape grammars. Additionally, Chapter 2 provides a problem formulation and corresponding research questions for this thesis. Chapter 3 explains the applied study designs and methodologies. The applied methodologies for demand assignment are explained in detail in Appendix A. Furthermore, a new network generation algorithm is presented in Chapter 4. Rules are extensively determined and evaluated for an example boulevard design (Section 5). Further evaluations of potential shape grammar rules are presented in Chapter 6 and 7 especially focussing on network topology and intersection type choice. Chapter 8 extracts and summarizes potential rules from the previously described results.

Chapters 1 – 4 can be read independently. However, the later results (Chapters 5 – 8) require knowledge of all previous chapters.

Figure 1.3: Research context, topics covered and associated fields.



1.3 Relevance

Various settlements were designed and implemented in the past (e.g. Figure 1.1). Still, it is not clear if and which of the past visions of the various developments can be copied and exported to current and future times. Changing requirements (e.g. densities), different growth rates of agglomerations, and new technologies require rethinking of the current status. Sustainability goals in all three dimensions pose new and complex constraints. Limited energy and natural resources as well as decarbonisation foster a responsible stewardship. Therefore, it is of utmost importance to know more about the functionality of network elements and their dependence, also with other urban infrastructure. For future use, knowledge about the functionality and network characteristics can be reformulated in design guidelines, or rules. The following subsections distinguish between network design in general and shape grammar rules in particular.

1.3.1 Transport Networks and Designs

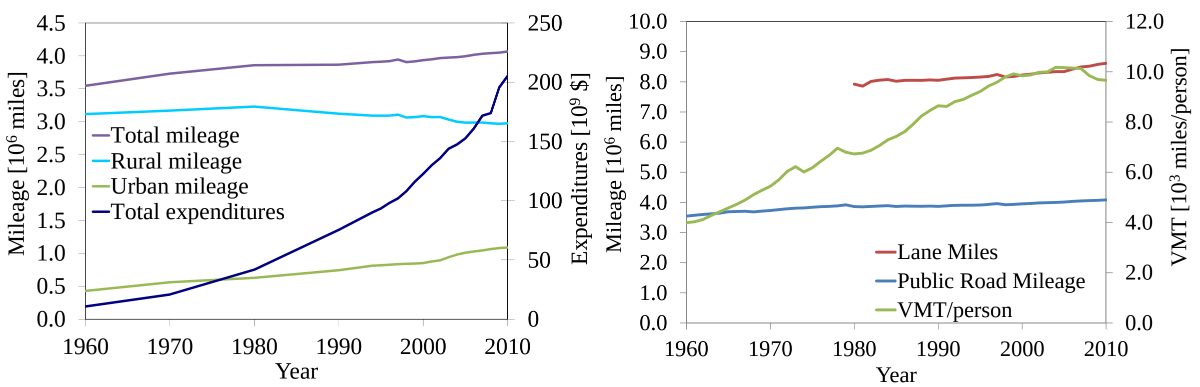
At least since the economic models of Ricardo (1817) and Thünen (1910, second edition) and the definition of opportunity and marginal costs, it is known that spatial separation of products and trading can produce overall net benefits. In the meantime, the current trading patterns emerged worldwide. Beside trading, Venables (2007), Graham (2007), and Melo et al. (2009) quantified the effect of single agglomerations, their sizes and corresponding productivities.

They found that wages increase 2.8% to 3.5% when doubling the range of travel. In addition to economic reasons, migration is an ongoing issue around the globe, due to climate, political and social reasons (Figure 1.2), which causes the extension of existing settlements, densification, or new settlements. Moreover, governmental control is a major issue for the construction of networks (Tilly, 1992). Ever since the Roman Empire, and even earlier, authorities required tools to access their country. In addition, knowledge exchange, and social activities are increasingly relevant in today's societies, and require corresponding infrastructure.

Figure 1.4 shows the historical expenditures for infrastructure in the U.S., and the historically growing VMT and road mileage. Similar figures can be drawn for Switzerland, and likely for many other countries. Figure 1.4 mirrors the incredible and growing relevance of the transportation system in the past. The ability to travel seem to become a strong need and desire of our society. Polynomial approximations and future trajectories based on the past data are uncertain, e.g. due to the discussion of peak travel and differences between countries (e.g. Millard-Ball and Schipper, 2011) and the various reasons for ongoing changes of travel behavior (e.g. Le Vine and Jones, 2012).

Figure 1.4: Development of network length, expenditures and VMT in the US between 1960 and 2010.

(a) Urban and rural mileage and expenditures in the US. (b) Network length and VMT.



Source: U.S. Department of Transportation (2012) and Federal Highway Administration (2013).

Despite the straightforward definitions of network graphs, transport networks are complex systems on their own. It is a complex task to design even small networks due to the following reasons. The majority of network design problems cannot be solved analytically despite their relatively simple problem formulation (Johnson et al., 1978). Similarly, the standard static assignment cannot be solved analytically (Sheffi, 1985) which increases assessment costs. One reason might be the lack of order within a given set of network elements (Lämmer et al., 2006). Due to the complexity, profound research is required for network design and the corresponding planning tasks. Moreover, transport systems interact strongly with e.g. energy and communication systems, or spatial developments. In addition, knowledge about reliability and robustness is required to absorb external influences and changes in both demand and supply. Summing up, network design remains complex and interdisciplinary, and further research is required for future and successful changes and improvements of networks.

1.3.2 Shape Grammar Rules

Grammar rules are applied for a longer time already. Christaller (1933) proposed a central place theory and introduced a hierarchical order for places and road links. German planning norms adapted some part of his theory (FGSV, 2008b), and apply similar rules for long-term master planning. Not only in Germany have planning rules had a considerable influence on urban and regional planning for a long time. Handbooks and standards for urban and spatial design often describe guidelines in the form of rules. Beside planning guidelines, rules are extracted from historical settlements to increase the understanding of historical urban transformation processes, and current urban fabrics (urban morphology) (e.g. Duarte et al., 2007), which allows comparison, evaluation, and maybe even transformation to contemporary designs. Often, historical settlement designs rely on rules, but they lack specific definitions, and therefore are not available for evaluation and application not even in contemporary urban planning. Beside morphology, rules are also used for modelling future growth. They are defined and transformed in computer codes and algorithms and finally applied in urban simulations (e.g. Vanegas et al., 2009a).

Summing up, grammars consists of rules, which govern the fundamental elements of a language. They define how elements of the same or different type are added to each other. Key advantages for shape grammars applied in the planning context are listed below:

- Shape grammars provide straightforward application tools for planning processes (Jacobi et al., 2009; Parish and Müller, 2001; Watson et al., 2008). Planners prefer robust and reliable methods to fulfill economic and social requirements. Shape grammars can satisfy these requirements and still remain adaptive to different scenarios (Marshall, 2005; Weber et al., 2009; Jacobi et al., 2009).
- Carefully defined design rules can be stated in guidebooks for future planning applications. A rule set allows to retain an urban vision for a longer time (e.g. LeCorbusier, 1955; Alexander et al., 1977), and for long-term strategic master planning. Planning authorities might change over years, but detailed grammar descriptions allow to bequeathing planning rules to future generations. Rules can be applied in a piecemeal approach, which allows certain flexibility in time. They are applicable to different planning sites.
- Urban economics, transportation, and energy supply form complex decentralized systems (e.g. Lämmer et al., 2006). Knowledge about efficient leverage effects are essential for a successful design. Moreover, bottom-up rules are often accepted regulation methods.

- Shape grammars originating from various disciplines can be joined together for an even larger set of grammars for interdisciplinary applications (e.g. Alexander et al., 1977; Haas, 2008). The multidisciplinary potential contrasts the distinct languages of specific disciplines. The distinct languages are often too sophisticated to interact with each other. The distinct disciplines often deploy methods and models, which are unable to be merged with methods of other, even cognate disciplines. Shape grammars overcome this interdisciplinary complexity by their straightforward definitions. The multidisciplinary rules can enable the accomplishment of encompassing tasks, e.g. energy demand and supply (Keirstead and Shah, 2011).

- The application of shape grammars permits low computational costs (Parish and Müller, 2001; Watson et al., 2008) and can be implemented in interactive planning tools (e.g. Jacobi et al., 2009; Weber et al., 2009) given limited staffing resources. Therefore, grammars are in contrast with spatial optimization, such as bi-level network optimization, regarding computational requirements.

- Deeper understanding of the structure of urban systems enhances overall urban planning, and the understanding of urban guidelines (Michie, 1974; Hillier et al., 1976). Beirão (2012) stated that certain solutions might appear during the course of exploration of a certain problem. So grammars can be transformed into urban guidelines for future planning applications. This contrasts complex "blackbox" and cumbersome mathematical optimizations, and the corresponding results, which are restricted to a specific site.

Disadvantages of shape grammars:

- The effectiveness of shape grammar rules is often unknown in urban planning applications. Especially the assessment challenges the definition and application of grammars. The assessment requires a deeper understanding of the corresponding fundamental urban processes. E.g. network design rules often lack a systematic evaluation, e.g. cost-benefit-analyses, and do not remain explicit in their recommendations.

- The vast majority of research results are not formulated in shape grammar notation. We lack shape grammar formulations, despite the broad expertise in the distinct planning disciplines. However, a potential transformation of the existing expertise and results into shape grammar rules would allow to enlarge the rule sets considerably, and simultaneously exploit the enormous potential for various grammars applications.

- Grammar rules might need adaption due to changing environments, because rules might become impractical in the future, e.g. due to technological and behavior changes.

- Rules are often based on a expert knowledge and experience, common understanding, human perception, and aesthetic preferences. The validation especially of subjective rules might be ambiguous.

1.4 Applications of Shape Grammars and Rules

Example applications were used at developing sites, e.g. Tysons Corner (Fairfax County, 2014) in the US, or sites in Asia, e.g. Singapore, or China, and, more generally, at sites of large ongoing urbanization around the globe and growing urban centers (Figure 1.2). Additionally, after natural disasters, such as earthquakes or Tsunamis, transport supply and economies need to recover as quickly as possible. Beside designing new districts, existing urban networks are under constant changes and improvement. Existing areas have new or changing spatial requirements such as changing living or commercial space, or changing travel demand. One goal of the authorities is to maintain the level of service on the supply side also for changing demands.

A large number of researchers and planners have applied shape grammars to an increasing extent in recent years, e.g. for urban simulations. Beside applications in transportation, also applications in cognate fields of urban planning, architecture, and computer simulations are described in this section. Some fields have overlapping aspects, such as the street network, which is often designed in urban planning. Shape grammars are applied to simulate urban growth (e.g. Vanegas et al., 2009a; Weber et al., 2009), urban redesign (e.g. Yerra and Levinson, 2005; Bramley and Power, 2009), changes on the demand side (e.g. Dutton, 2000), or even to visualize the potential of future technologies (Geddes, 1939; Vanegas et al., 2009b). Figure 1.5 shows four selected examples of grammar rules from different fields, Figure 1.6 depicts the corresponding planning results. Both figures and the related fields of the examples are explained in the following. A comprehensive list of shape grammar rules and additional examples are provided later in Section 2.2.

In *transport planning*, norms and guidelines are provided by handbooks (AASHTO, 2004; IHT, 1997; VSS, 1994b; FGSV, 2008b). Handbooks play a key role in planning new or in improving existing sites. The Swiss norm for transport network design (VSS, 1992) specifies a strong hierarchical design for road types, where types of adjacent road links differ in maximum one hierarchy level (Figure 1.5(a)). Figure 1.6(a) shows an example network of the current Swiss norm for network design and hierarchical road type distribution.

In *urban planning*, rules or codes are developed for consistent design, for specific purposes, such as urban densities, and also to improve livability, orientation and perception of a city. Kaisersrot (2011) and the "SmartCode" (Duany et al., 2009) are two example implementations based on specific rules. Moreover, the movement of New Urbanism often describes its ideas in codes (Dutton, 2000; Haas, 2008). Figure 1.5(b) refers to urban planning, and shows the recommended clustering of houses around common land with in-between paths to improve quality of the neighborhood, and to increase comfort of the inhabitants. Figure 1.6(b) exemplarily shows a city quarter and the application of various rules by Alexander et al. (1977).

In *architecture*, similar approaches are applied as in urban planning. Rules are defined for the design and construction of new buildings, such as the specification of rooms and their spatial relation. E.g. Stiny (1985) and Mitchell (1990) contributed to shape grammar rules in architecture. Figure 1.5(c) visualizes the grammar of a prairie house, based on the ideas of

Frank Lloyd Wright (Stiny, 1985), and Figure 1.6(c) shows the final building and floor plan.

In *computer science*, rule-based approaches were widely applied from the beginning. Related to urban design, software tools like ESRI (2012) or Synthicity (2013) considerably advance urban simulations and offer new possibilities in planning. Grammar rules can be directly implemented in computer codes. Figure 1.5(d) shows an example scheme which defines direction and length of new roads, in relation to the road elements of previous development steps. The outcome of this and additional grammar rules are displayed in Figure 1.6(d).

Figure 1.5: Examples of shape grammar rules in transportation, urban planning, architecture, and computer science.

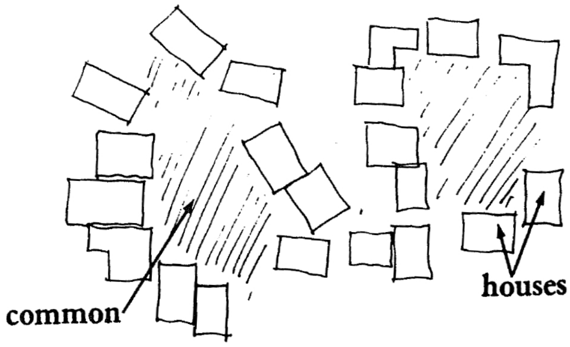
(a) Strict hierarchical road type distribution proposed by the Swiss norm VSS (1992).

Hierarchy of link 0 \ Hierarchy of link 1 (Road type)	0	1	2	3	…
0	✓	✓	✗	✗	
1	✓	✓	✓	✗	
2	✗	✓	✓	✓	
3	✗	✗	✓	✓	
…					

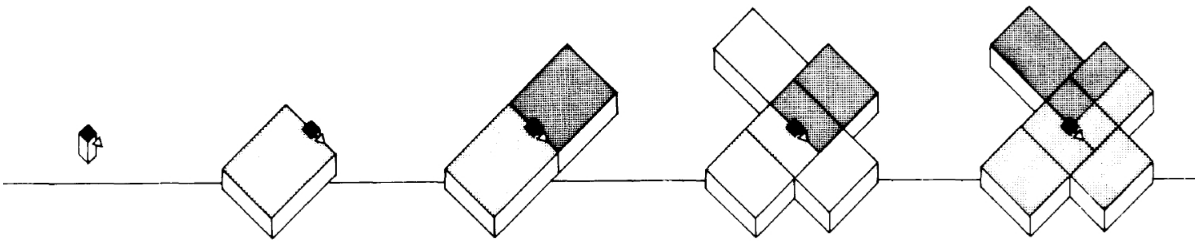
✓ Potential connection

✗ Prohibited connection

(b) Clustering of about 8 to 12 houses around some common land and paths (Alexander et al., 1977, p.202).



(c) The beginning of a prairie-style house with rooms located in a butterfly-shaped composition (Stiny, 1985, p.13).



(d) The design and geometry of road elements based on Weber et al. (2009) p.5.

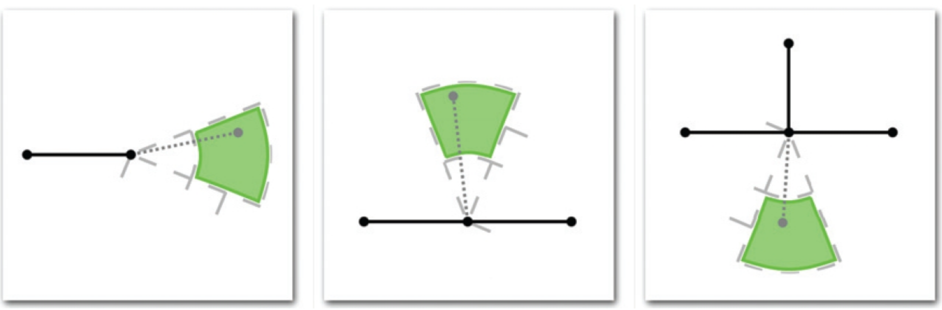
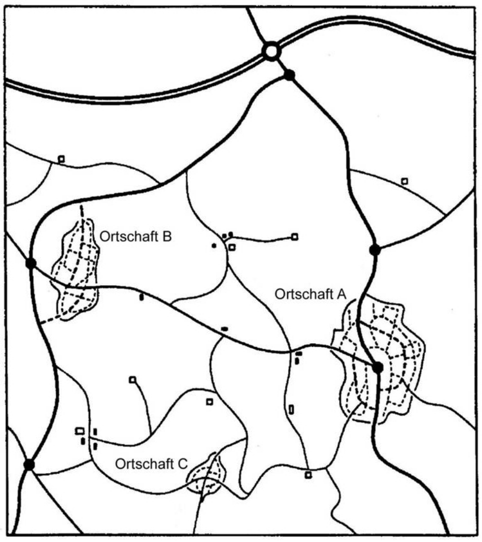


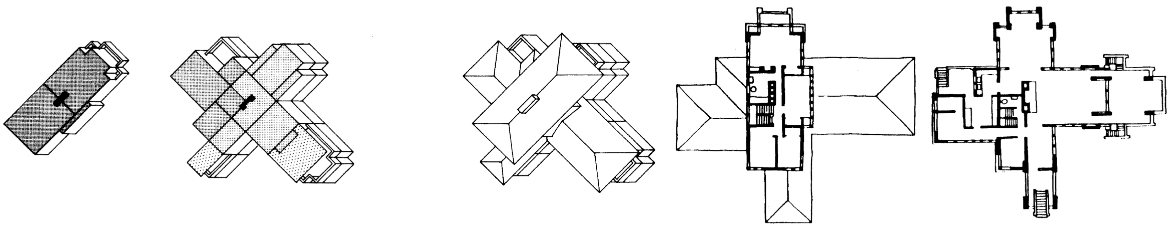
Figure 1.6: Examples of grammar rule applications related to the rules in Figure 1.5.

(a) The Swiss norm for road network design (VSS, 1992) p.5.

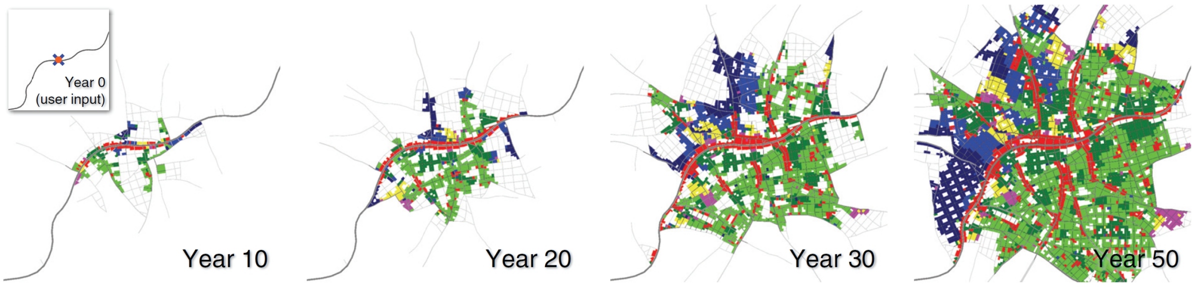


(b) Example city design of Alexander (1979) p.190.

(c) Prairie house from Stiny (1985) p.12 built on grammar rules.



(d) Urban simulation outcome of Weber et al. (2009) p.4.



Chapter 2

Terminology, Review and Objectives

"An advantage of a constitution-led approach is that it builds into it the desired relationships of structure between local and strategic routes and route types, without presupposing any particular final form. This makes it particularly suitable for use in design guidance, since a single ' code' or 'program' can generate a diversity of layout patterns which can themselves be adapted to local circumstances. And, although the final pattern is not prescribed, when a pattern does emerge, it should be coherent, legible and functional, because the parts that are put together embody the relationship with the whole." (Marshall, 2005, p.227).

This chapter defines the most relevant technical terms (Section 2.1). Furthermore, Chapter 2 discusses the various shape grammar applications (Section 2.2). It classifies the applications systematically regarding their content, purposes, and fields of origin (Section 2.3). Consecutively, this chapter condenses the existing rule based approaches to formulate a general definition of shape grammars for transport planning (Sections 2.4 and 2.5). Relying on the consolidated definition of grammars from the previous section, this chapter crystalizes the general problems in network and urban design (Section 2.6) and defines the research questions for this thesis focussing on grammars (Section 2.7)

2.1 Terminology

This section discusses technical terms which are found in the field of network design. These terms are picked up again later in this thesis.

2.1.1 The Network Design Problem (NDP)

In the literature, the graph optimization problem is well known as the network design problem (NDP), and focuses primarily on adding infrastructure to an existing network topology. In the literature, the NDP has been studied in depth; some examples are LeBlanc et al. (1975) or Sumalee et al. (2006). Often, the NDP is formulated and solved based on a general bi-level framework with network optimization in the upper level for a given objective function (e.g. Gao et al., 2005; Kepaptsoglou and Karlaftis, 2009), and an assignment problem in the lower level. In public transportation, headway, line routing are most relevant, and can be solved with appropriate design algorithms (e.g. Fan and Machemehl, 2006b).

The NDP can be formulated as a standard optimization problem. The problem statement for road networks encompasses the candidate road links **x** between nodes $(i, j) \in N$ of length $l_{i,j}$. a defines the the total construction costs of the transport network. c defines the generalized user costs, and depends on the network and selected road links **x**. A penalty p_+ penalizes budget B violation.

Additionally, link type $t \in T$ is determined with the corresponding infrastructure costs w_t, which comprise construction costs, but omit maintenance costs for simplicity here. Including T refines the problem definition, compared to a standard definition in literature.

The total costs result from the minimization:

$$\text{minimize} \quad a + c + p_+ \tag{2.1}$$

$$\text{subject to} \quad a = \sum_{(i,j)} x_{i,j,t} \cdot l_{i,j} \cdot w_t \tag{2.2}$$

$$c = f(\mathbf{x}) \tag{2.3}$$

$$p_+ = \begin{cases} 0.0 & \text{if } a < B, \\ \gamma \cdot (a - B) & \text{else.} \end{cases} \tag{2.4}$$

$$\text{whereas} \quad (i, j) \in N, t \in T, \mathbf{x} \in \{0, 1\}^{|N| \times |N| \times |T|} \tag{2.5}$$

$$\mathbf{c} > \mathbf{0}, B > \text{cost for minimum spanning tree network.} \tag{2.6}$$

Depending on the problem formulation, the necessary calculations to solve the NDP might become very costly and cumbersome due to high complexity, often making the proposed solution algorithms impractical for a realistic case. After solving a specific NDP problem, the outcomes are valid on one specific site, and might not be transferable to other sites. Moreover, the NDP can fail in political and social decision making processes, and in jurisdictional initiatives for new infrastructure developments (Levinson et al., 2012).

Transport network design goes beyond the standard NDP focussing more on topology, and can additionally cover road and intersection type design (capacity, speed, ...) in a discrete manner, e.g. in hierarchies. Intersection type choice is relevant especially in denser networks.

2.1.2 Topology and Morphology

The American Planning Association (2006) defines urban morphology as

"the study of the city as human habitat. Urban morphologists analyze a city's evolution from its formative years to its subsequent transformations, identifying and dissecting its various components. The city is the accumulation and the integration of many individual and small group actions governed by cultural traditions and shaped by social and economic forces over time. Urban morphologists study the outcomes of ideas and intention as they take shape on the ground and mold cities. Buildings, gardens, streets, parks, and monuments, are among the main elements of morphological analysis" (American Planning Association, 2006, p.401).

Topology rather focuses on the network graph, and studies shapes and their properties. Topology refers to non-metric information such as connectivity, orientation, adjacency and containment, or proximity, separation, succession, continuity, and closure (Marshall, 2005, p.103).

2.1.3 Patterns

The meaning of pattern is twofold. Patterns can be designed or patterns may be emergent. In the first case, patterns often refer to a particular geometric layout, as a scale plan, featuring absolute position and lengths. Patterns can describe an extracted spatial form which is made of a number of elementary building blocks. A pattern can be used as an archetype for future planning. Example patterns are layouts often used in design handbooks (e.g. AASHTO, 2004; VSS, 1994b; FGSV, 2008b). Lynch (2001) mentioned star, grid, axial, nested, and other kinds of patterns, similar to Marshall (2005). Network patterns are assessed and compared in science (e.g. Snellen et al., 2002; Xie and Levinson, 2007; Estrada et al., 2011).

In the case of emergent patterns, patterns can be used as algorithmic structures to generate urban designs (Alexander et al., 1977), which is in contrast to the above definition. In a bottom-up approach, no preconceived pattern exists; urban patterns unfold incrementally (Marshall, 2005). So the result is an assembly of urban elements. Alexander et al. (1977) describe the unfolding process in their seminal books "A Pattern Language". This can lead to some misunderstanding, especially when comparing with the archetype patterns described above.

2.1.4 Syntax

The syntax consists of the rules to govern distinct elements, like words in linguistics, or elementary building blocks in urban planning. The expression is widely used in computer science to describe the combination of elements to build up a structured source code. Also, architects and urban planners often refer to the syntax, and assemble urban elements according to distinct rules.

The following definition extracts the major components of an early definition (Chomsky, 1956, 1959). The syntax $\mathcal{R}$ describes in the form of a finite number of rules how elements e of the same or different type are added to each other. $\mathcal{I}$ defines the initial assertion where the algorithm starts. $\mathcal{E}$ is the finite set of non-terminal elements e. $\mathcal{R}$ is a set of rules r in the form of $\alpha \rightarrow \beta$, where $(\alpha, \beta) \in \mathcal{E}$. $\mathcal{R}$ includes rules to stop the algorithm after initialization. The result is the infinite set of urban transport systems.

The rules describe how given planning states and urban geometries are extended to another state. Normally, $\alpha \neq \beta$ is valid, which means that an element e cannot be transformed in itself, in order to build up an urban system. Additionally, $\alpha \rightarrow \{\beta_1, \beta_2\}$, and $\{\alpha_1, \alpha_2\} \rightarrow \beta$ are valid, because network design shape grammars are nonreversible. The stopping criteria is often related to budget, or space constraints in planning applications.

As an example, Table 2.1 proposes a context-free syntax $\mathcal{R}$ with corresponding elements $\mathcal{E}$ for hierarchical design. $\mathcal{R}$ ignores external specifications, and therefore is called context-free (e.g. Friedman et al., 1992). The elements e can further be subdivided for more details, to follow further rules, and to cover additional fields in urban planning, besides transportation. Figure 2.1 displays another example of a hierarchical design, which is similar to $\mathcal{R}$ in Table 2.1, but extended with additional intersection types. Marshall (2005) explained the rather "mechanistic" character of these rules. Many advantages occur as a rule based approach is used. Rules allow flexibility and a diversity of outcomes. The application of rules allows for more adaptive networks e.g. for variable urban densities of terrain, compared to the rigid and standardized patterns like gridirons.

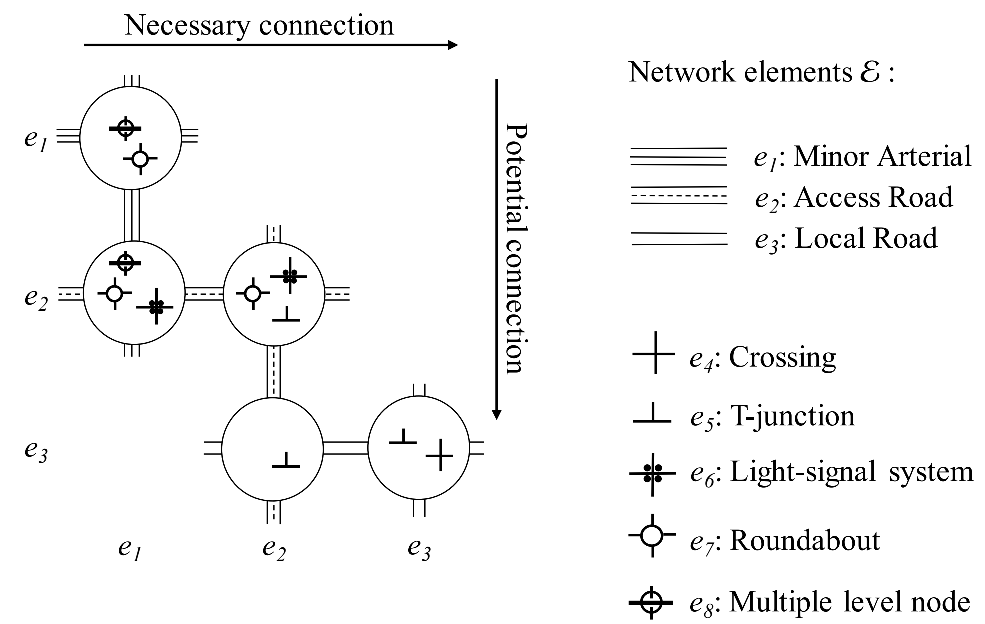
2.1.5 Shape Grammars

Grammars are defined differently in various fields of science. Chomsky (1959) and Stiny and Mitchell (1980) provide definitions for linguistics, architecture and urban planning, respectively. It can be summarized that grammars consist of a well-defined set of rules (syntax). However, it is claimed that the syntax alone is insufficient to generate a reasonable outcome. It is claimed that grammars further include application specifications which resembles semantics. Application specifications are instructions for efficient applications. Moreover, they can

Table 2.1: Example context-free syntax $\mathcal{R}$ for hierarchical network design with a corresponding set $\mathcal{E}$ of defined, generic road and intersection elements e.

Formal rule	Description
Vocabulary $\mathcal{E}$ ={e_1, e_2, e_3, ...}	
e_1	*Arterial road*
e_2	*Access road*
e_3	*Local road*
e_4	*Right of way junctions*
$\rightarrow$	The left side of "$\rightarrow$" is transformed to the right side of "$\rightarrow$".
$+$	The left side of "$+$" is adjacent to the right side of "$+$".
Context-free syntax $\mathcal{R}$ ={r_1, r_2, r_3, ...}	
r_1: $e_1 \rightarrow e_1 + e_1$	Network connectivity requires arterial roads to connect to other arterial roads.
r_2: $e_1 + e_1 \rightarrow e_1 + e_1 + e_2$	Arterials can be joined with an access road if a connected arterial network is maintained.
r_3: $e_2 + e_3 \rightarrow e_2 + e_3 + e_4$	An access road connected to a local road requires a right of way junction.
r_4: ...	

Figure 2.1: Example of rules for a hierarchical road network design.



Source: based on Marshall (2005).

refer to background information and therefore contain information about the origin of the corresponding rules. The application specifications can e.g. define the adjacent spatial structures, and requirements. "Shape" refers to a planning and design context. The application of shape grammars at different adjacent spatial structures can therefore lead to different outcomes.

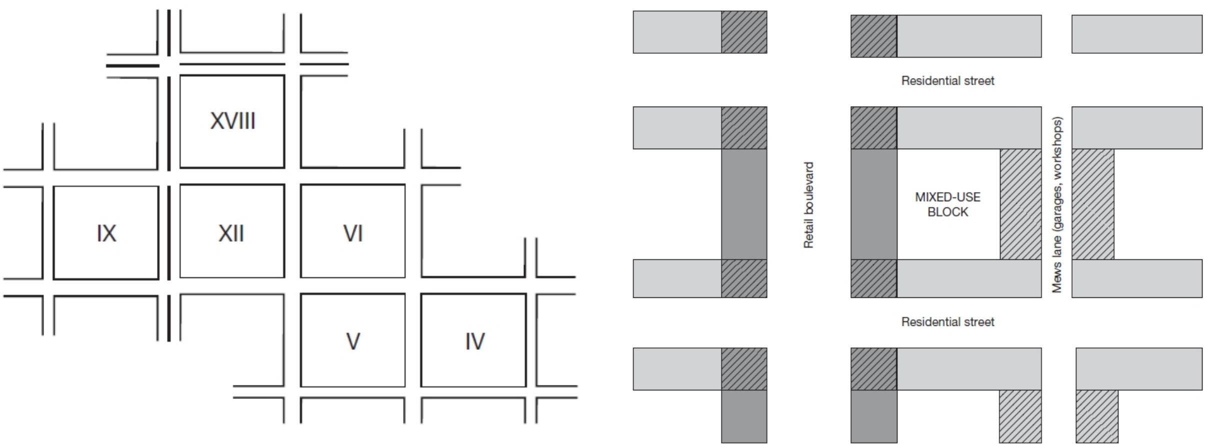
The differentiation between shape grammars and patterns is subtle and not necessarily universal; shape grammars are also said to enable the codification of patterns. Section 2.4 elaborates on the definition of shape grammars as suggested in this thesis.

2.1.5.1 Example Shape Grammars 1

Example 1 refers to road type distribution within a given network topology. The syntax of a hierarchical network design is described already in the Section Syntax and in Figure 2.1. Application specifications are further required for more meaningful designs. In the example of Figure2.2, Marshall (2005) additionally defined land use types adjacent to the road types. These specifications state that the grammar rules need to be embedded in a denser urban area, and moreover, they should match the land use types adjacent to the roads for meaningful design. Figure 2.2(a) shows the assignment of 6 block types and the interplay with adjacent street types. Figure 2.2(b) allows even mixed-use within the same block. Both examples show that the rules stated above are not stand-alone rules, they are embedded in a set of additional specifications, which have to be considered in planning.

Figure 2.2: Hierarchical road network design and adjacent block types.

(a) Adjacent block types. (b) Mixed adjacent block types.

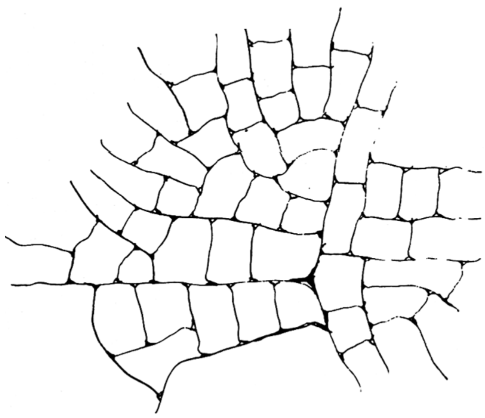


Source: Marshall (2005) p.240, 241.

2.1.5.2 Example Shape Grammars 2

Example 2 refers to an network topology, suggested by Alexander et al. (1977). Example shape grammars 2 state that junctions should not have more than 3 arms, justified by safety reasons. Safety therefore is the main objective in this case and when applying this specific grammar. Similar to that, T-junctions were suggested in the United States due to safety reasons (Southworth and Ben-Joseph, 2003). Alexander et al. (1977) proposed rules for different purposes, such as towns, buildings and construction. Alexander et al. (1977) provide comprehensive description and application specifications along with many of the described rules. It is shown that rules are applied in a certain environment and serve a specific purpose. Background information on the objectives of these rules is additionally provided, as well as general advice on the application of the rules. Figure 2.3 shows a potential outcome when applying T-junctions in network design.

Figure 2.3: Exemplary T-junction network layout.



Source: Alexander et al. (1977), rule Nr. 50.

2.2 Research and Application of Shape Grammar Rules

Grammars are widely applied in different fields of science. Table 2.2 lists selected cognate disciplines applying grammars, referring first to the field of linguistics and computer science as early milestones in grammar evolution. The subsequent achievements evolved in parallel or consecutively and are described consecutively. The fields listed are all tied to transport and urban planning, however, even more fields apply grammars, such as anthropology (e.g. Baumann, 2004).

Grammars are systematically applied in *linguistics*. Chomsky (1956, 1959) has been one of

Table 2.2: Major cognate fields of shape grammars applications.

Field	Elements (vocabulary)	Grammars	Results	Exemplary sources
Linguistics	Words out of characters, punctuation	Phrase structure, grammar rules	Text	Chomsky (1956, 1959)
Computer Science	Objects, instances, abstraction, inheritance	Methods, algorithmic procedures, cellular automata	Software program	Abady and Gardelli (1997), Wolfram (2002), Batty (2005)
Geometry	Alphabet of symbols and shapes (Point, edge, ..., n-dimensional object)	Algorithmic procedures, geometric transformations, structural relationships	n-dimensional shape	Stiny and Gips (1972), Stiny (2000), Lord and Wilson (1984), Prusinkiewicz and Lindenmayer (1996)
Architecture	Building Blocks	Standards, structural rules, zoning plans, function based rules, aesthetic rules	Building, structure, extensions	Alexander et al. (1977), Mitchell (1990), Wang and Duarte (2002), March (1972), March (1976), Coates (2010), Yazar and Colakoglu (2007), Duarte et al. (2007)
Urban Planning	Buildings, public and private areas, parcels, neighborhoods, cities	Standards, zoning plans, function based rules, aesthetic rules, urban codes	Urban layouts, city plans, neighborhood design, regions	Stiny and Mitchell (1980), Sorkin (1993), Cowan (2002), Duany et al. (2009), Lehnerer (2009), Beirão (2012)
Transportation	Roads, pathways, intersections, lanes, tracks, lines, vehicles, stations, stops	Standards, safety rules, guidelines	Transport networks and supply for different modes	Marshall (2005), Yerra and Levinson (2005), van Nes (2003), AASHTO (2004)

the first contributors to formal grammars. A formal language is defined as a language $\mathcal{L}$, independent of its field or origin, of an infinite set. However, the language and structure of $\mathcal{L}$ can be investigated through the study of finite devices, which are the grammars $\mathcal{G}$, and which are capable of enumerating its sentences (Stiny and Gips, 1972). Based on this linguistic definition the shape grammar language $\mathcal{L}(\mathcal{G})$ has been modified, specified and transferred to many other fields.

Mathematics, and particularly *logic*, employed grammars at an early stage. Logic defines an alphabet which consists of terms, symbols, and variables. Formulations follow defined rules. E.g. "=" is defined as standard equality; both sides of the formulation are equal. Sentences can be generated, following the rules and above alphabet. At this point, it is interesting to note that Fagin (1974) subdivided all sentences of logic, especially complex problem formulations, into two distinct classes: $\mathcal{P}$ (solvable in polynomial time) and $\mathcal{NP}$ (Non-deterministic Polynomial-time hard). This classification subdivides sentences according to their complexity (Garey and Johnson, 1979; Zimmermann, 2008). If n is the problem size, and $\mathcal{O}\big(f(n)\big)$ the calculation costs, $f(n)$ is a polynomial function for all problems in $\mathcal{P}$. Design problems, e.g. network design, are often $\mathcal{NP}$ (Johnson et al., 1978) and solvable only in exponential time. This affects transport and spatial planning considerably, and leads to long calculation times in its optimization algorithms. Therefore, heuristics have become more interesting in recent years to solve complex problem formulations.

Operations research and especially *artificial intelligence* profit from optimization rules to solve complex problems, especially in (meta-)heuristics. An example is given by Goldberg (2002). The well-known building blocks are defined clusters in a genetic code, similar to genes in a genome. Instead of recombining single elements of the genome, clusters of multiple and efficient elements are recombined to futher improve efficiency. Coates (2010) takes up on this idea and defines buildings as clusters. Both examples show rule-based methods in the field of operations research.

Computer sciences implement precisely defined syntactic structures for various applications. One has to emphasize that the syntax alone is insufficient for working code. Interpreters are required to perform the actions indicated in the code. Errors can still occur even with a syntactically correct code, e.g. null-pointer exceptions. A working code does not necessarily fulfill the requirements of the user, and is not meaningful per se. E.g. cellular automata (Wolfram, 2002) describe rules to continue from a starting or intermediate state to a consecutive state; however, they might not pursue an overarching goal. Therefore, stand-alone rules are inefficient without a detailed description of the application specifications. This also holds for planning, which can be shown later in this chapter.

In *geometry*, Stiny and Gips (1972) and Stiny and Mitchell (1978, 1980) remain influential. The geometry-based languages can be used for geometric art objects such as paintings, or sculptures. The application fields range from geometric paintings, procedural modeling, evolutionary and growth processes to conceptual design and aesthetic and visual arts. Beside many other geometric applications, Prusinkiewicz and Lindenmayer (1996) proposed the L-System, which consists of grammar rules and an alphabet of symbols, making larger and more complex system possible through recursion, such as plant morphologies.

Various authors have contributed to grammars in architecture, urban planning and transportation at the same time due to overlapping design aspects. The most relevant examples are mentioned below.

In *architecture*, the seminal contribution of Alexander et al. (1977) applied grammar principles to the languages of architecture and urban planning. The pattern language of Alexander et al. (1977) consists of a vocabulary including settlements, buildings, elements of the buildings and therefore varies in scale and covers architecture, urban and transport planning. The grammars describe which elements of the vocabulary and their combinations are more desirable and which combinations are inadvisable. March (1976) assign geometric design of buildings to an elementary boolean code, including elements and operations. The methods of Stiny and Gips (1972) and Stiny and Mitchell (1980) are also adapted to design and construction purposes. Especially the prairie houses of Frank Lloyd Wright were evaluated regarding their grammar (Koning and Eizenberg, 1981; Stiny, 1985). Recently, grammars are increasingly used in the visualization of buildings and in the film industry (Parish and Müller, 2001; Vanegas et al., 2010), which also relates to computer science.

In *urban planning*, Sorkin (1993) and Cowan (2002) developed guidelines and prescriptions for general urban development in a qualitative way. Their work can be related to the movement of New Urbanism (Dutton, 2000; Haas, 2008; Mehaffy, 2008). Following up on the idea of New Urbanism, a new set of codes were developed for urban design. At a very early stage, Stübben (1907) contributed to a formal definition of street segments, and their relations. Smart Code (Duany et al., 2009) is a well-known rule set, incorporating all scales of urban planning, and is applied in multiple neighborhoods in the US and worldwide. Sustainable Street Network Principles (CNU, 2012) were developed for transportation reform and contributed to the field of New Urbanism. The focus is on walking and improved pedestrian infrastructure and other modes of transport. A growing number of software solutions apply shape grammars for urban simulations (e.g. ESRI, 2012; UrbanVision, 2012).

In *transportation*, multiple norms and guidelines propose network design recommendations (AASHTO, 2004; IHT, 1997; VSS, 1994b; FGSV, 2008b) such as hierarchical road layout. However, already at an early stage, LeCorbusier (1955) applied a strong hierarchical approach to city planning similar to a rule based approach. He suggested a hierarchical approach for road network design. The idea of a hierarchical approach is implemented in different standards of western countries. Alexander et al. (1977) contributed to the discussion of road network layouts. Marshall (2005) introduced shape grammars by defining relationships between network element types without presupposing any particular final form. Van Nes (2003) and Yerra and Levinson (2005) followed up on the hierarchical network layout and specified spacing, hierarchies, economic impacts and additional aspects.

2.3 Taxonomy

This section narrows down the broad view of Section 2.2 to urban and transport planning, and provides a systematic overview over the existing set of shape grammar rules.

Existing shape grammar classifications for urban planning and transportation can be found e.g. in Alexander et al. (1977) and Marshall (2005). Drawing on broader existing literature, shape grammars can be assigned to divisions and classes, as shown in Table 2.3 for transport networks, and Table 2.4 for urban planning. A function-based classification is proposed to address the purpose of each grammar. The divisions include *geometry*, *composition*, and *investments and regulations* to subdivide the entire shape grammar set for both urban and transport planning. Table 2.3 and Table 2.4 serve as an overview over existing shape grammar rules. They can be extended with more examples and even additional classes.

Two road network elements, road segments and intersections, and their attributes are classified in Table 2.5. Table 2.5 only describes attributes which affect network users directly. As an example, ownership of existing roads mostly does not affect network design and therefore is ignored in Table 2.5. In contrast, e.g. toll collection does affect the driver and is therefore included in the classification. Table 2.5 is an example classification for road elements. A potential classification in urban planning might include "roads", "tracks", "blocks", "zones", "landscapes" and "focal points" as elements of an urban design language (Lynch, 1960).

Table 2.5 provides three subcategories for a detailed taxonomy on the element level. The first subcategory *form* refers to geometry and spatial orientation. The second subcategory *regulation* refers to the elements and their types, attributes and restrictions, e.g. road types and characteristics. The third subcategory *characteristics* refers to the interpretation and cognitive perception of the driver regarding his/her actual situation and the classification of the road. After describing the elements of the road network (vocabulary), Table 2.6 shows a classification for shape grammars and specific evaluations for road network design.

Table 2.3: Classification of transport planning shape grammars.

Divison Class	Description	Exemplary sources
Geometry:		
Angle	Angle of adjacent road types	Vanegas et al. (2009a)
Loops	Circuit or cell-based road and line alignment, size of circuits	Levinson and Huang (2012)
Numbers	Number of arms for intersections, dead ends, number of lanes for road types	Alexander et al. (1977), Vanegas et al. (2009a)
Curvature, slope	Curvilinear design, steepness	Weber et al. (2009)
Composition:		
Connectivity	Connected elements, e.g. connected freeway or high speed rail	AASHTO (2004)
Function	Adjacent land use and building types, road access, parking, toll cordon	Marshall (2005), Dutton (2000)
Hierarchy	Hierarchical road and intersection type distribution, Hierarchical service type distribution, stop densities, service frequency	Marshall (2005), Weber et al. (2009), Gil and Read (2012), VSS (1992), FGSV (2008b), Marshall (2005)
Variation	Irregularity and variance in design (e.g. in old town vs. in uniform grid)	Alexander et al. (1977)
Investments and regulations:		
Density	Total road length, total number of intersections, block size, parallel roads, stop intervals	Van Nes (2003), Levinson and Huang (2012), Levinson et al. (2012)
System	Transport modes	LeCorbusier (1955), Geddes (1939), van Nes (2003)

2.4 Contextualized Grammar Definition

The following sections aim at a theoretical justification of grammars, and their theoretical feasibility for planning purposes with corresponding semantics. Therefore, theoretical arguments for grammar rules and their application, limitations and constraints are described in the following. Especially, it is claimed that grammar rules are insufficient for planning purposes without corresponding semantics.

Multiple distinct definitions of grammars exist in linguistics. The distinct definitions approach syntax, language, and semantics in different ways. Scanning recent literature about grammars discloses an ongoing debate even in linguistics, which complicates transferability of findings to transport and urban applications. Therefore, a general definition of shape grammars is proposed for urban and transport planning, contextualized, and justified based on the current literature

Table 2.4: Classification of urban planning shape grammars.

Division Class	Description	Sources
Geometry:		
Building shape	Footprint, 3D shapes, angles	Stiny (1985), Schirmer and Kawagishi (2011)
Parcels, neighborhoods	Assignment and design	Kaisersrot (2011), Lynch (1981)
City design	Assignment and design, land use, prices	Alexander et al. (1987), Lehnerer (2009), Batty (2005), Duarte et al. (2012), White et al. (2012), Duarte et al. (2007)
Constitution:		
Function	Building and neighborhood type	Kaisersrot (2011), Duany et al. (2009), Dutton (2000)
Material, and construction		LeCorbusier (1955), Stiny and Mitchell (1980), Heisel and Yitbarek (2013)
Investments and regulations:		
Density	Units, population, building mass and densities	Bramley and Power (2009), Geddes (1939), König and Müller (2011), Duany et al. (2009)
Ownership and social interaction	Public and private space	Copper Marcus et al. (1998), Lehnerer (2009), Dutton (2000), Mikoleit and Puerckhauer (2011)

about grammars in cognate fields. This section aims at the properties of grammars and seeks to define "grammars" as encompassing and ultimately necessary for planning applications.

It is assumed in the following that shape grammars are applied in an urban and transport planning context. Moreover, it is assumed that the planners act rationally and follow a certain overall intention, e.g. a sustainability goal or cost minimization, which is explicitly defined, or implicitly followed. The expression "objective" is deployed to define the intention in a qualitative or quantitative manner. Additionally, it is supposed that planners act in a spatially defined area, called "site", which they intend to change directly, or indirectly, through structural changes.

Figure 2.4 summarises and embeds the grammar context. It is shown that the grammars consists of syntactic rules and corresponding semantics. As in computer science, rules without semantics can generate outcomes with are meaningless. Therefore, the syntax alone as it is defined in Section 2.1.4 is insufficient to generate a reasonable outcome, e.g. for an urban planning environment. A priori it is not clear that "=" refers to equality on both sides of the sign, and

Table 2.5: Major attributes of roads and intersections.

Element e	Subcategory	Attributes
Road segment	*Form*	Number of lanes, width, curvature, steepness, adjacent parking and driveways.
	Regulations	Speed limit, driving direction, lane switching restrictions, permitted users, toll.
	Characteristics	Quality and condition, adjacent structures (e.g. sidewalk, land use types), year built, other modes.
Intersection	*Form*	Diameter, layout, number of lanes, roundabout / traffic refuges.
	Regulations	Control type, allowed and prohibited turns, right of ways, permitted users.
	Characteristics	Quality and condition, adjacent structures (e.g. sidewalk, land use types), year built, other modes (e.g. bicycles, pedestrians).

what is meant by equality. It is unclear if both sides need to be exactly the same object (e.g. same pointer in computer science), or if it is sufficient that both sides are congruent in their characteristics.

It is obvious that a rule is limited to a certain purpose or meaning. Certain rules are designated for a specific context. Application specifications can describe the required environment to apply the rules, e.g. housing construction in the tropics requires other rules compared to moderate climates. The environment can include adjacent infrastructure or global components like weather, social parameters, etc.. Or, certain rules might be defined for urban environments while others for rural environments. Therefore, beside the syntax, grammars moreover include application specifications. The application specifications are valid for one specific rule and therefore contrast the "site" definition above, referring to the planner's view. The inclusion of application specifications differs from the definition of context-free grammars (Chomsky, 1956, 1959). Applying the same rule with different application specifications might lead to a different outcome. Specifications are equivalents to semantics in linguistics. Therefore, Figure 2.4 subdivides grammar $\mathcal{G}$ in syntax $\mathcal{R}$ as a rule set, and semantics $\mathcal{S}$ as corresponding application specifications. $\mathcal{R}$ is responsible for the "mechanics" of a certain language $\mathcal{L}$. $\mathcal{S}$ is basically responsible for all the information except the rules themselves. In particular, $\mathcal{S}$ contains information about the effect of $\mathcal{R}$, such as effects on efficiency, safety, etc.. Moreover, $\mathcal{S}$ defines the application range in which $\mathcal{R}$ can be applied for reasonable design. This specific subdivision of $\mathcal{G}$ in $\mathcal{R}$ and $\mathcal{S}$ also allows a more specific phrasing. Semantics are excluded, when referring to rules. Rules and semantics are both addressed when referring to grammars. The application specifications obviously limit the application range of the grammar rules. Reassessment,

Table 2.6: More detailed classification of shape grammars and network evaluations for road network design.

Class name	Description	Sources
Hierarchy	Hierarchical road and intersection type alignment	Marshall (2005), Weber et al. (2009)
Geometry	Angle of adjacent road types	Vanegas et al. (2009a)
Cycles	Size and shape of cycles	Strano et al. (2012)
Densities	Number of arms for intersections, dead ends, number of lanes for road types	Alexander et al. (1977), Vanegas et al. (2009a)
Spacing	Block size, parallel roads	Van Nes (2003)
Curvature, grade	Curvilinear design, terrain grade	Weber et al. (2009)
Density	Total road length, total number of intersections	Strano et al. (2012)
Coherency	Coherent elements (e.g. connected freeway)	AASHTO (2004), VSS (1994a)
Function	Affiliated land use and building types, distribution / road access, parking, toll cordon.	Marshall (2005)
Variation	Irregularity and variance in design (e.g. in historical cores vs. uniform grid).	Alexander et al. (1977)

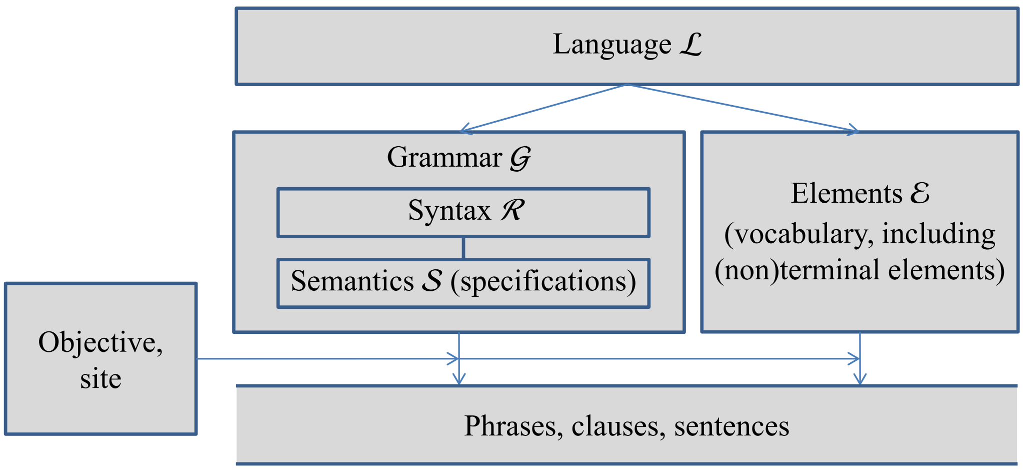
discretion, and expert knowledge might adapt existing rules and application specifications.

The lower two elements in Figure 2.4 refer to the application of shape grammars, and therefore include planners objective, site, and the resulting urban design. Obviously, the phrases, clauses or sentences represent buildings, neighborhoods, or transport networks in the case of urban shape grammar applications.

Supplementing the definition of shape grammars, "shape" can be defined in a rather technical way. From a geometric perspective (e.g. Lord and Wilson, 1984), shape includes a set of marks, with position and orientation. Here "shape" refers to a planning and design context. Stiny and Mitchell (1980) or Beirão (2012) also defined shapes from a strongly geometric perspective.

"Shape" is slightly ambiguous in the context of transport network, due to the fact that grammars not only apply to physical shapes, but also to certain functionalities like speed limits for road types and priority rules at intersections. Still, "shape" is widely used in the urban planning context. Therefore, it is referred to shape grammars in the following but the expression also

Figure 2.4: Contextualized language setup for shape grammars with exogenous planner's objective.



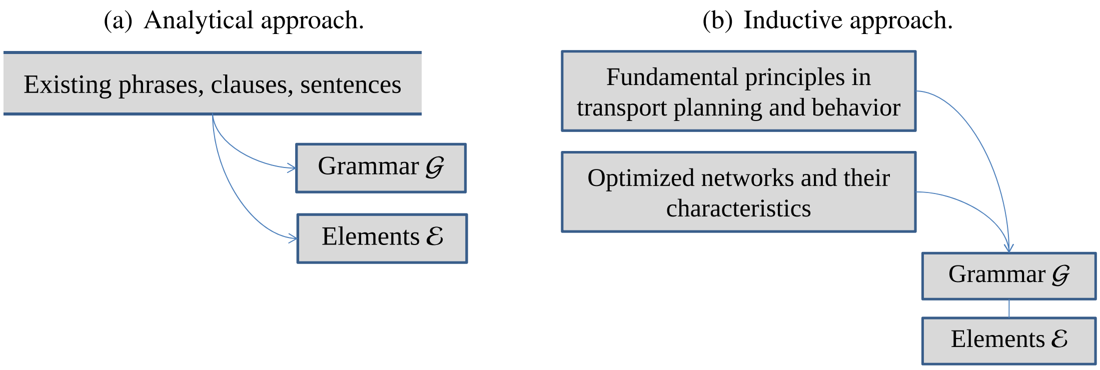
includes shapes in the wider sense, therefore also e.g. capacities, speeds.

2.5 Similarities and Differences Regarding Existing Approaches

Beirão (2012) referred to shape grammars and semantics. He highlighted the missing interpreter, which is similar to the missing semantics stated above, and similar to Fleisher (1992) who also recognized the failure of the missing linkage between grammar rules and semantics. Moreover, Beirão (2012) stated that literature exists about rules, but they are difficult to apply due to the lack of meaning and interpretation. The stated matching problem refers to the difficulties of applying the grammars in the right way.

Beirão (2012) mentioned that grammars of natural languages are already accepted agreements and a premise in applications. This leads to a consistency problem when designing, because the grammar is not a premise but one of the products of the design process. Therefore, on one side, grammars already exist in natural and eventually design languages. Then, grammars can be extracted and determined analytically from the environment, e.g. case studies, and can be further pursued in future applications. On the other side, grammars have evolved over time and are the results of the needs and requirements of the language users. At this point, the analytical approach of extracting grammars and the applied approach of this thesis fork in their methodologies. Whereas the analytical approach (Figure 2.5(a)) extracts grammars from the environment by reverse engineering (e.g. Courtat et al. (2011) and the empirical evaluation of link lengths and angles), the following approach of this thesis defines grammar based on fundamental knowledge of the functioning of a design issue, here transport networks. If it is known that certain features, e.g. a specific intersection type, is more efficient in certain cases, this knowledge should be formulated and stated within an appropriate rule. Moreover, existing design handbooks can rely on these findings. This approach is named inductive approach (Figure 2.5(b)), and is elaborated throughout this thesis.

Figure 2.5: Schematic differences between the analytical and inductive approach for shape grammar definition.



Differences between the analytical and inductive approach can be observed in the existing literature, e.g. between the grammar approach of Stiny and Mitchell (1980) or Beirão (2012) which focuses especially on geometry and which is based on case studies, and the approach of Alexander et al. (1977) which describes the grammars in a more descriptive manner based on e.g. safety consideration.

Similar to Alexander et al. (1977), the proposed shape grammars are formulated and defined in a descriptive manner. Reasons for a descriptive formulation of shape grammars might be the complexity of urban networks, e.g. the design conflict (Section 8.5). It is stated that the generated grammars cannot be defined in an abstract manner or as geometric output. E.g. the city design might be a combination of a gridiron and signals, but depending on the purpose and the major modes using the gridiron, the gridiron has a different spacing and is combined with different intersection types. It will be shown that the spacing should increase as turn delays increase. Summing up, a context-free rule can not exist for a final definition of a network topology such as road spacing.

2.6 Problem Formulation

Numerous rules for urban and transport network design can be put up for a generic urban design, some of which were discussed in Section 1.4. This section focuses on the current drawbacks of existing rules for planning, specifically on the missing guidelines and missing knowledge about shape grammar rules and their impacts.

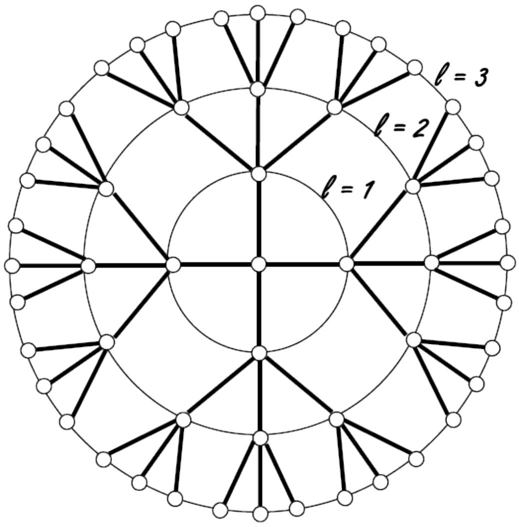
Norms and design guidelines are well-known platforms for recommendations about network design for both transport and urban planning. As already discussed in Section 1.1, current transportation design guidelines describe only some aspects of urban design and network topology. Some of the planning recommendations are vague, while others merely rely on past developments and needs. Overall, a consensus in "best practise" on transport network design is currently vague, despite numerous existing and distinct urban networks, and extensive planning expertise.

Historical spatial development has created various network patterns, which are bequeathed to the current and future generations. Medieval structures contrast baroque layouts and gridirons, garden cities, modernist, and lollipop networks (Figure 1.1 or e.g. Lampugnani, 2010). Urban networks are considerably different across cities, as shown in e.g. Jacobs (1993), and as shown in corresponding statistics for various network attributes in Cardillo et al. (2006). A graph-based evaluation of transport networks of Cardillo et al. (2006) showed low performance, based on shortest paths of dendritic networks, e.g. Walnut Creek, and modernist fabrics which often are designed from scratch and in a top-down approach, e.g. Irvine, Brasilia. In comparison, the performance increases considerably in medieval (e.g. Ahmedabad, Cairo, London, Venice) and grid networks. The question arises whether these findings can be confirmed from a transportation perspective, and how results can deepen the understanding of network design, and improve recommendations for urban planners.

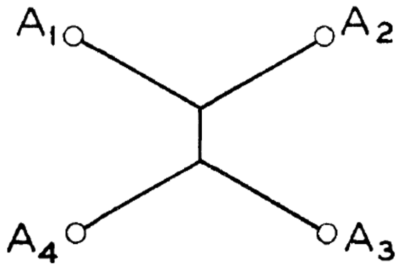
The determination of appropriate urban network topologies is tackled widely in literature and practise. To fulfill these tasks, researches and planners face major challenges due to the complexity of urban networks. This paragraph explains on two characteristics related to road network topology and its complexity. Both characteristics can largely be reduced to the principles of graph theory (e.g. Clark and Holton, 1991). The first characteristic is the decentralization of any given network structure. With some exception graphs, such as radial trees with root nodes (hub-and-spoke network), Cayley trees (Clark and Holton, 1991), or Steiner Trees (Figure 2.6), there is a lack of a predefined hierarchy within the set of elements in a graph G, such as nodes and edges, e.g the definition of centralized objects is lacking (e.g. Lämmer et al., 2006). A priori, nodes and edges lack of an order or relevance, also e.g. for reliability and resilience improvements (e.g. Erath, 2011). Peripheral or minor edges might be equally relevant to a certain networks, regarding reliability and resilience, as centralized and major edges (e.g. Johnson et al., 1978). The lack of order or relevance differs from many biological networks such as tree graphs, described e.g. in Viana et al. (2013). Biological networks, such as vascular systems in plants, generally are more affected by a disfunction of an edge closer to the root node. Lämmer et al. (2006) confirms these findings, and states that the "topological organisation is less

Figure 2.6: Selected example tree networks.

(a) Cayley tree with three hierarchy levels.



(b) Steiner minimal tree.



Source: Mazilu et al. (2012) p. 3, Gilbert and Pollak (1968) p.2.

obvious and a hierarchical structure similar to a Cayley tree is not found at all" (Lämmer et al., 2006, p.95).

This brings us to the second characteristic which is the lack of a decomposition of a given urban network into independent subnetworks (subgraphs G_n), similar to a mathematical formula, and therefore the potential reduction in complexity. This holds again for most graphs, except e.g. radial graphs with root nodes. The second characteristic also implies that network elements and their attributes (a) might depend on other attributes $a = f(\mathbf{a})$, including characteristics such as vehicle flow q (Hackney et al., 2007). An example of potential dependencies of attributes is the nonlinear problem of travel demand assignment (Appendix A.2 or Sheffi (1985, p.213)). Another example is the design and choice of road types, which might depend on urban densities and adjacent land use (Figure 2.2). In summary, both characteristics might be obvious, but explain the vast complexity arising in network design.

2.7 Research Questions

The research questions and its constraints are formulated in this section. An overall research question serves as an umbrella, and is subdivided consecutively in more specific research questions 0 – 3. Except for research question 0, the questions are independent of each other. Table 2.7 summarized the research questions below.

Overall research question:

Is it possible to determine shape grammars for transport network design relying on the fundamental principles of transport networks and travel behavior?

Research question 0 deals with the definition and corresponding requirements of shape grammar rules to support existing or new rules with theoretical background information. **Is it theoretically possible to determine shape grammar rules for urban transportation networks?**

Research question 1 queries the effectiveness of existing shape grammar rules, e.g. boulevard design (Jacobs et al., 2002). Only if the effectiveness of existing rules is known, can recommendations for design standards be made for the future. Research question 1 focuses on the evaluation of existing shape grammar rules. **Is it possible to determine the effectiveness of existing shape grammar rules?**

Research question 2 focuses on the determination of new grammar rules. The question is, **if and how new rules and recommendations can be determined for transport network design.**

Research question 3 describes existing but more complex shape grammar rules with interdependencies and their application in network design. Certain shape grammar rules are less evident in their specific application and require additional information. E.g. a hierarchical road type distribution requires specific information about the distribution of the road types; higher infrastructure requirements are necessary at more relevant roads. Moreover, traffic flows and relevance can change quickly in transport networks due to rerouting. Distribution of road types requires a more sophisticated approach. **Can the effectiveness of complex and interdependent shape grammars be evaluated systematically?**

Table 2.7: Research questions summary.

#	Focus of research question
0	General definition and requirements for shape grammars.
1	Evaluation of existing shape grammars.
2	Definition of new grammars.
3	Evaluation of complex shape grammars.

In addition to the research questions, further specifications are necessary to define the scope of the questions. More specifically, with the above research questions, shape grammars are needed to be designed and evaluated for transport planning. Regarding potential shape grammar applications, rules have to be applicable for future planning, and should not only rely on historically contingent real-world transport networks. Due to the fact that historical transport networks were built for past technologies, historical networks might not be appropriate for extracting rules for future developments. Regarding technical feasibility, shape grammars should rely on fundamental principles of transport planning, and consider e.g. delay functions for roads and intersections, or user equilibria. Demand uncertainty should be accounted as well when answering the questions, which means that the effect of a rule is needed to be determined systematically in different networks under various conditions, so to be able to understand the rule in various conditions.

Chapter 3

Methods

"In contrast to many material transport networks in biology, such as vascular, ... the topological organisation (of road networks) is less obvious and a hierarchical structure similar to a Cayley tree is not found at all" (Lämmer et al., 2006, p.95).

Based on the problem definition and research questions of the previous chapter, this chapter propose methods on how to define and evaluate grammars (Section 3.1, 3.2 and 3.3). In addition, Sections 3.4 and 3.5 describe the underlying assumptions for the proposed methods and the evaluated intersection types and turn delay calculations.

3.1 Study Designs

The proposed study design is subdivided below to match the research questions above. Figure 3.3 shows a schematic overview of three proposed study designs. The study designs are independent of each other. As it is shown earlier in Table 2.3, shape grammar rules can be diverse in their content. Some rules describe the overall topology, like the T-junction rule of Alexander et al. (1977), while others describe very specific designs, such as boulevards, or house clustering (Figure 1.5(b)). The definition and validation of one rule might differ from the validation of the other rule. Three study designs are proposed to address the diversity of shape grammar rules and corresponding verification problems. The complexity of the shape grammar rules increase from study design 1 to 3. Study design 0 refers to research question 0 and provides a theoretical justification for grammars.

3.1.1 Study Design 0

Study design 0 discusses the theoretical aspects and justification of shape grammars for a complete and sound definition of their rules for urban planning and refers to research question 0. The goal of study design 0 is to evaluate if the concept of shape grammar rules is sound and feasible in a theoretical and qualitative way, and what prerequisites for shape grammars and the necessary definitions are needed for meaningful applications. Study design 0 is required as a theoretical foundation for further quantitative evaluation methods.

As it is shown in Sections 2.4 and 2.5, the grammars are already theoretically defined, and contextualized in the language environment. Existing research about shape grammars and the general definitions are evaluated and consolidated for an encompassing and contextualized definition of grammars (Section 2.4). Therefore, Sections 2.4 and 2.5 refer to research question 0 and study design 0.

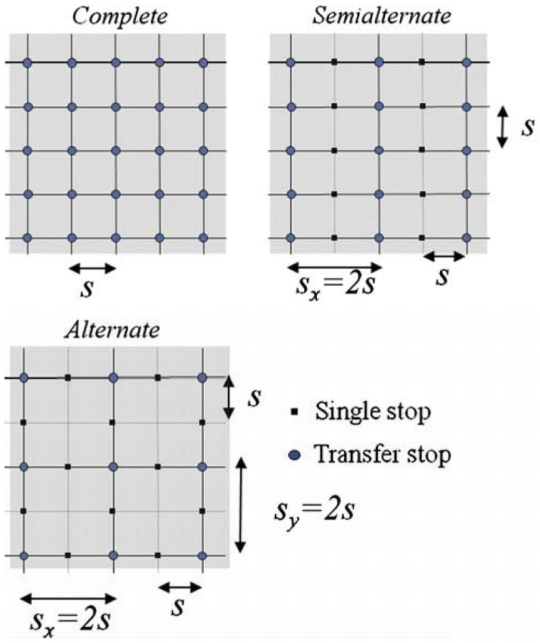
3.1.2 Study Design 1

Study design 1 focuses on already existing and defined shape grammar rules, but which lack specific quantitative evaluations. In study design 1, shape grammar rules are applied and evaluated systematically in different network scenarios and compared with reference scenarios without rules (Figure 3.3(a)). This allows a quantitative comparison of scenario 1 (after implementation), and scenario 0 (before implementation). Therefore, evaluation can be conducted based on the differences between scenarios 1 and 0. The methodology of study design 1 is similar to standard scenario evaluations. However, study design 1 focuses on rules, their effect and the enhancements of rules. It is important, that rules are not evaluated themselves as stand alone rules, but their effects on networks or study areas.

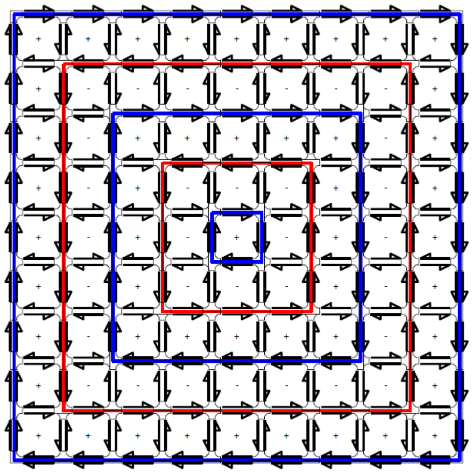
Two examples of evaluations similar to study design 1 are provided in Figure 3.1. Figure 3.1(a) refers to the design of public transport networks. These networks can be described by many variables, such as stop type and spacing, or line density. Figure 3.1(a) shows three public transport networks designed according to certain characteristics (Estrada et al., 2011). These networks are evaluated, and compared regarding an objective function. Additional parameters, such as spacing, are evaluated as well in the paper mentioned. Figure 3.1(b) refers to Eichler et al. (2012), who determined specific intersection types and turn configurations, and evaluated network patterns in multiple example gridiron networks. Eichler et al. (2012) basically applied the study design 1 and evaluated the resulting network for travel distance changes. Both examples in Figure 3.1 describe network scenarios with implemented infrastructure changes. This allows a comparison between scenario 1 (after implementation) and scenario 0 (before implementation).

Figure 3.1: Examples of study design 1.

(a) Public transport network design and different stop types (Estrada et al., 2011, p.940).



(b) Specific intersection types and turn restrictions (Eichler et al., 2012, p.10).



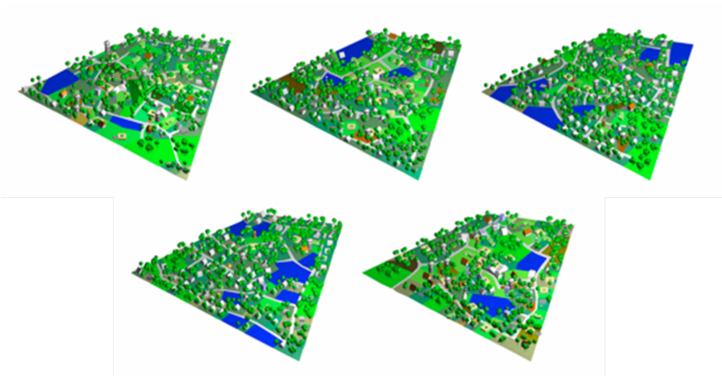
3.1.3 Study Design 2

Study design 2 aims at extracting rules from already designed networks. This approach is only applicable, if it is known which networks are efficient or optimized. Study design 2 assumes that optimized networks feature certain characteristics, which can be determined and extracted for future recommendations and shape grammar rules. It is assumed that the definition of new shape grammar rules can rely on feasible and optimized networks. Then, the designed and optimized networks are statistically evaluated regarding potentially significant characteristics. Multiple networks are needed for statistical analysis and trust in the results. New rules are extracted and statistically justified under various transport conditions. Figure 3.3(b) shows a scheme of the proposed study design 2.

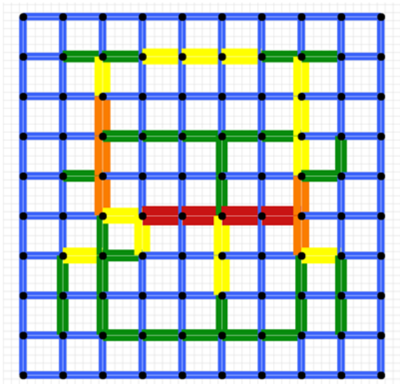
Figure 3.2 shows existing applications of study design 2. They are not specifically applied for shape grammars, but use congruent methodologies. Figures 3.2(a) and 3.2(b) refer to spatial optimization methods, whereas Figures 3.2(c) and 3.2(d) refer to statistical evaluations. Figure 3.2(a) shows some results of the project Kaisersrot (2011). The software developed in this project simulates and evaluates urban scenarios iteratively. The software is applied for parcel relocation and optimization, dependent on certain exogenous parameters. The software designs and optimizes urban scenarios, but excludes potential grammar rule application or extraction. Figure 3.2(b) shows a network on a featureless plane with self-evolutionary structures, evaluation and investment models for optimized road type choice. Both examples in Figures 3.2(a) and 3.2(b) optimize scenarios based on infrastructure change. In study design 2, it is additionally suggested that network characteristics are extracted from the optimized scenarios. Figures 3.2(c) and 3.2(d) depict two example approaches, each focussing on statistical evaluation of network characteristics. Figure 3.2(c) shows the evaluation of a real-world parcel shape distribution, based on multiple existing road networks. Figure 3.2(d) depicts the angle distribution of adjacent links in the Paris network in a descriptive evaluation.

Figure 3.2: Examples of study design 2.

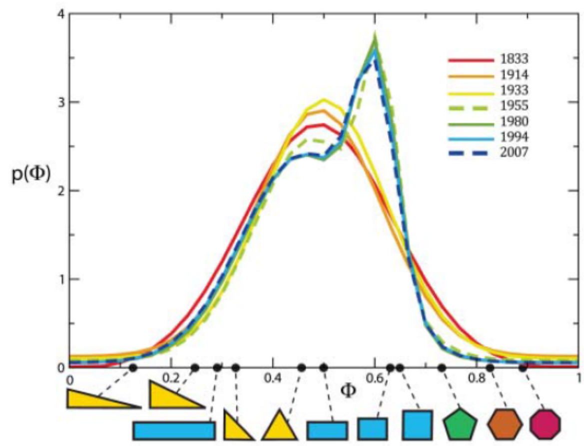
(a) The software Kaisersrot (Kaisersrot, 2011) generates and optimizes parcel distributions.



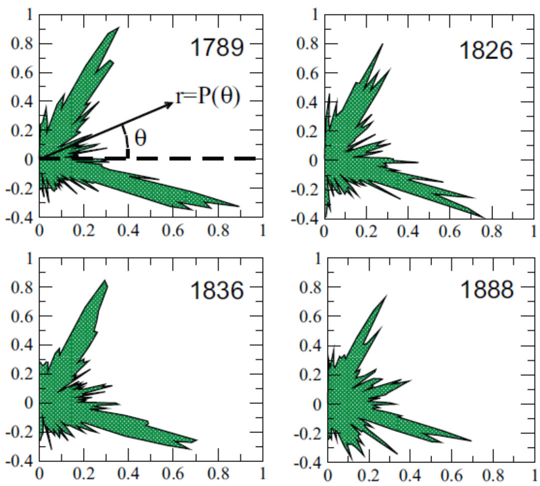
(b) Self-evolutionary networks design (Yerra and Levinson, 2005).



(c) Distribution of parcels and its change over time (Strano et al., 2012, p.4).



(d) Angle distribution and historical evolution of the network of Paris (Barthélemy et al., 2013, p.6).



Two issues potentially occur in study design 2. First, the problem of increasing complexity hampers the design and optimization of large networks considerably. Therefore, reasonable assumptions are necessary to narrow down the vast search space. Second, study design 2 lacks reference networks similar to study design 1. Therefore, the approach of study design 2 does only allow statistical analyses of a set of networks under consideration. Study design 2 comes close to the analytical extraction of rules of existing cities (Section 2.5), with the major difference that study design requires optimized networks to extract rules from.

3.1.4 Study Design 3

Study design 3 focuses on more complex shape grammars compared to study design 1, such as road type choice and design (see Section 2.7 for more details). While certain shape grammars can be implemented and evaluated right away (e.g. boulevards), other shape grammars are less concrete in their implementation (e.g. hierarchical network design). Especially rules which affect the global topology are more complex and study design 1 cannot be applied right away. In study design 3, the shape grammar rules are defined first, and then applied and implemented within a network design method. Networks are designed and optimized based on the designated shape grammar rule and an underlying design method, e.g. as shown in Figure 3.2(a) and 3.2(b). Study design 3 applies the rule during the scenario design and optimization, and therefore contrasts study design 2, which does not apply any rules during optimization.

Quantitative evaluation measures compare the network designs with a comparison set of reference networks designed without the designated shape grammar rule, or with a set of networks designed with different shape grammar rules. Furthermore, to gain additional insights, the evaluation takes place under various patterns, such as variable travel demand. However, it is emphasized that shape grammar rules are not evaluated in isolation but rather after application for different network conditions. Figure 3.3(c) shows study design 3 schematically.

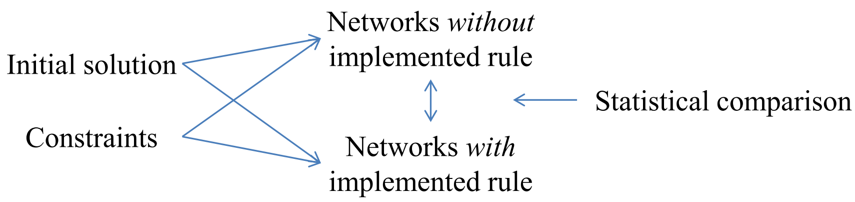
3.1.5 Definition of Shape Grammars

There is a major difference between the three study designs described above related to the definition of grammar rules. Both study designs 1 and 3 assume preexisting and predefined grammar rules. These grammar rules can then be implemented in the suggested study designs 1 and 3. However, study design 2 does not require preexisting grammar rules, but is able to determine new rules based on the suggested and applied methodologies.

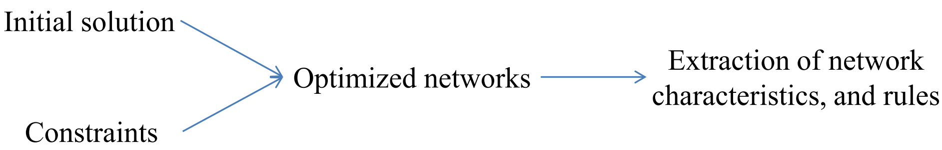
Independent on the study designs, it has to be stated that also the process of encompassing and systematic evaluation of existing rules is able to crystalize new grammar rules. As it is going to be shown, the results of study design 1 and 3 contain certain rules, which were not predictable, e.g. in the case of boulevard design. These rules were the result of the evaluation process of other rules.

Figure 3.3: Study designs applied to tackle research questions 1 to 3.

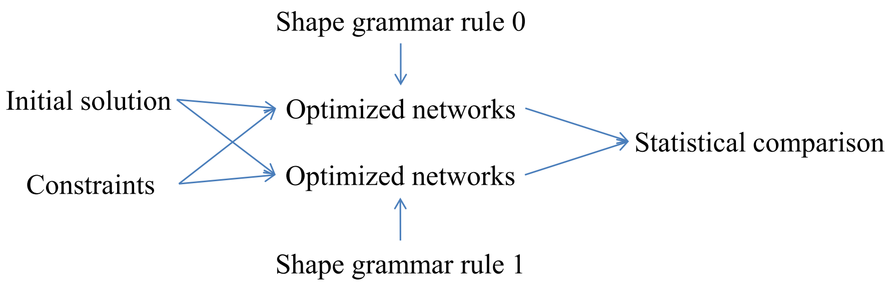
(a) *Study design 1*: Evaluation of existing rules.



(b) *Study design 2*: Extraction and definition of new shape grammar rules.



(c) *Study design 3*: Evaluation and comparison of complex shape grammar rules.



3.1.6 Shape Grammar Rules under Consideration

Obviously, only a subset of shape grammars is evaluated due to the sheer number of potential shape grammars. This thesis especially focusses on road network design, but bridges the gap to transit and pedestrian networks when evaluating the results. A brief overview of the evaluated shape grammars and network characteristics is provided in Table 3.1. Table 3.1 assigns the shape grammar rules to the study designs discussed above. The specific shape grammar rules are discussed in more detail in the next chapters.

3.2 Assessment of Shape Grammars

The goal of this research is to shed light on the assessment of potential shape grammars. Therefore, assessment methods are reviewed in this section, requirements are formulated for shape

Table 3.1: Overview of the envisaged shape grammars, with references to the relevant sections.

Study design	Envisaged shape grammars	Chapter / Section
1	Boulevard designs	5
2	Network element densities	6.4
2	Network meshedness	6.5
2	Number of arms per intersection (cardinality)	6.5
3	Road type distribution	6.7
3	Intersection type choice (isolated intersections)	7.1
3	Intersection type choice (intersections in networks)	7.2, 7.3
0	General theoretical justification	2.4

grammar assessments, and limitations are uncovered for future assessments.

3.2.1 Objectives and Application Specifications

Objectives of urban planning projects include one or multiple goals, e.g. with an economic, social or environmental focus. The objective might be increasing quality of urban live, ecology, economy, or a compound measure. Planners apply explicit and implicit rules to reach the objectives. Knowledge about the outcome of shape grammars and their implementations enhances future applications, and might become even a touchstone for reapplications. Therefore, the distinct grammar rules are assessed regarding specific objective functions. Literature provides a variety of assessment tools focussing on generalized costs, economics or environmental indicators. Table 3.2 lists example objectives and assessments methods. Sensitivity analysis (Saltelli et al., 2008; Kleijnen, 2008) can be applied with all methods, and complement Table 3.2. Some of the assessment methods might focus more on an analytical approach, e.g. the empirical evaluation (Section 2.5).

Table 3.3 describes example shape grammar rules with corresponding effectiveness measures. Moreover, the application specifications describe the potential area of application. Three examples of grammar rules, effectiveness measures, and application specifications are provided in Table 3.3.

Table 3.2: Potential assessment methods and effectiveness measures for shape grammars.

Evaluation method	Effectiveness measure	Example sources
Cost–benefit analysis	Generalized costs, external effects	Van Nes (2003), Estrada et al. (2011), VSS (2006c)
Sustainability measures	Sustainability	Gil and Read (2012), Duarte et al. (2012), NISTRA (Lieb et al., 2003), HEATCO (University of Stuttgart, 2014)
Empirical evaluation	Modeling historical development	Strano et al. (2012), Levinson et al. (2012), Stiny and Mitchell (1980), Strano et al. (2012)
Qualitative analyses	variable	Marshall (2005), Alexander et al. (1977)
Surveys	Behavior, acceptance	Bramley and Power (2009)

Table 3.3: Three examples of objectives, grammar rules, effectiveness measures, and application specifications.

Purpose	Grammar rules $\mathcal{R}$	Effectiveness measure	Application specifications
Private transport and transit network characteristics (van Nes, 2003)	Road spacing and hierarchies, transit network characteristics	User costs and infrastructure costs	Model application with lanes, headways, roads etc.
Social sustainable living (Bramley and Power, 2009)	Urban density planning	Social sustainability	Survey of English Housing, Census of Population (England and Wales)
Road network design (Yerra and Levinson, 2005)	Hierarchical street design	Link–based revenue	Road infrastructure investment, model application

3.2.2 Enhanced Choice Set Generation

Planners generate subsets of rules which are more appropriate in certain planning sites compared to other subsets of different rules. The defined application specifications of grammar rules is able to narrow the set of rules down to a well-defined subset. The aim is to derive an optimized set of the most relevant grammar rules, in order to support planners' objectives. It is proposed to subdivide the effectiveness measure into two parts: the direction of the transformation, and the degree of transformation.

- The direction describes the transformations of the system related to an effectiveness measure. There might be a negative, positive, or no effect regarding the objective.
- The degree describes the changes of the system regarding the actual effectiveness measure. There might be a substantial change within the system, when the system is in an elastic state. There might be a minor change in an inelastic (stable) system regarding the given objective.

This research proposes marginal effectiveness and elasticities ϵ for the further measurement of the effectiveness measure. Elasticities are robust and accepted measures to assess the response of an observed variable. Marginal changes and accessibility assess the variations of an outcome of an objective function related to the changes of an independent variable. In the current case, dependent variable O equals e.g. the user costs, and the independent variable equals an underlying investment I change: $\left(\frac{\delta O}{\delta I}\right)$. In the context of shape grammars, marginal costs describe the efficiency of a specific rule with regards to a given effectiveness measure.

Elasticities are free of units $\left(\epsilon = \frac{\delta O}{\delta I}\frac{\bar{I}}{\bar{O}}\right.$, when assuming linearity$\left.\right)$, facilitating comparison between different studies (e.g. Ewing and Cervero, 2010). Recent achievements in survey methodology have enhanced elasticity estimations, aiming at e.g. more sophisticated urban and transport modeling (e.g. Goodwin et al., 2004; Hackney et al., 2007; Weis and Axhausen, 2009; Sanni and Albrantes, 2013). Table 3.4 provides three examples of elasticity calculations in urban and transport planning.

Table 3.4: Three examples of elasticities in urban and transport network design.

Scope of grammar	Efficiency measure	Independent variables	Source
Hierarchical network	VMT	Intersection and street densities	Ewing and Cervero (2010)
Properties of planar graphs	Efficiency	Relative costs (densities)	Cardillo et al. (2006)
Road network investment (expansion)	Accessibility, travel demand	Speed, capacity, infrastructure cost	Weis (2012)

Potential applications of elasticities are related to energy consumption, emissions, generalized travel costs, quality of urban space, satisfaction of residents (e.g. Bramley and Power, 2009). The determination of the elasticities requires systematic data collection and processing. A major drawback of many elasticities evaluations relate to the assumed underlying linear function involved and the calculation of the average utility (Train, 1986). Elasticities are calculated for mean values. Single values can be under- and overestimated. E.g. in value of travel time estimations, the linear model is outperformed by a more detailed nonlinear function (Hess et al., 2008). Section 5.4 proposes an approach to overcome some aspects of this issue.

Elasticity calculation also includes sensitivity analyses. Sensitivity analyses uncover technical errors, find critical input variables, and determine model quality. Sensitivity analyses quantify and analyze uncertainty propagation, and bring into relationship the uncertainty of the output to different sources of uncertainty in the model input (e.g. Saltelli et al., 2008; Kleijnen, 2008). It is emphasised that sensitivity analysis also enhances model understanding and enables model improvement.

3.2.3 Limitations

Two issues are addressed related to the quantitative evaluation as described above, and related to the research questions (Section 2.7). First, shape grammars should be applicable independent of a specific case or scenario. Second, the evaluation should be applicable to future cases.

Aspect 1: It is not feasible to precisely predict the effect of a proposed shape grammar rule, since transport networks are rarely identical, especially when considering flows, and since the problem of network improvement is $\mathcal{NP}$-hard (Garey and Johnson, 1979). This limitation has the following consequences. Given an optimal infrastructure improvement recommendation for a specific transport network, this recommendation is not transferable to another, even similar network, claiming an identical effect on the network and its use. The reason for this intransferability is due to the complexity of network design. Therefore, uncertainties always remain when specifying shape grammar rules, and, due to the complexity of urban network design, these uncertainties can not be eliminated. Here, it is proposed that these uncertainties are approached with a syntax – semantics methodology, explained in Section 2.4 and exemplarily applied in Section 5. The methodology is based on pairs of rules and corresponding assumptions, which means that every rule refers to specific assumptions. An assumption, on which the rule relies on, is defined within the semantics, serving as background information about the designated shape grammar rules. Figure 2.4 visualized the language definition, referring to the syntax – semantics approach, and the rule – assumption pair.

Obviously, the methodology should remain as general as possible regarding the design and evaluation of shape grammar rules, so to allow for a larger potential application field, and less restrictions in applications. Planners might be able to apply planning rules more often. Generalization implies less specific assumptions, which potentially narrow down the set of potential networks suitable for application. Therefore, only essential network components are considered so to shed light on the most relevant network design aspects. Moreover, reliability analysis increases the application range, as discussed above.

In the following, it is assumed that mathematical models are able to evaluate complex transport network dependencies, such as network flows or accessibility. Moreover, mathematical network models enable a specific focus on certain network design components and their interactions. Additionally, it is assumed that certain shape grammars can be implemented in network models.

Aspect 2: The conducted evaluation and the potential effect of a given shape grammar rule must be known for planning purposes. The evaluation can take place according to economic, social, environmental, or reliability measures. Again, the specific measure and the potential effect must be declared within the semantics. Preferably, the evaluation measure for a shape grammar rule is exchangeable due to different application purposes, and to correspond with the scopes of the tasks of planners. Semantics describe the evaluation measure and the effect of the designated shape grammar rule.

3.3 Maximum Network Supply Approach

Obviously, the efficiency of a network is of major relevance. Widely applied evaluation methods allow to show the effect of capacity investments in both roads and intersections, e.g. cost benefit analysis. However, what happens if the estimated future demand exceeds the expectations, and thus the infrastructure capacity? Authorities might face this situation whenever their road networks are saturated. An approach to face this problem is proposed in the following.

The proposed method accounts specifically for unknown future travel demand. At the beginning of a planning process, planners might not know about future population and job densities. Therefore, it is interesting to know much density one network could supply and cater for without a considerable travel time increase ($\Delta t^{x\%}$). Therefore, the method assesses the maximum increase in urban density $\Delta d_{\textit{structural data}}\left(\Delta t^{x\%}\right)$ that a network could supply, without an unacceptable travel time increase $\Delta t^{x\%}$, when d is the urban density (jobs, population, ...). The focus is on travel time due to its importance in economic evaluation. An upper limit is assumed for travel time changes $\left(20\% \text{ in the following } \rightarrow \Delta d_{\textit{structural data}}\left(\Delta t^{20\%}\right)\right)$, which is achieved by gradually increasing urban densities. An average peak hour demand is defined for each density based on census data. Obviously, travel demand depends on other activities, daytime, mode share, car occupancy, which for simplicity are ignored in this evaluation. The aim is to determine the effect of overall travel time changes. The major advantage of this measure is its focus on the relative difference and reduced dependence on transport infrastructure density, such as total lane length.

3.4 Underlying Assumptions and Limitations

3.4.1 Experimental Design Approach

This thesis describes the design of different networks on featureless planes so not to bias the outcome due to historically and politically driven solutions and is therefore similar to Eichler et al. (2012), van Nes (2003), Yamins et al. (2003), Yerra and Levinson (2005), Xie and Levinson (2007), Levinson and Huang (2012). A featureless plane allows comparisons between sets of networks designed with different rules. Therefore, the impact of the rules on network design can be evaluated for an improved understanding. The design of the networks can be evaluated with an objective function, e.g. generalized costs, and evaluated regarding their characteristics and properties. This research relies on the well-founded methods of transport planning, and therefore applies transport models, objective functions for evaluations, and optimization methods. In this light, this research is in the opposite to real-world network evaluations and surveys. Only a very limited and distinct number of networks can be evaluated in the real-world. Moreover, existing transportation networks and patterns are historically contingent.

3.4.2 Travel Demand Estimation

This section especially elaborates on the assumptions for trip generation and distribution, but also looks at travel demand independent network approaches. Various possibilities can be found for evaluating networks. Demand independent evaluations can be found in space syntax approaches and measures of the network structure such as centrality and treeness, but also empirical network evaluation methods, such as Cardillo et al. (2006) or Barthélemy (2011) or experimental approaches (Eichler et al., 2012). Since shape grammars for urban networks might depend on flows and urban densities, a demand based approach is proposed in this research. However, modeling travel demand is very complex when considering time, mode, destination choice and long term decisions like home and work location choice. Because of multiple interdependencies, such as congestion due to changing home locations, and costs and land prices which influence all choices, these decisions are not yet understood and modeled in all details. Moreover, trip generation and distribution can vary significantly, making specific descriptions of corresponding trip rates very difficult, e.g. Schneider et al. (2014) observed large variances in the trip generation rate of the Institute of Transportation Engineers (ITE) depending on the dwelling type. Additionally, issues of convergence occur especially with the optimization algorithms which are applied later, but also when considering the potential decisions over time and space. Therefore, a robust and straightforward methodology is chosen for travel demand estimation.

In this research it is assumed that travel demand is generated evenly over the entire study area. Long distance travel, which causes additional complexity, is ignored in the following. Long distance travel require many different hierarchical network levels, such as local neighborhood roads, access and arterial roads and highways. Each level might have different characteristics and requirements. Designing all levels at the same time including their requirements exceeds the search space and would be less focused on a singular level, which might impact the results. Therefore, this research applies a straightforward approach by producing and attracting a constant demand (similar to e.g. Yerra and Levinson, 2005) and spreading the demand evenly across the study area. Obviously, more sophisticated demand generation methods can be applied (e.g. Levinson et al., 2007).

Travel demand is determined in a straightforward way. The data for travel demand estimation (Table 3.5) refers to a medium dense neighborhood in Zurich. The listed quantities are taken as default parameter values, similar to e.g. Levinson et al. (2012).

Table 3.5: Data for travel demand estimation.

Description	Value	[unit]
Population density (d_{pop})	15'068[1]	$pers/km^2$
Job density (d_{jobs})	6'685[1]	$jobs/km^2$
Car trips per resident (as a driver)	1.32[2]	$trips/day$
Car trips per employee	0.47[2]	$trips/day$
Average car trips	26'172[2]	$trips/km^2/day$
Peak hour share	11[2]	$\%$

Source: [1]Amt für Raumentwicklung, Baudirektion Kanton Zürich (2012), [2]Swiss Federal Statistical Office (BFS) (2012).

However, a detailed reliability approach is applied in addition to the straightforward demand generation approach mentioned above. Due to the general uncertainty in planning, future developments and future demand and trip generation, it is regarded as relevant to approach the future uncertainty with a reliability evaluation method to account especially for the uncertainty itself. This can be done by changing the demand such that the infrastructure is used up to the maximum, which also allows to determine maximum utilisation. The reliability approach allows to determine and evaluate shape grammars in predefined urban densities but also in extreme densities. The reliability approach is presented in Section 3.3 and Section 6.5.3.

For simplification, the buildings are not modeled (see also Figure 4.3), due to the fact that this research focuses more on the transport side, and overall urban densities. Single building shapes and their variability would explode the search space. However, research about building designs and corresponding shape grammars is summarized in Section 2.2.

3.5 Turn Delays

It is believed that research on topology should include turn delays as this effects overall travel costs considerably, especially in dense urban areas. However, intersection types and delays are often disregarded in prior research and in practice. This might be due to missing data, complexity, or minor importance for certain studies. This thesis shows the importance of intersections in urban networks and aims to fill the gap about the effect of different intersection types on network topologies. Moreover, intersection types are applied in all study designs, therefore, the applied intersection types and methods to calculate turn delays are described in the following section.

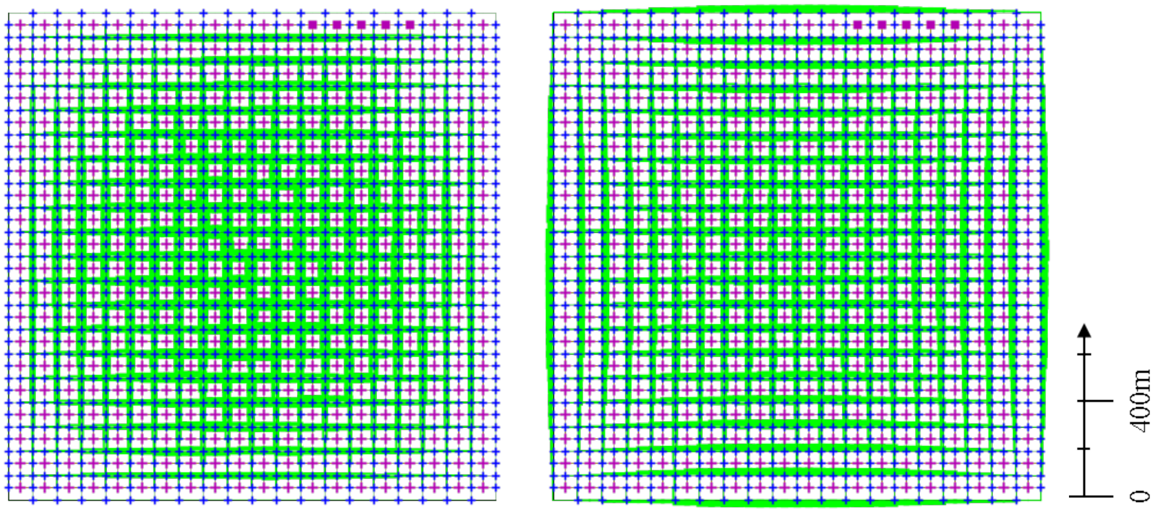
Intersections are omnipresent in transport networks. Traffic flows cross, merge or diverge at intersections. Different transport modes meet at intersections. Intersections and approaching lanes require considerable urban space. Intersections and network topology are strongly coupled, e.g. regarding the number of arms per intersection (also called cardinality or degree of the node) or traffic flows. Intersection type choice plays an increasing role due to increasing urban densities, generally increasing traffic flows, relatively smaller budgets for land acquisition and infrastructure reconstruction and improvement, and higher land prices. Government investments and costs are higher in urbanized areas compared to rural areas (Florida Department of Transportation, 2014). In a world with many fast growing agglomerations (UN, 2009) and urban structures, urban design and intersection type choice will increase in relevance. The relatively low average speed for cars in Switzerland (38.6 $[km/h]$, Swiss Federal Statistical Office (BFS), 2012), compared to free flow speeds, underlines the relevance of turn delays and deceleration, which is also highlighted in the microcensus (Swiss Federal Statistical Office (BFS), 2012). It is obvious that the integration of intersection type choice in network design is valuable and relevant for transport and urban design research and as well as in practice (e.g. Heimgartner and Menendez, 2013).

Turn delay calculations are cumbersome due to complexity, long calculation times and convergence reasons. However, ignoring turn delays can lead to considerable flow and travel time changes. On an example gridiron network (Figure 3.4) with uniformly distributed demand (based on the density assumption defined in Table 3.5, flows change 24.4% on average (standard deviation σ = 62.0%) when assuming roundabouts, 39.2% on average (σ = 146%) when assuming right of way controlled intersections, and 7.81% on average (σ = 23.2%) when assuming signals. Turn delays are calculated based on the HCM (Transportation Research Board, 2010). Signal phases and green times are optimized individually for each signal, but their timings are not coordinated within the network (see Section A.6 for more details). Summing up, this thesis considers turn delays for evaluations due to their major relevance.

Figure 3.4: Flow divergence between uniform and detailed turn delays (right-of-way intersection).

(a) Link flows with uniform turn delay distribution (10 [sec] for each turn movement).

(b) Link flows with detailed turn delay calculation for right-of-way intersections.



3.5.1 Literature Review

Regarding isolated intersections, Webster (1958) was one of the first author contributing to the optimization of traffic signals and timings, due to increasing car flows and the need for regulations starting at this time. Fundamental research is also provided by Cowan (1975) on headway distribution at intersections to be used for further intersection delay modeling. Allsop (1972) determined capacities for signalized intersections. Akcelik (1981) described the basic delay functions for various signalized intersections. Gündogan and Fellendorf (2011) suggested a pattern recognition for optimizing timing plans based on detector data. Dion et al. (2004) investigated multiple delay functions for signalized intersections. Regarding right-of-way intersections, Grossmann (1991) evaluated parameters for delay calculations. Brilon et al. (1997) analyzed two-way stop controlled intersections. A two phase turn movement is applied for left turning movements, in which vehicles stop just in front of the opposing traffic. Moreover, they contributed on capacity estimation for roundabouts. Akcelik (1998) studied capacity and performance analysis of roundabouts, and proposed delay models for various roundabout characteristics. Akcelik (2007) provided an overview of different gap acceptance models for right-of-way intersections, roundabouts, and opposed turns at signalized intersections. Beside geometric parameters for intersection design, like widths, and diameters (FGSV, 2001; AASHTO, 2004; Spacek, 2009), guidelines provide methods and parameters for encompassing delay calculations, e.g. the German norms for intersections determines capacities and delay functions for signal lights, and uncontrolled intersections (FGSV, 2009, 2010).

Beside literature on isolated intersections, there is literature on intersection design within entire road networks. Among others, Köhler and Strehler (2012) modeled signal optimization in road networks. Signal optimization in networks is still an open research question due to the complexity of the problem (e.g. Lee and Machemehl, 2005). Yang and Yagar (1995) merged traffic assignment and signal control in saturated road networks. Lämmer and Helbing (2008) proposed self adapting traffic light timings in urban networks. The approach assumes anticipation of vehicle flows and platoons, which affect short-term signal timings. The results of static assignment can also be used as an initial solution for dynamic assignment (Edelhoff et al., 2007); optimized flows, routes, and signal light settings can be migrated from the static assignment to initialize the dynamic assignment.

3.5.2 Specific Delay Sensitivity Analyses at Intersections

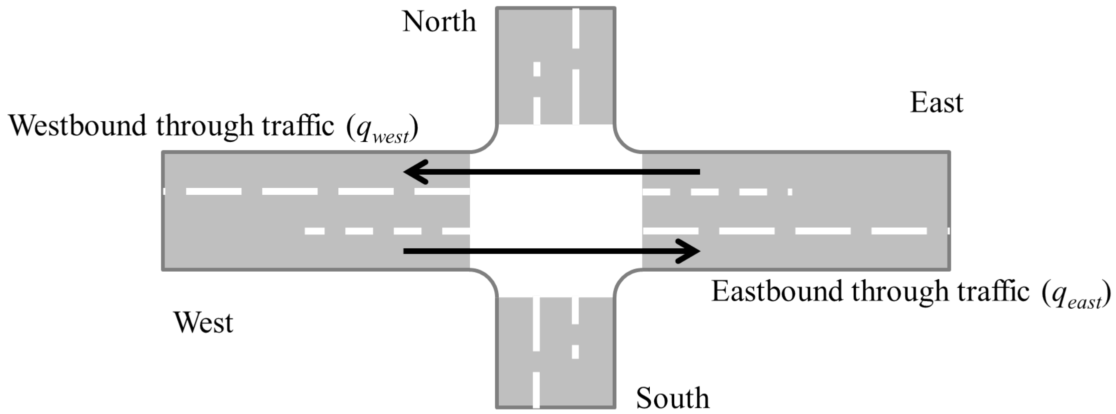
Obviously, turn delays depend on the flows of other turn movements. To assess the turn delays in a first instance a simple model is employed for an initial turn delay comparison, similar to e.g. Yang and Yagar (1995) or Gartner et al. (2002). In this simple model, turn delays are evaluated for different flows on different turn movements to gain additional insight in turn delays of intersection types, in particular at various levels of through traffic flows. Therefore, the proposed measure τ is sensitive to through traffic flows, which cross an intersection from one approaching arm to an opposing arm. More specifically, τ compares increasing q_{east} and q_{west} flows (through movement) with a reference situation of equally distributed flows q_r on all 12 turn movements (Figure 3.5, and Equation (3.1)), excluding U-turns. τ is suitable for sensitivity analyses of various intersection types under different flows (q).

$$\tau = \frac{\big((q_{east} + q_{west}) - 2 \cdot q_r\big)}{q_r \cdot \nu(\nu - 1) + (q_{east} + q_{west})} \qquad \text{whereas } \{q_{east}, q_{west}\} \geq q_r. \tag{3.1}$$

τ: Through traffic share ($0 \leq \tau \leq 1.0$).
ν: Number of arms.
q_{east}, q_{west}: Flow of through movements on the east-west axis.
q_r: Flow on all other turn movements.

- $\tau = 0\%$ if q_{east}, and q_{west} equal the flows of the other 10 turn movements: $\{q_{east}, q_{west}\}$ = q_{eq}.

Figure 3.5: Through traffic scheme for sensitivity analyses, with priority for east-west-east traffic flows.



- $\tau > 0\%$ if there is increasing through traffic on the east-west axis. $\tau = 100\%$ if there are traffic flows only on the east-west-east axis q_{east} and q_{west}.

Vehicles from north and south have to yield to vehicles from east and west (Figure 3.5) at right-of-way intersections. Three arm intersections are modeled without the northern arm. Angles between approaching arms are ignored due to their minor influence according to the HCM (Transportation Research Board, 2010). Values for τ at various intersection types are calculated in Section 7.1.

3.5.3 Intersection Type Specifications

The highway capacity manual (HCM, Transportation Research Board, 2010) provides consistent delay formulae for signal controlled intersections, roundabouts, two-way stop-controlled (TWSC) and all-way stop-controlled (AWSC) intersections. The HCM is based on current research. Although other manuals provide differing delay formulae, the HCM is a widely used standard reference for many planners worldwide. Therefore, this thesis applies the HCM formulae and parameters for signals, roundabouts and right-of-way intersections. All-way stop controlled intersections are ignored due to their general absence outside the USA. More details about the implemented formulae can be found in Appendix B and in the HCM (Transportation Research Board, 2010)

Different intersection types are obviously only comparable with consistent technical specifications. For comparability, two approaching lanes for each inbound road link are assumed for all intersection types modeled. Additional approaching lanes are added in the reliability analysis. The lengths of the approaching lanes are ignored as well as truck shares, slopes, angles of roads, and pedestrians due to complexity and partially missing empirical data. The specific characteristics of the different intersection types are discussed below.

Signalized intersections have relevant operational parameters, such as cycle length, green time split, and number of phases. Cycle length and green time split will be optimized here to minimize total turn delays according to the parameters of the HCM and the ring and barrier system explained in Roess et al. (2011). Both 4 and 8 phases are often deployed at signalized intersections (Figure 3.6(a) and 3.6(b)). Both 4 and 8 phase settings were originally considered for evaluation. More conflicting turns occur in 4 phase settings (described e.g. in Akcelik, 1981) compared to the 8 phase setting, e.g. as proposed in the HCM (Transportation Research Board, 2010). The 8 phase settings have higher overall turn delay at low flows especially due to the additional time lost between phases at low volumes. For evaluation, 4 phases are modeled in signalized intersections to reduce complexity. Two approaching lanes allocate incoming traffic. One lane allocates left turn movements, the other lane allocates straight / right turn movements. Opposing inbound traffic delays left turn movements.

At roundabouts, circulating traffic delays inbound traffic, which is considered in the calculations. Two approaching lanes are assumed for consistency. They double the capacity for inbound traffic (Transportation Research Board, 2010, p.21-7) compared to one approaching lane. Only one circulating lane and no bypasses are assumed to reduce complexity and urban space consumption.

At right-of-way intersections, two approaching lanes are assumed for consistency. Vehicles yield to traffic from the opposite direction or from approaching roads of a higher hierarchy level. Vehicles on roads of the highest hierarchy level are allowed to pass without stopping.

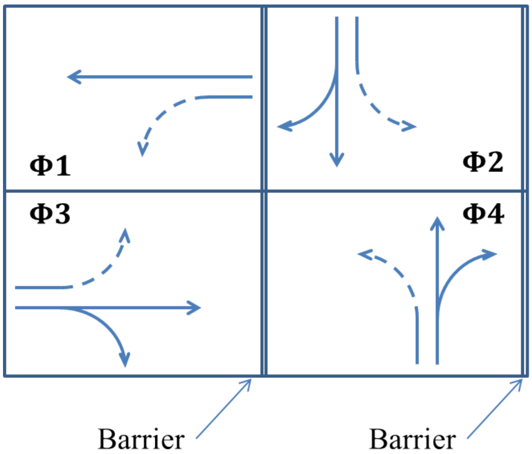
3.5.4 Employed Programming Platform

All algorithms were implemented in the Java environment (ORACLE, 2014). An advantage is the ability to integrate the calculations for turn delays with the optimization algorithm IACGA (Section 4.5). In the case of the IACGA, an objective oriented language is appropriate due to the evolutionary and population based approach. Moreover, the Java language allows to implement many software packages of which a few were applied, e.g. Kronfelder et al. (2010) for the Genetic Algorithm or Apache Commons (2013) for statistical evaluations. Moreover, the platform was extended with a user interface (Eclipse, 2014) for a course application in Singapore (ETH, 2013) (Appendix C).

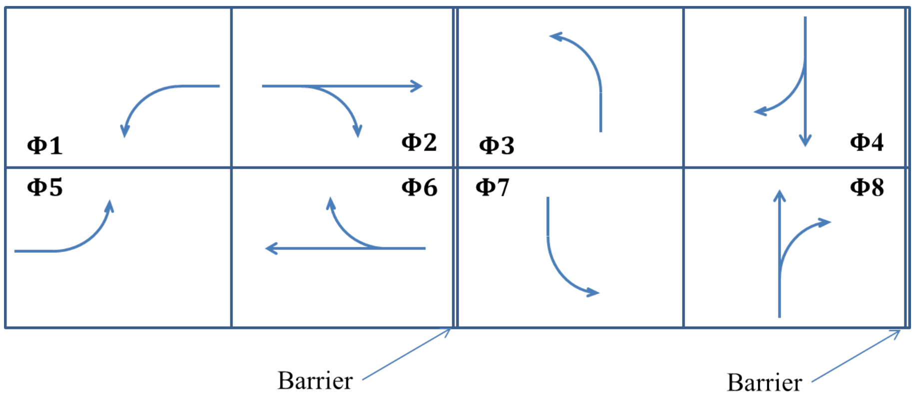
The results of the Frank and Wolfe implementation are compared with the results of VISUM (PTV, 2013) with different networks and traffic flows to ensure the correctness of the results. Additionally, test cases were written to additionally avoid programming errors.

Figure 3.6: Signal light diagrams with different number of phases (Φ).

(a) Four phases, similar to Akcelik (1981).



(b) Eight phases and a dual ring structure.



3.5.5 Comparison with Commercial Products

A few commercial software solutions exist which consider turn delay and demand assignment. PTV (PTV, 2011) provides different UE methods. The intersection capacity analysis (ICA) methods takes the turn movements specifically into account. This method relies on an iterative procedure. On the one hand, the standard UE determines the turn volumes. On the other hand, capacities and delays are calculated for each intersection. Additionally, a capacity restraint function is estimated during a sensitivity analysis for each turn movement, resulting in its own volume-delay-function.

SATURN (2014), introduced by e.g. van Vliet (1982) (Simulation and Assignment of Traffic to Urban Road Networks) serves as a combined traffic simulation and assignment model for traffic management and junction simulations. An adapted algorithm for demand assignment is implemented to reach the convergence based on a standard Frank and Wolfe algorithm (Frank and Wolfe, 1956).

TRANSYT (TRL Software, 2014) is a software tool and combines optimization of signal timings including platoons and actuated signal control, and assignment of the travel demand including queue spillback. A genetic algorithm optimizes cycle length, phasing sequence, splits, and offsets.

Chapter 4

Network Design Algorithms

This chapter provides a methodology to generate transport networks for further evaluation, and extraction and verification for certain types of more complex shape grammar rules. It therefore addresses research question 2 and 3, and provides a methodology for study design 2 and 3.

4.1 Aim

This chapter describes a methodology to crystalize and extract shape grammar rules for planning purposes. The methodology and results enhance basic network design understanding. Furthermore, the methodology aims at a quantitative evaluation of the effect of candidate shape grammar rules. The methodology aims also at complementing existing approaches of rule-based and procedural modeling, e.g. urban modeling (ESRI, 2012), Kaisersrot (2011), Vanegas et al. (2009a), or Duarte et al. (2007) with a stronger focus on transportation. Many proposed shape grammar rules are evaluated on a qualitative basis, or rely on experience and expertise. However, planners might be unfamiliar with the domain of specific shape grammar rules. Then, the application of rules remains difficult due to missing background information, and missing knowledge about the effect and impact of these shape grammar rules and their application. Therefore the described methodology enhances knowledge which is required about the effect of grammar rules.

A network design algorithm is proposed for multiple reasons. Algorithms are able to automatically design networks based on different evaluation measures, which is valuable for statistical evaluation of multiple networks. It is expected that a single network design is insufficient for grammar rule extraction due to potential site-specific characteristics. Multiple networks enable statistical evaluation. In addition, it is emphasized that the goal of the design algorithm is the extraction of grammar rules. Algorithms are able to design entire transport networks and to implement different design rules. An algorithmic approach can therefore overcome the currently missing evaluation for shape grammars. While evaluation is established in scenario based approaches, shape grammar rules have not been evaluated for their effects in transport planning. In this light, shape grammar rules are the opposite of general transport planning regarding the existing evaluation methods. However, it is possible to overcome the missing grammar evaluation when implementing the grammar in a network design algorithm and evaluating the outcome and especially the effect of the implementation (see also study design 2 and 3, Section 3.1). The remaining section describes an algorithm for quantitative shape grammar evaluation, in line with the above requirements.

4.2 Existing Network Design Algorithms

4.2.1 Discrete and Continuous Formulations

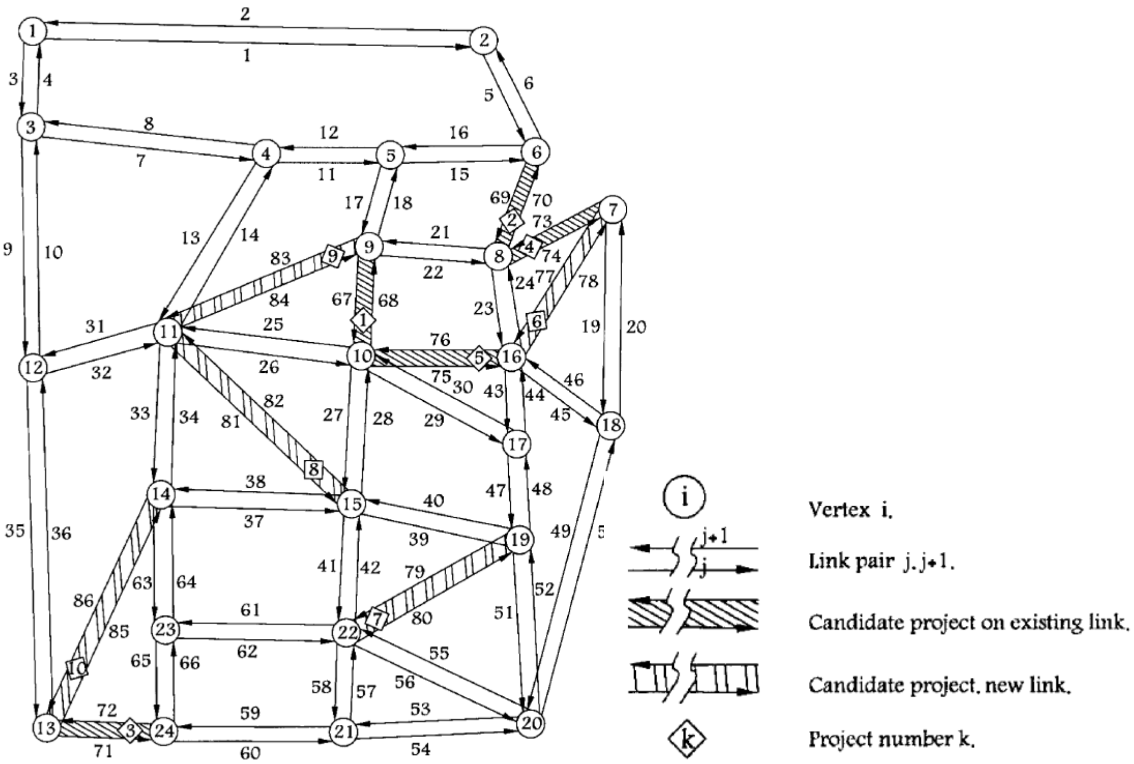
Similar to other constrained problems, network design problems have predefined constraints such as required connectivity, spatial perimeter and budget limits. The constraints lead to a well-defined search space. The search space includes the set of all candidate solutions which might be $\emptyset$ for an infeasible problem definition. Every feasible candidate solution which conforms to the constraints is an element of the search space. Normally, a large number of candidate solutions can potentially be generated despite the limiting constraints. The search space might be continuous, or discrete, or both. Discrete and continuous search spaces differ in their characteristics and eventually in the solution algorithms. Therefore, they are described separately in the following.

In a discrete network design formulation, all potential links are defined including their spatial position and characteristics, such as capacity. Potential links can be included or excluded in the design, however, their spatial position is predetermined. An example is visualized in Figure 4.1(a). Johnson et al. (1978) discussed on the complexity of the problem formulation (Section 2.1.1). Discrete network design formulations cannot be solved with linear or non-linear programming approaches. Moreover, discrete problems are often $\mathcal{NP}$-hard, such as the knapsack problem, which defines costs and benefits of single items, and maximizes the total benefit under a given cost constraint (Zimmermann, 2008).

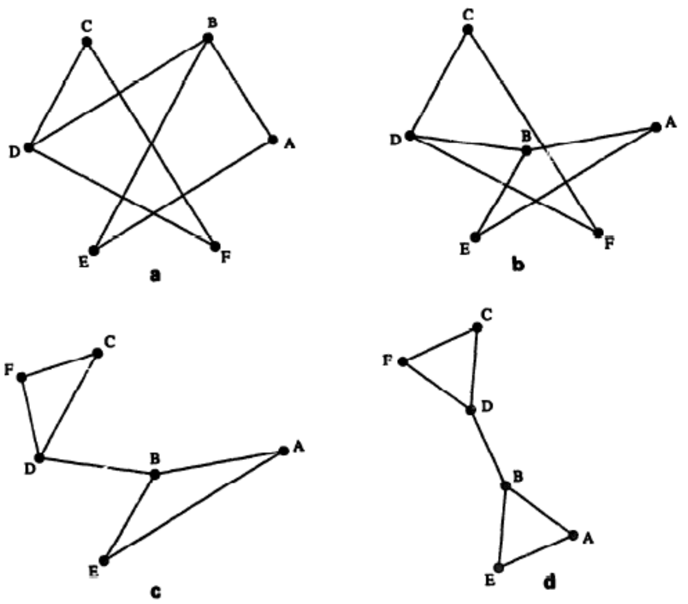
The optimisation problem changes when starting with an empty, featureless plane. The degree of freedom increases due to the spatial redesign potential, transforming the discrete problem into a continuous problem formulation. An abstract example is given in Figure 4.1(b). Links can be arranged and obviously need to be located between buildings and terrain constraints in an urban environment.

Figure 4.1: Potential network design problem formulation.

(a) Discrete optimization problem of the Sioux Falls network including candidate links.



(b) Continuous optimization based on an energy minimization approach.

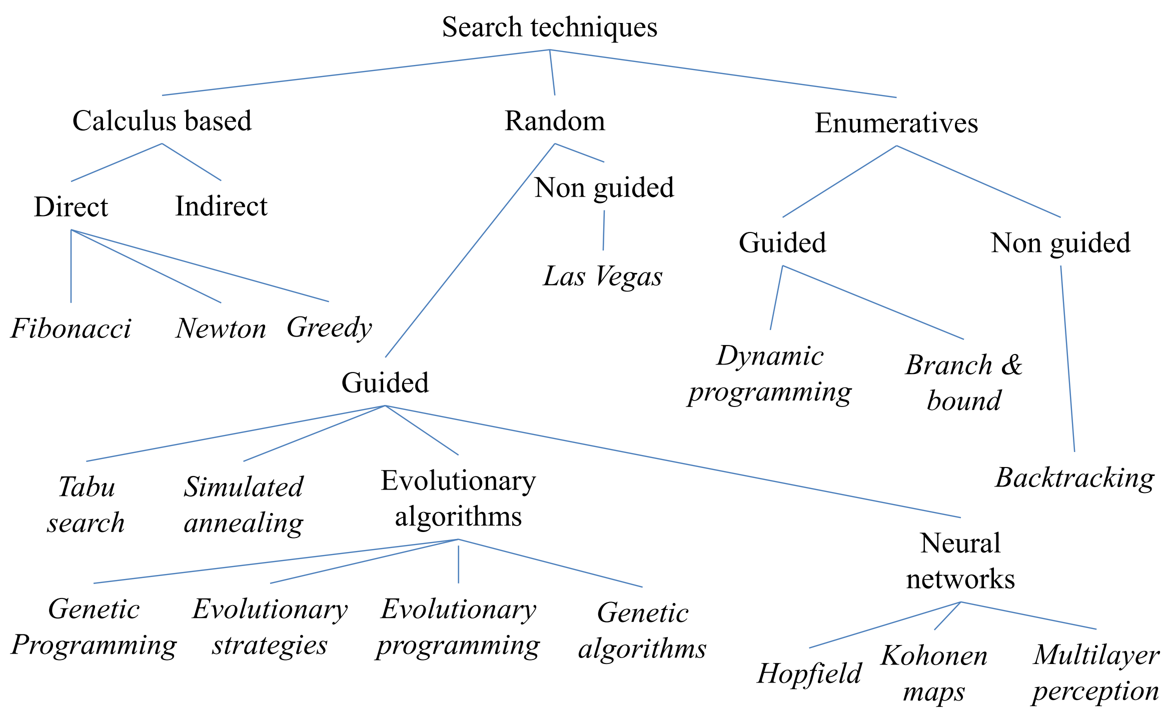


Source: Poorzahedy and Abulghasemi (2005) p.261, Kamanda and Kawai (1989) p.11.

4.2.2 Literature Review

Network design always leads to a result being between a Steiner tree (Robins and Zelikovski, 2000) and a fully connected graph. A Steiner tree (Figure 2.6(b)) connects all required access points including additional intermediate vertices, which need to be connected, with a graph of minimum total distance, which is a tree. A fully connected graph connects all required access points with direct links. Van Nes (2003) refers to the traveller optimum in the case of the fully connected graph, and to the investor optimum in case of the Steiner tree (Figure 2.6(b)). Figure 4.2 provides an overview of different search methods, of which a subset is described further below.

Figure 4.2: The relation of evolutionary algorithms to other search techniques.



Source: Based on Sivanandam and Deepa (2008) p.vi.

4.2.2.1 Existing Network Design Methods and Algorithms

Due to the often large transport networks and time consuming evaluations of real world networks, heuristics and meta-heuristics have gained acceptance and serve as network generation and optimization algorithms. The majority of heuristic approaches for network generation rely on evolutionary principles; a selection is discussed below.

Genetic algorithms belong to the class of evolutionary algorithms and mimic evolutionary mechanisms of genetic reproduction (Goldberg, 1989; Holland, 1975; Sivanandam and Deepa, 2008). The algorithms optimize iteratively a set of solutions with genetic operators for a given fitness function. GAs are promising for network generation and were already applied in, e.g. Hsieh and Liu (2004); Sharma et al. (2009); Vitins and Axhausen (2010).

Swarm intelligence techniques also belong to the class of evolutionary algorithms (Dorigo and Stuetzle, 2004; Merkle et al., 2002). Their methodology is adopted from social insect societies and mirrors self-organizing principles. As an analogy, their social behavior is used to solve complex computational problems successfully, among others network optimizations (Yang et al., 2007; Poorzahedy and Abulghasemi, 2005; Vitins and Axhausen, 2009).

Biological systems provide very efficient transport systems, e.g. mycelia transport systems (Fricker et al., 2008) or slime mold (Tero et al., 2010). They are very promising approaches, even though one has to distinguish between growing networks and optimal networks of constant size.

Force-based algorithms, or virtual springs, are analogies which replace edges in a graph with virtual springs (Kamanda and Kawai, 1989; Brandes, 2001). Intermediate nodes are relocated during the optimization process to reduce overall potential energy. Iterative procedures adjust and improve the network layout. Traffic flows can be simulated with the repulsion constants of the virtual springs.

Pipe routing algorithms and Euclidean Steiner tree algorithms (Robins and Zelikovski, 2000; Barthélemy and Flammini, 2006) are further examples of network related optimization methods. Both categories belong to the field of network generation, but do not give detailed solutions to our research questions, because the Steiner tree focuses obviously on tree structures and pipe routing mostly on slopes and / or unidirectional links.

Simulated annealing and Tabu search methods are widely applied heuristics in transport optimization (Frick et al., 2007; Friesz et al., 1992; Zhao and Zeng, 2008). They can be described as local search methods and may contribute as well to network generation.

4.2.2.2 Network Optimization

Network optimization works with predefined networks and are therefore not network generation algorithms. The field of network optimization is very broad and can be divided into the subfields of road, transit, multi-mode, as well as discrete and continuous optimization. Similar approaches can be implemented in the design of entire networks as well. Especially in transit network generation, route definition methods can be embedded in overall network generation.

Regarding discrete road network optimization, Jeon et al. (2006) and Hsieh and Liu (2004) applied genetic algorithms with extensive parameter evaluation. The first considers discrete capacity improvements and the latter a candidate set of possible links. Poorzahedy and Abulghasemi (2005) apply an ant colony algorithm to the small network of Sioux Falls (see Figure 4.1(a)), defining possible infrastructure additions in advance. Regarding continuous network optimization, Ukkusuri et al. (2007) and Ukkusuri and Waller (2008) considered uniform and peak demand structures with stochastic distribution and apply a genetic algorithm for link capacity adjustments.

Transit network optimization addresses route generation and infrastructure location, route selection, headway, timetable, vehicle and crew scheduling. Zhao and Zeng (2008) proposed a comprehensive approach and solved a route, headway and timetable design problem, employing an algorithm based on the simulated annealing methodology. Fan and Machemehl (2006a,b) introduced a route and headway optimization algorithm with variable demand. They compare a genetic algorithm approach with a simulated annealing algorithm. In early work, Axhausen and Smith (1984) provided an overview of heuristic transit network optimization algorithms including a real world application of one of the algorithms.

A multi-modal network optimization method is presented by Vitins and Axhausen (2009) employing an ant colony algorithm in a real world case study for a discrete network optimization. Si et al. (2008) considered competing modes and employ a sample network with fixed travel demand and assignment.

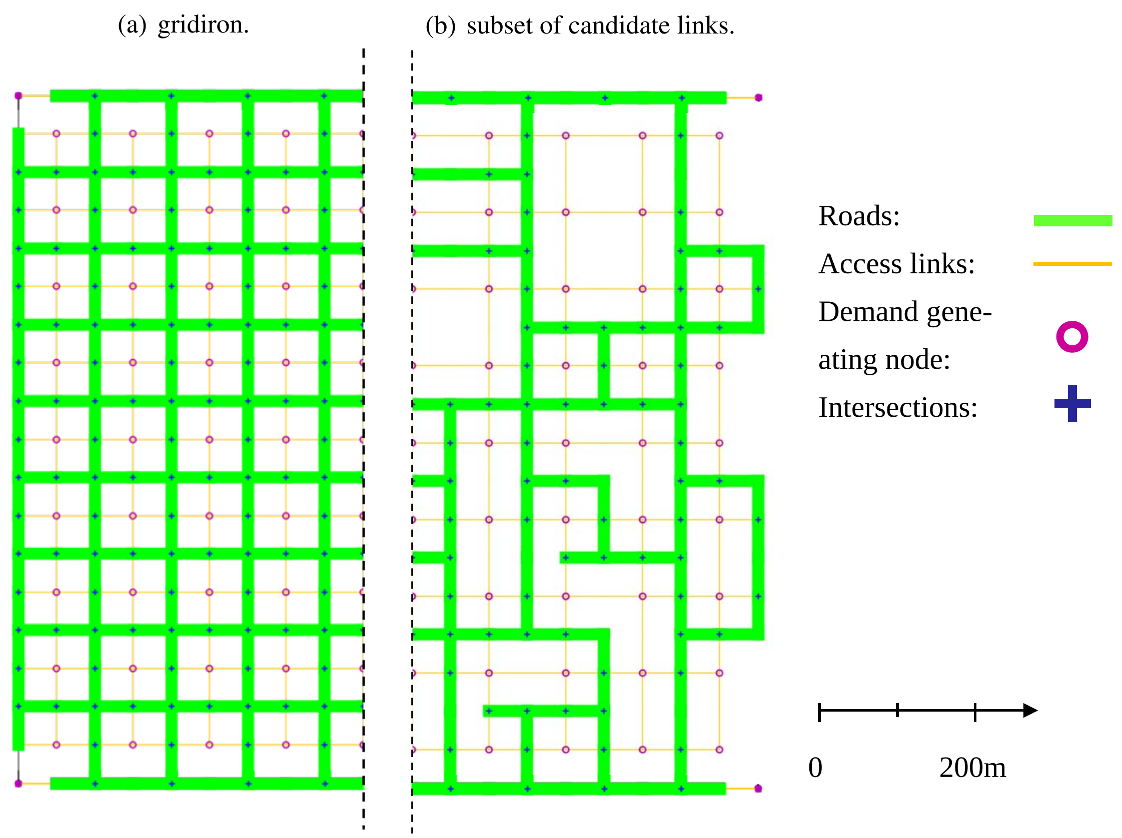
4.3 Requirements and Assumptions for the Proposed Research Tasks

The definition, extraction and evaluation of shape grammar rules are the overall goals of the proposed network design algorithm. However, the specific network design formulation (like e.g. in Figure 4.1) remains still open. Requirements and assumptions are therefore discussed in the following.

The focus of the subsequent research is on discrete network design. This is due to the fact that all road network elements are practically discrete, due to the hierarchical definition of network elements in many norms and guidelines. In a discrete approach, all candidate roads and intersections are provided in advance (like e.g. in Xie and Levinson, 2009). However, the proposed approach differs from a network optimization approach, as visualized in Figure 4.1(a), where only a small share of roads are actually candidates, compared to the remaining network. In the proposed approach, the candidate roads make up an entire network design, and predefined "given" road links are omitted. Figure 4.3 displays a set of candidate links based on a gridiron. However, not all candidate links might actually be proposed for the final design, since only a minimum of one access link suffices for each zone. Figure 4.3 displays a gridiron design of candidate roads. However, the gridiron design can be replaced, as shown in Figure 4.14 so the position of the initial candidates is also variable. Additionally, a budget constraint is required to limit road length and infrastructure expenses.

The predefined candidate roads enable the implementation of certain shape grammar rules, e.g. hierarchical network design. However, the proposed approach is not able to implement all kinds of shape grammar rules due to the constraints of the predefined candidate road set. Particularly, rules covering continuous design variables cannot be implemented, e.g. rules about the angle of incoming roads at intersections are excluded from such a design. Continuous approaches might overcome such limitations, as described in e.g. van Nes (2003).

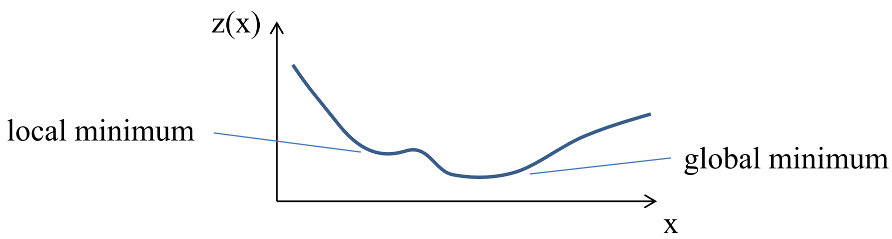
Figure 4.3: Examples of a



The search space increases disproportionally with increasing network sizes. When assuming a total number of 339 nodes and a total number of 432 candidate links (no connectors), the search space is $2^{432} \simeq 1.11 \cdot 10^{130}$, minus the infeasible networks, and the networks which exceed the budget constraint. An example area of $1.0{\times}1.0[\text{km}^2]$ leads to a density of 339 potential intersections [#/km^2]. However, regarding the calculation time, only the absolute number of candidate links influence the search space and not the density of the candidates. In addition, the number of demand generating nodes has to be considered when estimating the calculation time required for optimization. The number of demand generating nodes influence demand assignment directly, and its calculation time requirements.

Because of the quickly growing search space, the accuracy of the expected network design requires further specification. Due to the complexity of the problem formulation (Johnson et al., 1978) it is impossible to determine with 100% accuracy the most efficient network design without complete enumeration of all alternatives. The most efficient solution regarding a given objective function therefore remains unknown. Whenever designing networks, it is possible to generate networks, which refer to a local minimum regarding the objective function, compared to the desired global minimum (Figure 4.4), except with methods for complete enumeration of all alternatives. Complete enumeration means that basically all potential solutions are designed and evaluated. Complete enumeration is very cumbersome, even if certain networks might get discarded right away with appropriate methods (e.g. branch-and-bound). Because a complete enumeration of all potential networks is not feasible given the calculation time for large transport networks and their demand assignment, a heuristic approach is chosen for network design.

Figure 4.4: Local and global minimum of function z.



4.4 Evaluation and Objective Functions

When looking at transport planning, many scenario based planning approaches can be found with different objective functions. Many objective functions for economic, social, and environmental assessments are available for scenario evaluation purposes. Furthermore, reliability and robustness measures cover specific network characteristics and are increasingly applied in planning. For transport network evaluation, especially of complex large-scale networks, quantifiable measures are most useful for efficient evaluation and comparison reasons. Quantitative measures are also suitable for automated network evaluation, especially valuable in automated algorithms.

Mallard and Glaister (2008) summarized a cost-benefit approach, which mainly covers economic aspects. Moreover, accessibility is an alternative measure, focussing on economic productivity (Venables, 2007; Axhausen, 2008). Social aspects are covered by Bramley and Power (2009). Reliability and robustness measures emerged in recent years due to increasing complexity and dependencies (e.g. Helbing, 2013). Among the different evaluation measures, the evaluations here focus on economics, and therefore exclude aspects such as quality of urban life, safety issues, and external costs. It is anticipated that shape grammar rules can be evaluated in the future with additional evaluation measures, depending on the needs of the practitioners and authorities. The main components of the economic measure in transportation are generalized user costs, infrastructure costs including maintenance, and external costs (e.g. Mallard and Glaister, 2008; VSS, 2006c), similar to the evaluation in Section 5.2. The generalized user costs comprise demand weighted travel time by travel distance (Hess et al., 2008), wear and fuel cost. Calculation of total travel time is the computationally most expensive measure. Therefore, the function can be easily enriched with further quantitative variables without adding large amounts of additional computational time. Equation (4.1) summarizes the objective function applied in the chapters below.

$$c = f_{\textit{gen. user costs}} = \left(\sum_{o} \sum_{d} \textit{demand}_{od} \cdot \Big(t_{od} \cdot \gamma(l_{od}) + \textit{distancecost}_{od} + \textit{fuelcost}_{od} \Big) \right) \tag{4.1}$$

- o, d: Origins and destinations.
- t_{od}: Travel time between o and d.
- $\gamma(l_{od})$: Weighting factor (value of time as a resource) dependent on travel distance l_{od} extrapolated for a year.

Accessibility complements the costs-benefit related measure above. Accessibility is defined here as the logsum term of a choice model giving the expected maximum utility of all alternatives (Ben-Akiva and Lerman, 1985). The accessibility is weighted with the number of people benefiting from it, and therefore is also called person weighted accessibility (similar to Levinson et al., 2014). Equation (4.2) defines the accessibility measure used in this research.

$$\textit{Total Accessibility} \quad = \quad \sum_{\forall i} B_i \cdot \underbrace{ln \left(\sum_{\forall j} X_j \cdot f(c_{ij}) \right)}_{\text{Accessibility of location } i} \tag{4.2}$$

- X_i: Attractiveness of location i (here: sum of workplaces and residents).
- B_i: Weighting the accessibility (here: number of residents).
- $f(c_{ij})$: Weighting function, dependent on the generalized costs of travel c_{ij}, here: $f(c_{ij}) = e^{-\beta c_{ij}}$, β = 0.2, c_{ij} = travel time.

Literature often refers to "utility" in the field of transportation and economics. Here, the expression "objective function" is used, which refers to the evaluation background. However, both utility and the objective function are synonyms here.

4.5 Integrated Ant Colony and Genetic Algorithm (IACGA)

The proposed network design algorithm relies on the above requirements and assumptions. Therefore, it is designed to solve discrete problem formulations. The design method merges an ant colony optimization with a genetic algorithm. Both are applied for discrete optimizations and are applicable for network generation problems (Poorzahedy and Abulghasemi, 2005; Jeon et al., 2006). They are merged in order to reduce computational time. Network elements are exchanged between different candidate networks to generate more efficient networks given the objective function. Due to its heuristic nature, the IACGA does not guarantee to find the optimum solution.

The network design algorithm IACGA is capable of designing networks for different infrastructure budgets. Higher infrastructure budgets lead to denser networks, whereas lower budgets to less dense networks. The IACGA designs road networks. For other modes e.g. transit, it would need to be adapted.

4.5.1 Methodology

In the following, an overview is provided over the design method for road networks, including the potential implementation of shape grammar rules. The design method benefits from both the advantages of the GA and the ant colony optimization (ACO) methodologies, and therefore is referred to as Integrated Ant Colony and Genetic Algrithm (IACGA). Dorigo and Stuetzle (2004); Holland (1975); Goldberg (1989) describe the GA and ACO in detail. Identical to a standard GA, the IACGA is based on a population of individuals. Each individual represents a candidate network, which evolves over time given an objective function. The improvement of the individuals relies on a recombination method. Therefore, elements of other individuals and their networks are copied and merged for a modified network design. Similar to an ACO, a learning ability is implemented in the IACGA. The motivation is to improve the weak learning ability of a standard GA, which primarily relies on statistics and probability calculations (Goldberg, 2002), which often requires a lot of computational resources. Additionally, the nature of transport networks is taken into consideration, so to assure a coherent connected graph between the centroids, or to avoid unnecessary detours.

Methods considering both a GA and an ACO already exist, often applying both methods alternately. White and Yen (2004) introduced an integrated GA and ACO which is based on similar structures as the IACGA described here. The proposed algorithm is applied successfully to the Traveling Salesman Problem (TSP). However, the TSP is different from the NDP in many respects. In the following, the IACGA is explained step by step, an overview is provided in Figure 4.5, and as pseudo code (Algorithm 1 on page 69).

1. The initial population is generated, which consists of individuals each representing a feasible randomly designed road network. The randomly designed networks are built out of a subset of all candidate roads links. The initial population serves as the parent population in the first iteration.

2. Two individuals are selected randomly out of the parent population. Both individuals are merged according to a recombination procedure. The recombination procedure is conducted directly within the network. Therefore, the IACGA differs from a GA, which implements a recombination procedure based on a genotype bit string. Within the IACGA, road links are chosen from both individual networks. Road links are reassembled to achieve a feasible offspring individual. Thus, the potential candidate network elements are chosen according to a probability function. In the very first iteration, the probability is random. However, in the consecutive iterations, the probability function for choosing candidate elements accounts for the success of the networks, which were designed in previous iterations. If a candidate element is under consideration, which was already implemented in networks of previous iterations with high scores, it is more likely that the candidate element will be chosen again. Elements such as links ij are chosen with probability p_{ij}^g, with the scores of the previously generated networks are stored as pheromones in τ_{ij}^g (see step 5 for further details):

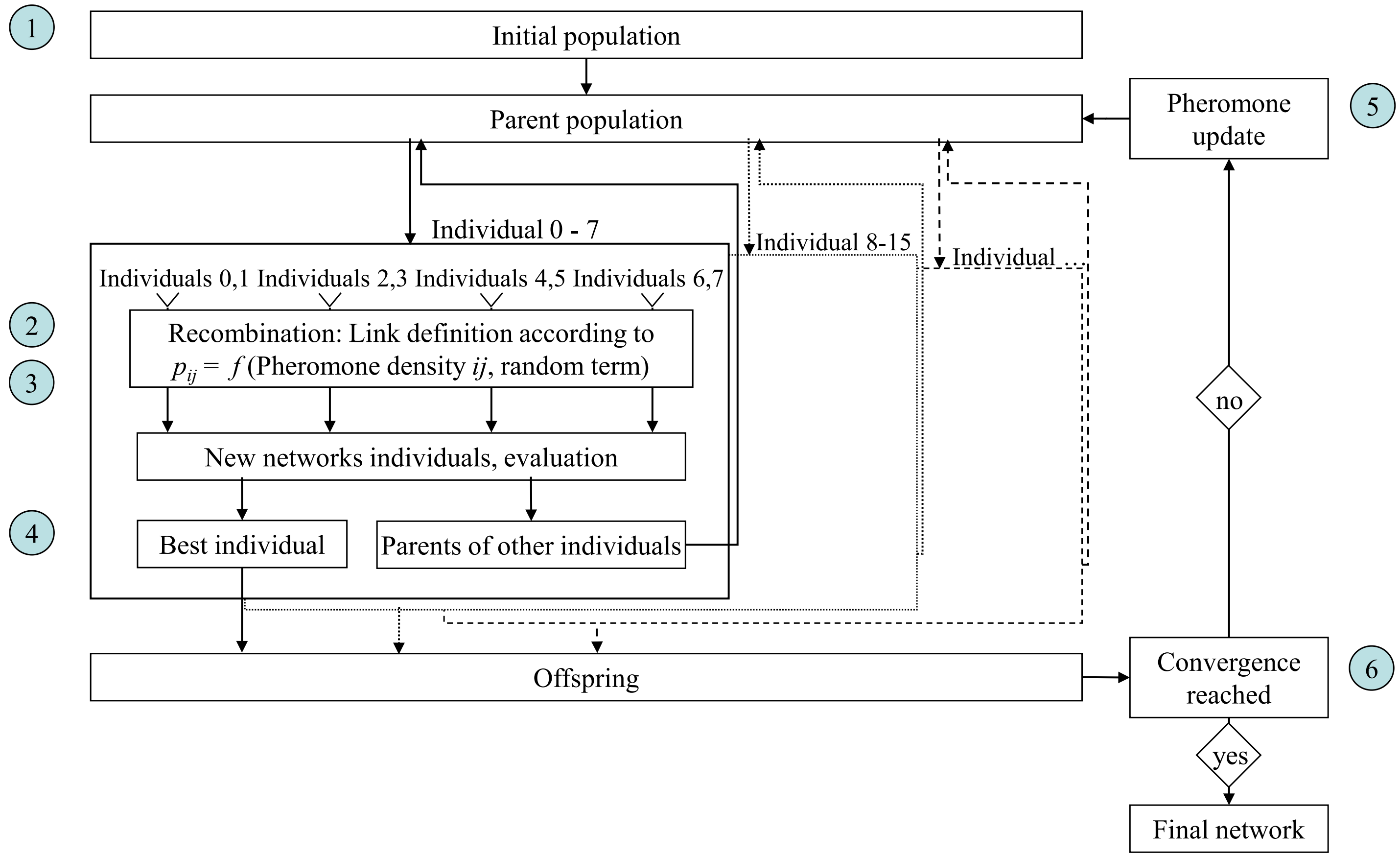
$$p_{ij}^g = \begin{cases} \dfrac{e^{\alpha \tau_{ij}^g} e^{\beta\,\varrho}}{\sum\limits_{i\text{-}j \in L_{Parents}} \left(e^{\alpha \tau_{ij}^g} e^{\beta\,\varrho} \right)} & \text{, when } i\text{-}j \in L_{Parents} \\ 0 & \text{, otherwise.} \end{cases} \tag{4.3}$$

p_{ij}^g:	Probability of choosing link i-j in iteration g.
τ_{ij}^g:	Pheromone density in iteration g on link i-j.
ϱ:	Accounts for additional randomness.
α, β:	Parameters, subject to calibration.
$L_{Parents}$:	Set of links i-j which are present in at least one parent network.

Elements from both parents are chosen with probability p_{ij}^g until the budget constraint is reached (step 3 for more details). Elements which are not part of one of the parent networks are not included in the new network. Figure 4.6 shows an example of two parent individuals and one offspring individual. Obviously, the initial population size has to be large enough to comprise all relevant network elements.

3. Shape grammars are applied in the design process. They either influence the choice of the network elements (and therefore modify Equation (4.3)), or modify the newly emerged offspring network. All rules have to obey the budget restriction. A penalty p_+ penalizes budget B violation ($p_+ = \gamma \cdot (a - B)$), also shown in Equation (2.4). It was found that a

Figure 4.5: Overview over the IACGA with numbers referring to the text.



γ-value of 20.0 is sufficient to reduce violations to a minimum within the network design algorithm. However, this value corresponds to the chosen road costs (Figure 6.7), and might vary for different costs.

4. Step 2 and 3 are repeated four times with new parent networks and only the best offspring is added to the offspring set. For this purpose, the parent networks are randomly chosen from the parent population. The parent individuals are returned if their evolved offspring candidate network is outperformed by another candidate offspring generated by other parents. This procedure reduces the risk of generating infeasible networks, e.g. networks, which do not connect all zones. Currently, the number of trials is set to four, which leads to only very few infeasible networks, but this parameter is subject to further calibration. Step 2 - 4 are repeated until a new population is generated with the same number of individuals as the previous population.

5. After a new population is generated, the pheromones on all candidate road links are updated with the scores of the individuals of the new population. The pheromones are responsible for preserving the information about success or failure of the network individuals. Therefore, the score of a network individual is used to determine the amount of the pheromones τ. The pheromone amount is mapped onto each network element. Equation (4.4) is derived from Poorzahedy and Abulghasemi (2005, p.258). The score of the individuals are subtracted with travel times from a hypothetical case of crow fly distances (monetarized) to reduce the absolute value of the score and is called therefore $\boldsymbol{\Delta}\tau_{ij}^{g}$. In case that two network individuals contain the same element, the higher corresponding score is used for the pheromone amount calculation. The evaporation rate δ is responsible for the adaptive learning process, similar to an ACO.

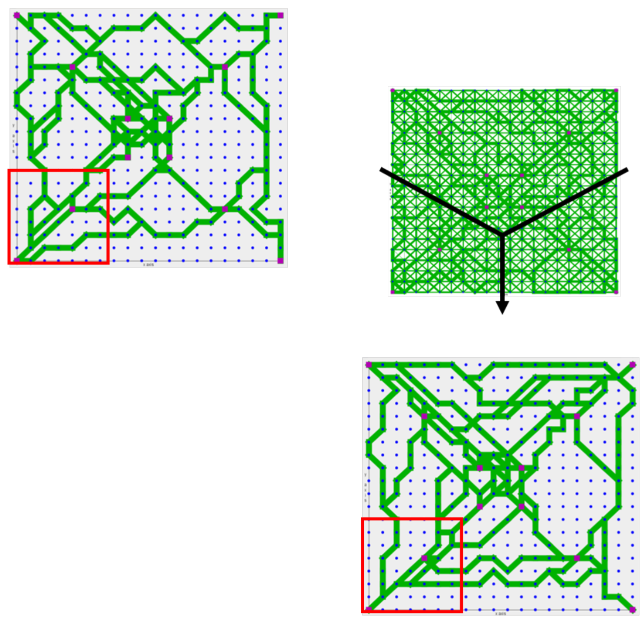
$$\tau_{ij}^{g} = (1-\delta) \cdot \tau_{ij}^{g-1} + \max(\Delta\tau_{ij}^{g}) \tag{4.4}$$

δ:	Evaporation rate.
$\max(\Delta\tau_{ij}^{g})$:	Score of the best individual out of all networks containing link ij.

6. The algorithm returns to step 2 if convergence has not been reached yet. Convergence is reached when the pheromone densities on individual links are not changing any more or when a substantial part of the population consists of individuals with the same optimal networks regarding the objective function. The best performing cutoff criterion so far applies the pheromone density on links. This criterion reflects the fact that only links which are elements of high performing networks with high scores can maintain their pheromone densities on a high level. Thus, when reaching the optimum network, the pheromone densities on all links are decreasing, except the densities on the links of the optimum network.

The described algorithm is implemented in a Java platform (see Section 3.5.4) and parallelized to reduce calculation time. The design of 1.0×1.0[km^2] networks with 432 candidate links and 104 demand generating nodes, similar to Figure 4.3 takes about 19[h] on 24 parallel threads and 3.33[GHz] (12 cores). The rather long calculation time is due to the complexity of network design and evaluation.

Figure 4.6: The merging procedure based on both parent individuals and a pheromone matrix visualized in the center.



4.5.2 Advantages and Disadvantages

Several advantages emerge with an IACGA, especially in comparison with a GA:

- A GA is able to solve discrete optimization problems of objects and the combination of objects, which can be quickly translated into a string formulation (e.g. bit string). Examples are found in matching problems, scheduling, traveling salesman problem, and related problem formulations. After translation of the objects (also called phenotype) into strings, the GA modifies the string formulation, also called genotype or genetic code, through recombination procedures. Then, the string is retranslated in objects again. However, one has to be aware that the recombination procedures are based on string modifications, such as mutation, crossover, and other methods (Goldberg, 2002; Sivanandam and Deepa, 2008). Specifically, the genotype does not allow the deduction of characteristics of the phenotype. E.g. a network graph can be translated in a genotype string, which should be obviously long enough to store all characteristics of the network graph. However, the string representation of a connected network graph can not be distinguished from a genotype string representing two unconnected subnetworks, which is a major drawback of the phenotype – genotype transformation, and maybe the GA in general. However in the IACGA, the merging procedure is adapted and based on the phenotype, and therefore excludes genotype transformations. The phenotype recombination therefore differs from the standard recombination procedure of a GA. In the IACGA, network elements are reassembled including their attributes, such as capacity, so that a consistent graph evolves out of the merging process (step 2 in Section 4.5.1 and Figure 4.6).

Algorithm 1 Integrated Ant Colony and Genetic Algorithm (IACGA)

Start

Initial population P^0 contains randomly generated individuals p_m^0, and pheromone density $\tau_{i,j}^0 = 0 \; \forall(i,j) \in A^0$.

repeat

while $P^n \neq \emptyset$, **do**

Choose 4 pairs (or less, when $|P^0| < 8$) of individuals (p_k^n, p_l^n) randomly.

for all pairs (p_k^n, p_l^n) **do**

while $a < B$ **do**

$a = 0.0$.

for all $(i,j) \in \{A_{p_k^n}^n;\ A_{p_l^n}^n\}$ **do**

$$\text{prob}(n) = \begin{cases} \dfrac{e^{\alpha \tau_{i,j}^n} e^{\beta\,\varrho}}{\sum\limits_{\forall(i,j)\in\{A_{p_k^n}^n;\,A_{p_l^n}^n\}} \left(e^{\alpha \tau_{i,j}^n} e^{\beta\,\varrho}\right)} & \text{when grammar rule compatible} \\ 0.0 & \text{, otherwise.} \end{cases}$$

end for

Choose (i,j); update a.

end while

end for

The generated individual p_m^{n+1} with highest score ($f_{obj.}$) is selected and proceeds to P^{n+1}. The parents of the remaining children, as well as 1 (0 if $|P^n| = \varnothing$) parent of p_m^{n+1} return to P^n.

end while

for all (i,j), **do**

$$\Delta\tau_{i,j,\max}^{n+1} = max\Big(\Delta\tau_{i,j}^{n+1}(p_n^0),\ \Delta\tau_{i,j}^{n+1}(p_n^1), ...,\ \Delta\tau_{i,j}^{n+1}(p_n^{|P_{n+1}|})\Big)$$

$$\tau_{i,j}^{n+1} = \begin{cases} (1-\delta)\cdot\tau_{i,j}^n + \Delta\tau_{i,j,\max}^{n+1} & \forall(i,j) \in A^{n+1} \\ 0.0 & \text{, otherwise.} \end{cases}$$

end for

until convergence criterion is met.

End

- In the proposed IACGA the recombination of network graphs (phenotypes) offers also the possibilities of additional modifications, especially the implementation of shape grammar rules. A standard GA disables the possibility of a shape grammar implementation in the design process.

- Beside shape grammar rules the IACGA allows the implementation of transport network expertise. A transport network graph obviously serves for transport needs, therefore, it has specific characteristics, e.g. the graph has to be connected (Clark and Holton, 1991). The recombination process can exclude infeasible solutions right away (e.g. unconnected networks), without detailed evaluation. Links and nodes can be eliminated if they are unused. Therefore, feasibility and performance can be improved without cumbersome full evaluation.

- The IACGA can be parallelized for considerable calculation time reductions with low processor idling times. First, traffic assignment can be parallelized. Second, the population approach of the IACGA allows parallel processing of multiple individuals (which is applied in this research).

Disadvantages of the proposed IACGA:

- The IACGA remains a heuristic algorithm, similar to the ant colony optimization. Modification of the parameters, such as population size or evaporation rate, increases the robustness, but cannot statistically guarantee to find the globally optimal solution. This characteristics contrasts the GA which can guarantee in some cases to find the most optimal solution within a certain confidence interval (e.g. 95%). Therefore, the IACGA differs from the GA (Goldberg, 2002). However, one has to be aware that the NDP cannot be solved with 100% accuracy without complete enumeration method. Therefore, sound recombination procedures like the IACGA are promising design approaches. Moreover, the GA can only solve a problem formulation with sound parameter settings, such as a large enough population size (Goldberg, 2002). The IACGA has the potential to approximate certain GA characteristics if certain parameter settings are adapted (population size) or if the learning ability is deactivated (pheromone and probability function in step 2, Section 4.5.1).
- The shape grammar rules have to be implemented manually during the recombination procedure, which means that the shape grammars have to be programmed inside the code. Due to the diversity of potential shape grammar rules, e.g. their potential application on road and node elements, an automated shape grammar rule interface seems too complex to avoid programming. However, this argument might be valid also for other algorithms. Shape grammar rules are already implemented as codes, e.g. in procedural modeling (Figure 1.5(d) or Weber et al., 2009).
- Compared to the IACGA, the GA is a widely applied method mainly for discrete optimization. The GA is a general framework which allows implementations in many different fields. Numerous libraries exist for GA implementation in various programming languages.

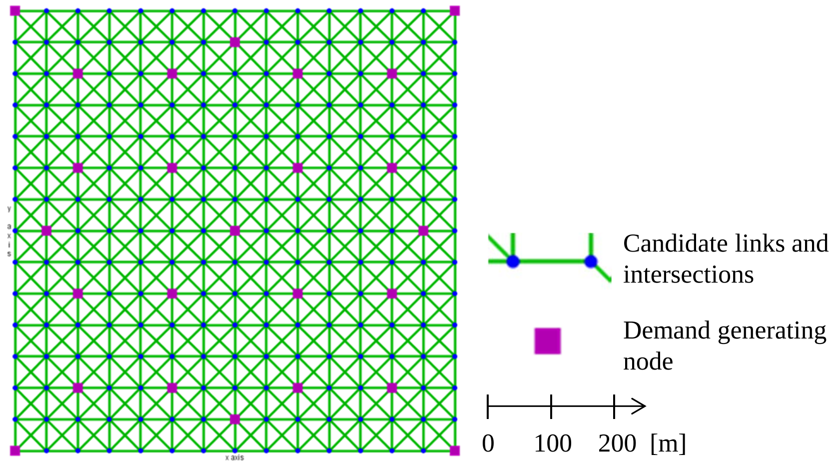
Table 4.1 summarizes the application potential for the GA, ACO, and IACGA based on their methodological background. The first two lines refer to the statistical principles of the algorithms based on probability and frequency explained above, and highlights that the methodology of the GA is based on probabilistic principles, and that the chances of successful optimization can be determined based on probability calculations. The last three lines of Table 4.1 refer the the type of network design, and separate between optimization of an existing network, the design of a completely new network, and the capability of shape grammar rule implementation.

A number of experiments were conducted with the IACGA and the GA for comparison based on different base scenarios. Table 4.2 compares the number of evaluations to find the optimal network based on an objective function of a GA and IACGA. The standard GA is applied from the framework of Kronfelder et al. (2010), including parameter calibration (details in Vitins and Axhausen, 2010). Different networks with different number of candidate links and nodes

Table 4.1: Qualitative comparison of the GA, ACO and IACGA characteristics.

	IACGA	GA	ACO
Heuristic	×		×
Probabilistic principles		×	
Applicable for network optimization	×	×	×
Applicable for network design	×	×	
Applicable for shape grammar rules	×		

Figure 4.7: Example network for comparisons between the IACGA and the GA.



were evaluated. Figure 4.7 shows the example network of 342 candidate links and 25 demand generating nodes which was used for the results in Table 4.2.

Table 4.2 shows that the IACGA outperforms the GA especially for larger networks. The main reason is the genotype-phenotype transformation, and the high share of infeasible offspring networks in the case of a standard GA (see above for more details). However, the calculation time also depend on the assignment and number of demand generating nodes, and not only on the number of candidate links.

4.5.3 Calibration of the Algorithm

Figure 4.8 shows the convergence characteristics of the IACGA. It relies on a dense network which is similar to Figure 4.3, with 360 candidate links and 85 demand generating nodes. The results include the penalty for infrastructure budget violation. The best individual of each iter-

Table 4.2: Comparison of a standard GA and the IACGA.

Network size [#candidate links]	Number of evaluations			Total calculation time [h] on a single CPU machine[a]		
	GA [#]	IACGA [#]	Difference [%]	GA [h]	IACGA [h]	Difference [%]
342	200.000	54.000	-73.00	6	0.75	-87.50
812	$1.7{\cdot}10^8$	140.000	-99.92	5.100[b]	2	-99.96
1482	$\sim 1.1 \cdot 10^9$ [c]	700.000	-99.94	33.000[b]	124	-99.62

[a]: on a Sun Fire X4600 with 8 CPUs (AMD Operon 2.66 GHz dual core) and 128GB RAM.
[b]: It is assumed that in the case of GA, calculation time grows linearly with the number of objective functions evaluated.
[c]: Based on the results of smaller networks, and extrapolated relying on the statistical assumptions of Goldberg (2002).

ation (generation) improves, and the corresponding result of the evaluation converges against the final solution. The improvement of the best individual is slow at the beginning, however, the improvement of the worst individual is fast in this period.

Figure 4.8: Convergence behavior of the IACGA.

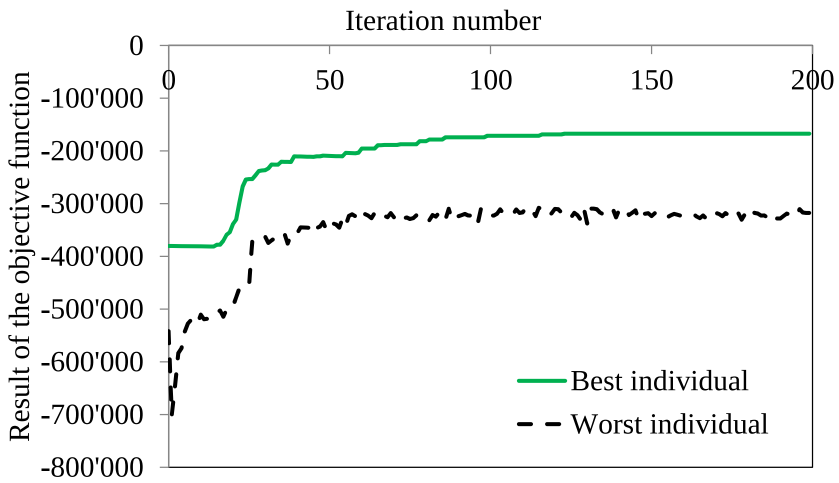


Figure 4.9 exemplarily shows the convergence behavior of the IACGA. It visualizes the pheromone distribution on the left (Figures 4.9(a), 4.9(c), 4.9(e)), and intermediate network design results on the right (Figures 4.9(b), 4.9(d), 4.9(f)). The bar width is proportional to the pheromone density and the road capacity, respectively. The road capacity corresponds to specific road types (Table 6.12). Additionally, intersection types are distributed according to given

rules originally derived from Marshall (2005) and described in Vitins et al. (2013). Connector links are ignored in Figure 4.9 for simplicity, unlike Figure 4.3 and the results in Chapters 6 and 7. The reader is referred to Chapters 6 and 7 for more detailed intersection type choice evaluations.

Figure 4.9 clearly shows the evolution of the most relevant connecting routes. The purple demand generating nodes are connected with each other in order to build a fully connected network. All detours, espcially in the area of top left and bottom right corners have low pheromone densities and therefore are practically ignored in the design of new networks already after 20 iterations. Only the most relevant routes are left after 200 iterations and mainly parallel routes with similar costs. Multiple network solutions with similar objective function evaluations might result due to parallel routes.

Figure 4.10 shows the effect of different population sizes on the outcome. The network topology is still similar to Figure 4.3, but the number of candidate links is smaller (168) as well the number of demand generating nodes (40) to reduce overall calculation time. Figure 4.10 visualizes that the increasing population size increases the chances, that the outcome is close the optimal solution. The values are higher than in Figure 4.8 due to the smaller network sizes ($0.6 \times 0.6[km^2]$, 168 candidate links and 40 demand generating nodes).

Figure 4.11 shows the results for different population sizes and evaporation rates. The network evaluation includes a penalty at infrastructure budget violation (168 candidate links and 40 demand generating nodes). Figure 4.11 shows again improved results of the objective function for larger populations. This is reasonable because the chances are higher to find the optimal design during optimizations with larger initial populations.

Results of Figure 4.11 are less clear when looking at the evaporation rates. Improved results are expected for evaporation rates of about 0.01 and 0.001 and for large populations. A rate of 0.005 seems less stable, but achieves high results as well when looking at a population size of 300. A high evaporation rate reduces the influence of previous results within the design of new individuals. Low evaporation rates means that the previous results are considered to a bigger extent. However, this is only valid for higher population sizes. For low population sizes, the results are more uncertain. Overall, the evaporation rate has a weaker influence compared to the population size.

Figure 4.12 displays the values of Figure 4.11 in a 3D graph. Figure 4.12 shows that large populations generate efficient networks. Again, results are less clear on the evaporation rate side. It seems that the algorithm is less sensitive to the precise evaporation rate, the results just shows that the evaporation rate should be lower than 0.1 and eventually 0.05. The reason for this relative insensitivity to the evaporation rate and the low suggested value is the update method of the pheromones on the candidate links, which considers the score of the best performing network (Equation (4.4)), when higher than the parent networks (see above). The updated pheromone values do not change drastically between the considered rates of 0.01 and 0.001 since the pheromone values get updated with a network score which is higher on the links which are relevant. Poorzahedy and Abulghasemi (2005) elaborated on the evaporation rate δ for an ACO application, and also showed less clear results on their rate (their suggested range is $\Delta\delta \simeq 0.2$).

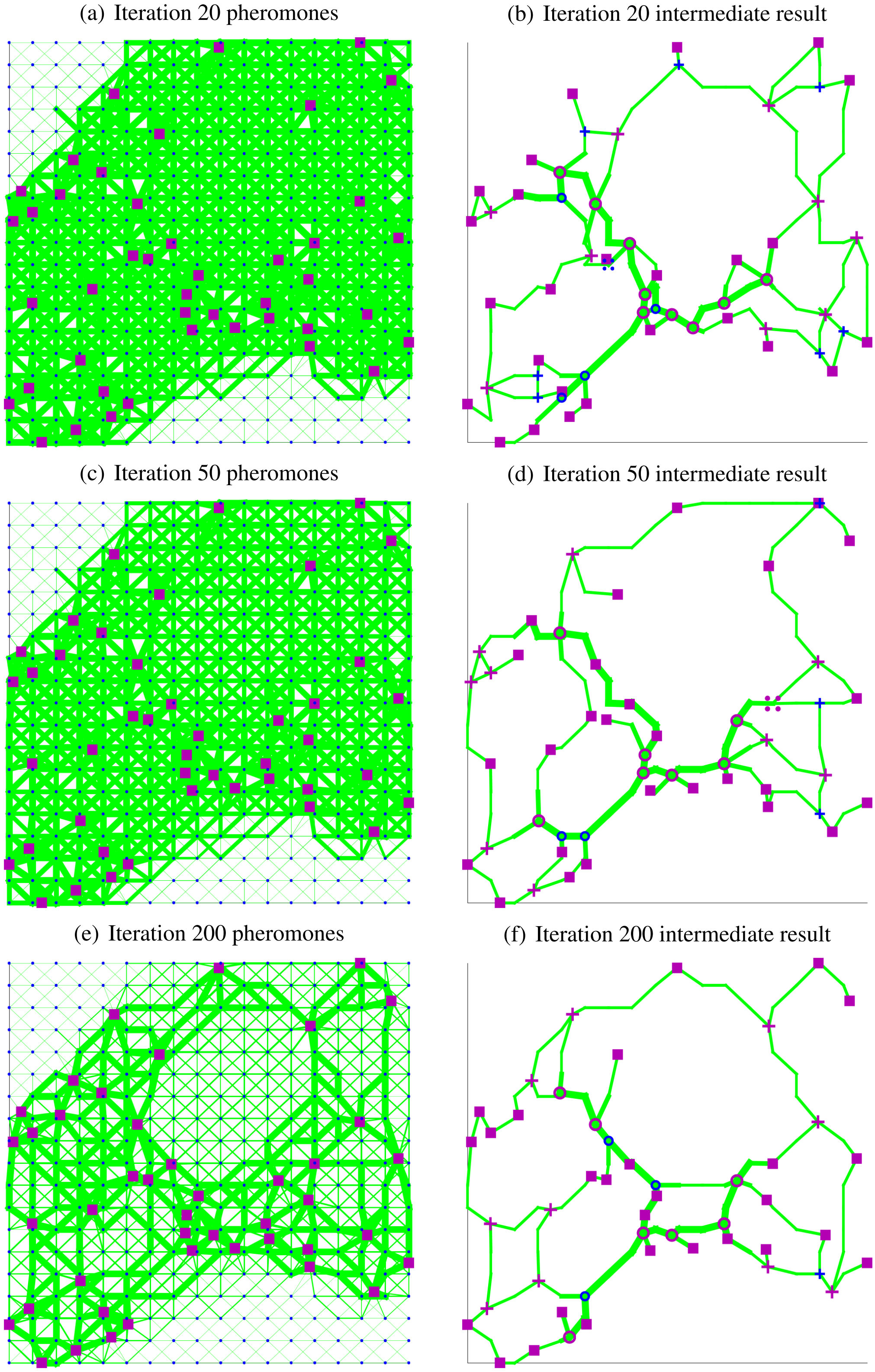
For further verification, accessibility and network user costs are calculated as a function of the overall network length. Figure 4.13 depicts accessibility (Equation (4.2)) and user costs (Equation (4.1)) as a function of road density d_r for networks similar to Figure 4.3, with 360 candidate links and 85 demand generating nodes. The results in Figure 4.13 ignore turn delays. Figure 4.13 shows increasing accessibility with increasing network density d_r. User costs are decreasing. Both increasing accessibility and decreasing user costs are reasonable.

4.5.4 Potential Applications

It is mainly the number of candidate links, and therefore the size of the search space, which limits the application of the algorithm. Recently increasing computational power has enabled larger number of network evaluations, and therefore a larger search space. As stated above, the design of 1.0×1.0[km^2] networks with 432 candidate links, and 104 demand generating nodes, similar to Figure 4.3 takes about 19[h] on 24 parallel threads at 3.33[GHz], which certainly limits the algorithm for larger cases.

Figure 4.14 shows an example application of the IACGA including a terrain constraint. Figure 4.14(a) shows the intermediate result of iteration 20. Figure 4.14(b) shows the final result after iteration 200. Figure 4.9 and Figure 4.14 demonstrate that the IACGA is applicable for various predefined candidate links and various network topologies.

Figure 4.9: Intermediate results during the design of a network with the IACGA.



Left figures: Bar width ~ pheromone density.
Right figures: Link Types: Minor arterial, Access road, Local road
Intersection types: Roundabout, Signal control, Right of way control
Both figures: in purple (●): demand generating node.
0 200m

Figure 4.10: Population size and the outcome of the IACGA (n=40).

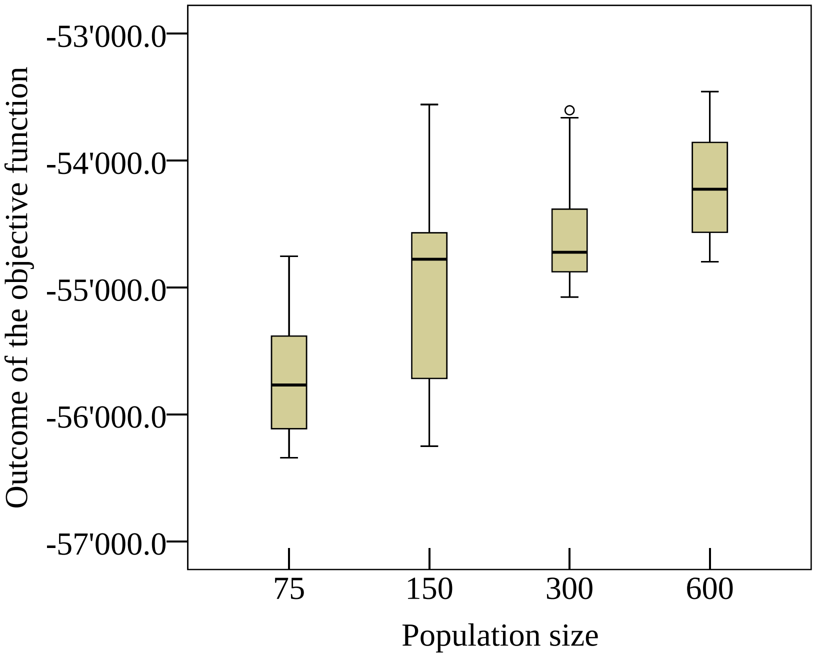


Figure 4.11: Output of the objective function depending on different evaporation rate evaluation (n=240).

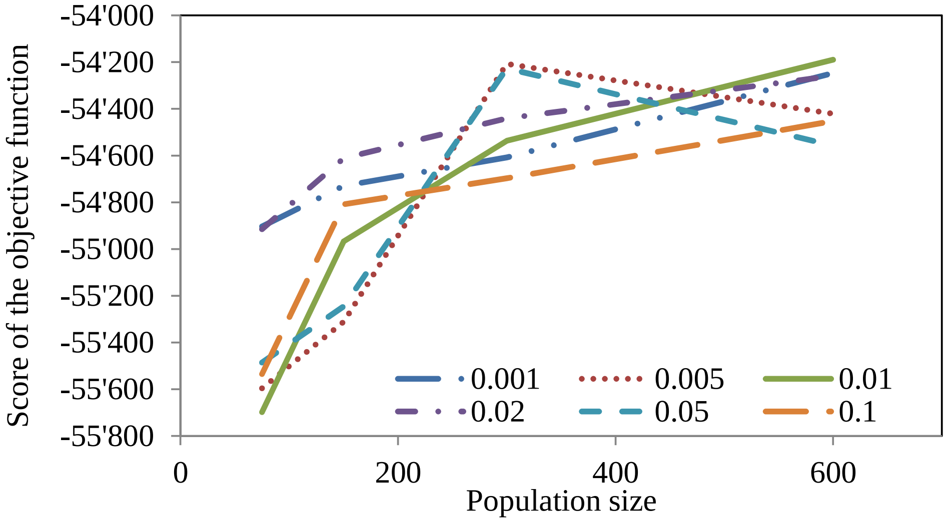


Figure 4.12: Population and evaporation sensitivity, based on average values and n=240.

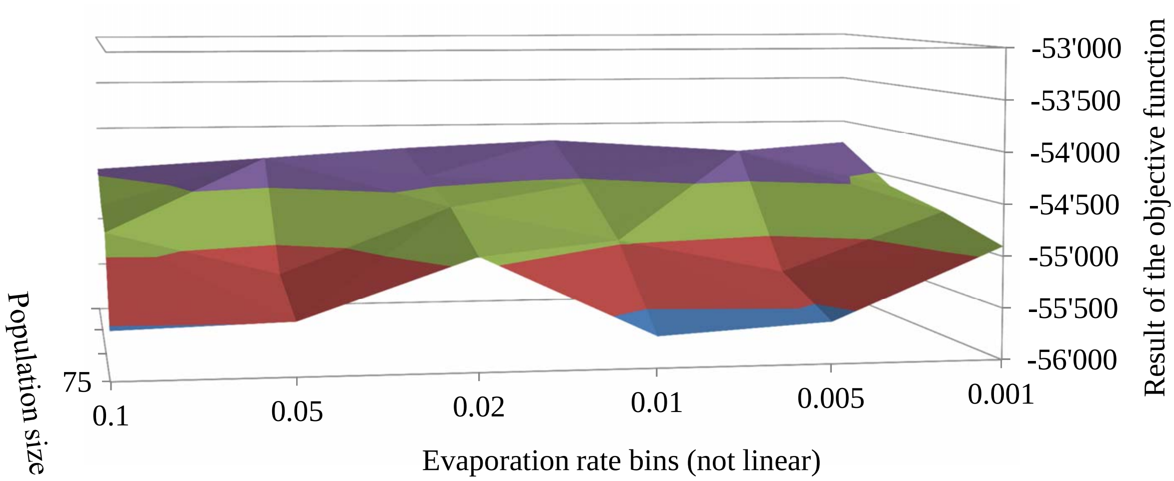


Figure 4.13: Network user costs and accessibility vs. road density d_r.

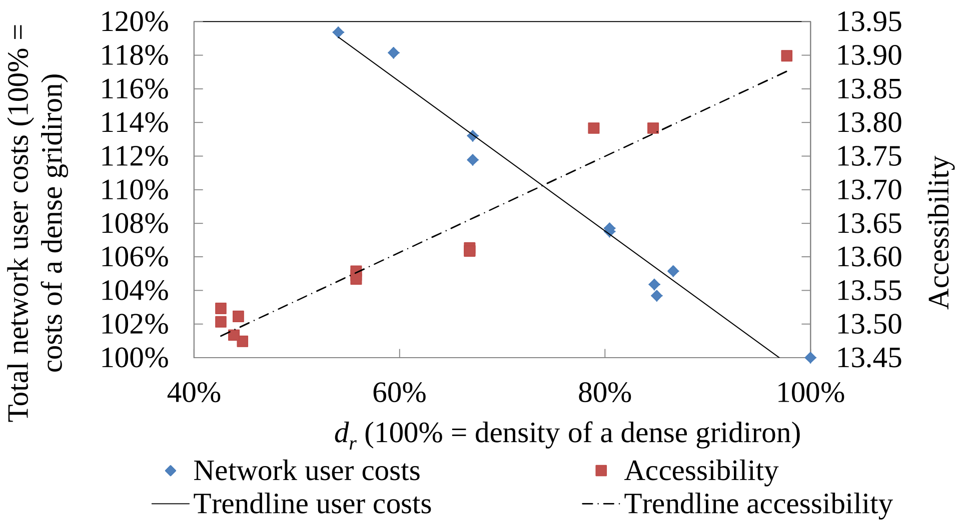
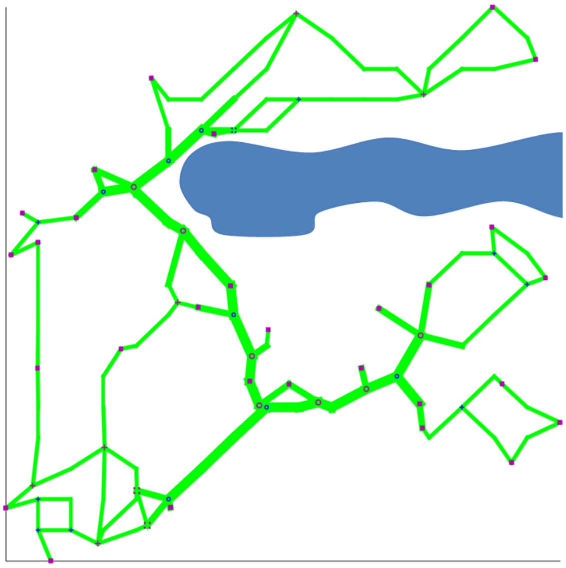
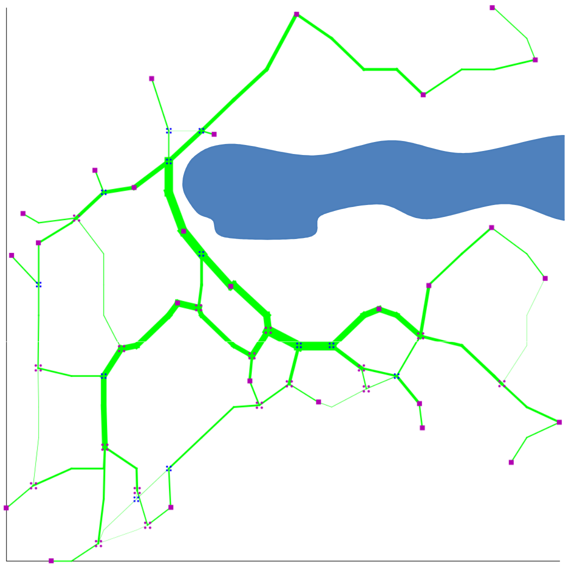


Figure 4.14: Example application of the IACGA including a terrain constraint.


(a) Iteration 20.


(b) Iteration 200, and post-processing.

Source: Vitins et al. (2011a).

Chapter 5

Boulevard Design

This example illustrates the methodological approach elaborated above about shape grammar assessments, more specifically in study design 1 (Section 3.1.2). The example covers the design of boulevards deployed in larger cities around the world. Often, the boulevard is embedded in a local road network. Boulevards also serve as through traffic infrastructure. Obviously, through traffic can be handled in many different ways, totally separated from local traffic, or fully integrated in the local road network, such as the boulevard network.

This section aims at a better understanding of boulevards, their characteristics, and potential impacts in various (un-) congested network states. The impacts of boulevards are quantitatively estimated based on the model and objective functions discussed below. Different shape grammars are applied for the boulevard design, and are compared with efficiency measures discussed above to networks without a boulevard.

5.1 Objective and Application Specifications

The application specifications include a featureless plane to avoid biases due to historical design decisions and terrain. The featureless plane is a square of either 2×2 or 3×3[km^2] with a grid network of 100[m] bock size (400 or 900 blocks in total), similar to Yerra and Levinson (2005) or van Nes (2003). The modeled multiway boulevard is situated in the center of the network, and has a high capacity two-way center road, and parallel minor one-way roads on both sides for access (Figure 5.1(a)). The boulevard center line can be accessed and crossed at every second block (similar to e.g. Avenue Foch in Paris, Passeig de Gràcia and Diagonal in Barcelona, Ocean Parkway in Brooklyn). The remaining gridiron network contains homogeneously distributed blocks. Four boulevard types are proposed in the following each differing in their design of the major center road intersections (Figure 5.1(b)–Figure 5.1(e)).

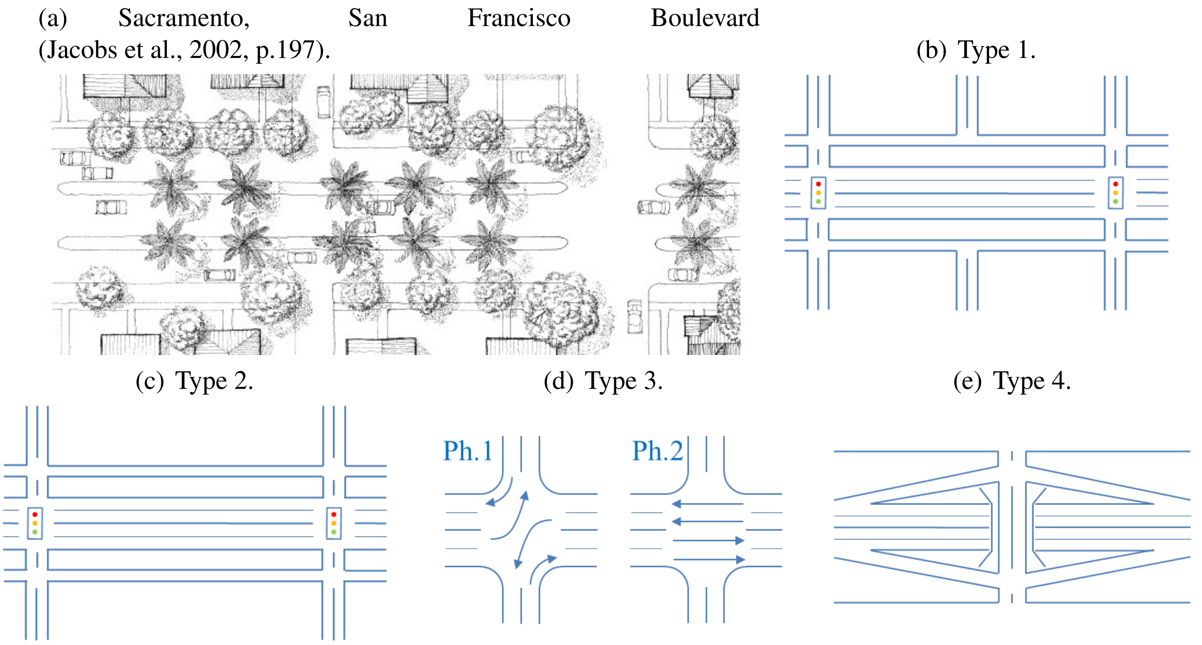
Type 1: Signalized intersections are located on the center road (Figure 5.1(b)), according to Figure 5.1(a), but with higher center road capacities.

Type 2: Signalized intersections are located on the center road with longer parallel minor roads for pedestrians and retail without intermediate access roads (Figure 5.1(c).

Type 3: Signalized intersections are located on the center road, but with reduced number of conflict points and with only two phases (Ph.1 and Ph.2), prohibiting direct boulevard crossing (Figure 5.1(d)).

Type 4: Multilevel intersections of diamond shape to increase safety and efficiency, but require additional space, or construction on a lower level (Figure 5.1(e)).

Figure 5.1: Boulevard designs.



5.2 Objective Functions

The objective is to assess the effects of a boulevard from a transport planning perspective. On the one hand, the boulevard can either reduce the overall network capacity due to turn restrictions and high signal delays. On the other hand, the boulevard can increase overall network capacity due to additional lane miles. Additionally, the costs can exceed user benefits, even over time.

Three objective functions are used to cover changes in user costs, spatial impact and external costs. User costs include monetarized travel time as a function of distance (Hess et al., 2008), including operating costs (VSS, 2006c). Regarding spatial economics, an accessibility measure is proposed, which is widely used in transport and economics. Theory is based on Rice et al. (2006) who stated that doubling the working population proximate to an area raises productivity. Additionally, Porta et al. (2008) showed correlations between a centrality measure, and the distribution of commercial and service activities. Levinson and Huang (2012) summarized the theory of economies of agglomerations.

Accessibility A is calculated as described in Section 4.4 and Equation (4.2). Here, the approach ignores land use dynamics, which also affect traffic flows in the longer term, and only calculates the initial effect of a boulevard on routing and travel times.

Regarding the external costs, multiple variables are considered for evaluation (Table 5.1). Jacobs et al. (2002) evaluated safety of boulevard intersections. In general, boulevards seem not to be more dangerous compared to streets with comparable capacities or flows, according to an evaluation of empirical data (Jacobs et al., 2002). Therefore, safety changes due to the specific boulevard design is ignored in the following. Trucks and public transportation are also excluded in the calculation of external costs as well as tax revenue due to additional gasoline consumption.

Table 5.1: External costs calculation for cars according to the Swiss cost-benefit norms.

	Measure	Value (year 2000)	Reference
Noise	Decibel	0.0140[sFr./veh.km]	VSS (2006b)
Air pollution	Particulate matter	$3.55 \cdot 10^{-2}$[sFr./veh.km]	VSS (2006b)
	Nitrogen oxide	$1.00 \cdot 10^{-2}$[sFr./veh.km]	VSS (2006b)
	Zinc	$1.30 \cdot 10^{-3}$[sFr./veh.km]	VSS (2006b)
Climate effect	CO_2 equivalent	$8.40 \cdot 10^{-3}$[sFr./veh.km]	VSS (2006b)
Accidents	Roads	0.1741[sFr./veh.km]	VSS (2010)
	Signal light	0.1142 [sFr./veh.]	VSS (2010)
	Right-of-way	0.1697 [sFr./veh.]	VSS (2010)

Costs for construction vary considerably in existing data and are often not available in detail. Cost information is taken from Jack Faucet Associates (1991), Litman (2011) and Alam et al. (2005). A major arterial costs about 1.3 [Mio.$/lane/km], a collector road costs 0.8 [Mio.$/lane/km] in a built-up area (year 2000), excluding land costs.

5.3 Methodology

Travel demand is uniformly spread in the area considered. Every block (400 or 900 in total) is modeled as a demand generating node. Uniform demand distribution avoids a bias due to specific demand flows. The total travel demand is according to a dense four story perimeter block development with courtyards in Zurich, and comprises all travel purposes according to the census (Swiss Federal Statistical Office (BFS), 2012). Through traffic is ignored here. The determination of through traffic is very case-specific. Moreover, it is assumed that through traffic can be catered for on additional lanes. The assumed block size of 100[m] is based on Strano et al. (2012) and is similar to e.g. Manhattan, Bogotá, or other cities. For each block, the centroid is linked by an access links to the nearest roads.

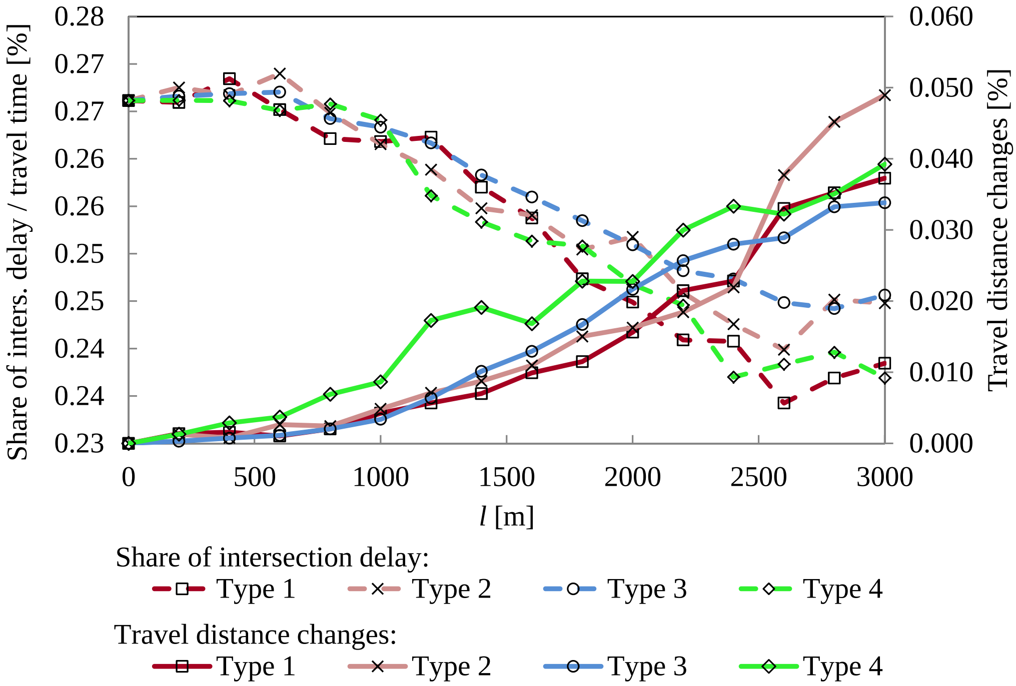
A high resolution static model is deployed with detailed intersection delay calculations. Intersection types and turn delay calculations are calculated according to the HCM (Transportation Research Board, 2010) and summarized in Appendix B. The demand assignment is conducted with a Frank and Wolfe algorithm (Frank and Wolfe, 1956). Unlike the assumptions above, in the case of boulevards synchronisation of signals is approximated to account for the boulevard green wave. Vehicles do not have to stop at consecutive intersections when driving on the boulevard. This method assumes a perfect green wave without queue spillover. Assignment is calculated with the algorithms described in Section A.6. Convergence is analyzed and stable according to Sheffi (1985).

5.4 Effectiveness and Elasticities

Figure 5.2 depicts the travel distances and relative intersection delay as a function of boulevard length. The reasons are threefold for increasing travel distances and decreasing relative intersection shares. Drivers remain longer on the boulevard due to its higher speed and lower intersection delays (green wave). However, drivers also reroute to avoid crossing the boulevard due to higher intersection delays at the boulevard crossings. Additionally, asymmetric travel behavior is observed due to higher left turn delays on the boulevard compared to straight or right turn delays.

Figure 5.3 depicts the results of the evaluation for the three objective functions compared to networks without a boulevard. Therefore, the data points approximate (x/y)=(0.0/0.0) at a boulevard length of 0[m]. On the one hand, Figure 5.3 indicates considerable nonlinear trends especially for short and long boulevards which complicate elasticity calculations. On the other hand, the resulting data in Figure 5.3 shows longer linear intervals allowing elasticity calculation based on linearity. Data are approximated with a polynomial function $f(l)$ to account

Figure 5.2: Share of delays and travel distance changes for 3×3 [km^2] networks with 900 blocks for designs for peak hour traffic.

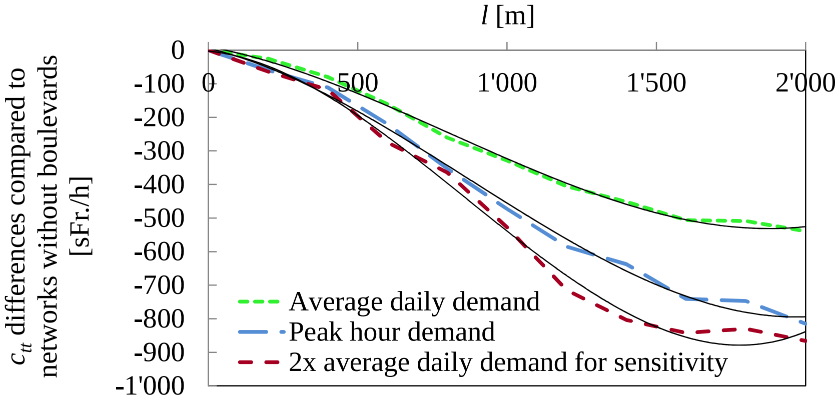


for both effects. Polynomials of degree 3 can account for the nonlinear effect of the very long and short boulevards (see Figure 5.3), and at the same time reasonably approximate a linear interval. Therefore, polynomials with a degree of 3 are able to account for slope changes at both ends, but avoid overfitting of the data points, and achieve a high fit (R^2). The highest slope values $f''(l_{max}) = 0$ are determined based on polynomials of s-shapes like in Figure 5.3. A two-sided application range $\{l_{min}, l_{max}\}$ is proposed, in which values close to the highest slope values can be expected $\left(f'(l_{min}, l_{max}) = f'(l_{max}) \cdot \lambda\right)$. Therefore, an approximated elasticity ϵ^s is calculated for the subset s of the data, which is inside the interval. Polynomials are approximated with the library of Apache Commons (2013).

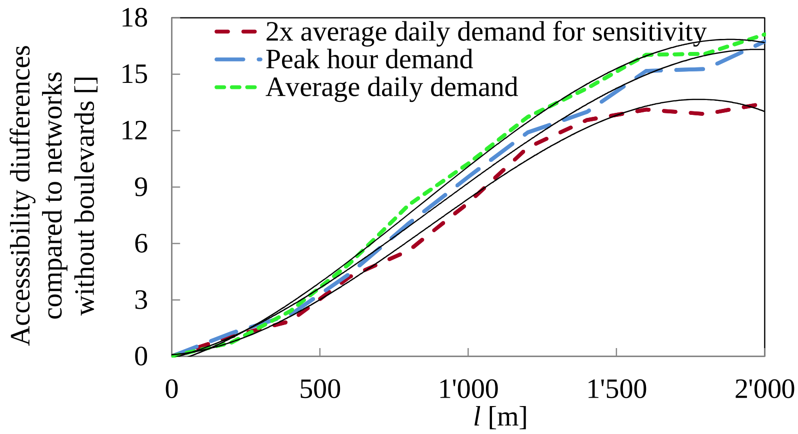
Table 5.2 summarizes the elasticities of the data for boulevard Type 1 with signalized intersections. ϵ^s is the elasticity within the application range. For example, travel time elasticity $\epsilon^{s,T}$ is calculated as $\epsilon^{s,T} = \frac{\delta t}{\delta l}\frac{\bar{l}}{\bar{t}}$ whereas l is the length of the boulevard. An increasing elasticity is shown at higher flows, especially for the 3×3 [km^2] networks. Additionally, the 3×3 [km^2] networks have higher values compared to the 2×2 [km^2] network, due to higher average travel distances. The minimum and maximum values of the application range l_{min} - l_{max} increase for larger networks. There is evidence that the effect of larger boulevards can be approximated with functions of higher slopes. The polynomial approximation changes, as well as the l_{min} and l_{max} values due to the higher slope and different polynomial approximation.

Figure 5.3: Total monetarized travel time (c_{tt}), accessibility and external effect changes for different boulevard lengths l of Type 1 and networks of 400 blocks.

(a) monetarized travel costs.



(b) accessibility.



(c) external costs.

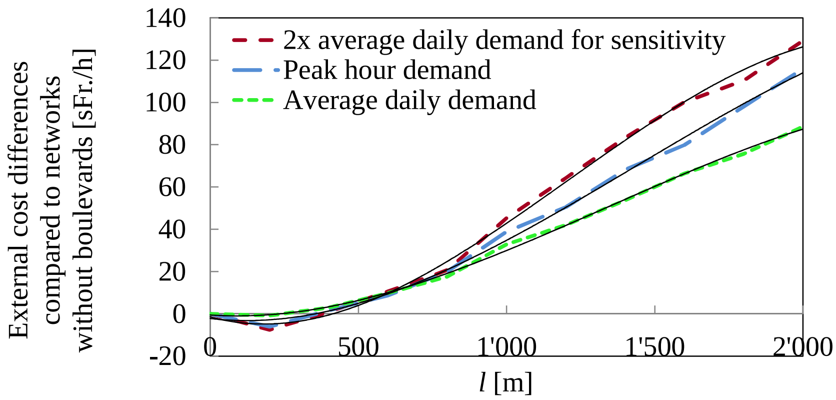


Table 5.3 compares different boulevard types, objective functions, and demand volumes (average, peak hour, 2· average for sensitivity), enabling future recommendations. Boulevards with signal lights at the major center road (Type 1) have the highest travel cost and accessibility elasticities. Boulevards with longer minor roads (Type 2) have the lowest travel cost and accessibility elasticities. Boulevards with conflict free intersections (Type 3) and boulevards with

Table 5.2: Marginal costs, application range, and elasticities for boulevards with signal lights (Type 1) of length l.

	Size of featureless plane [km^2]			
	2×2		3×3	
Marginal costs $\frac{\delta t}{\delta l}\left[\frac{sFr}{h \cdot m}\right]$ and application range [m], λ = 0.8	$\frac{\delta t}{\delta l}$ (lower – upper bound)	R^2	$\frac{\delta t}{\delta l}$ (lower – upper bound)	R^2
Average daily traffic volumes	-0.3970 (320–1'290)	0.9965	-1.067 (610–2'110)	0.9936
Peak hour traffic volumes	-0.5630 (370–1'370)	0.9958	-1.282 (970–2'270)	0.9766
2x daily traffic volumes (for sensitivity)	-0.7161 (440–1'280)	0.9933	-1.377 (1'010–2'240)	0.9006
Monetarized travel time elasticities $\epsilon^{s,T} = \frac{\delta t}{\delta l}\frac{\bar{l}}{\bar{t}}$ of	$\epsilon^{s,T}$		$\epsilon^{s,T}$	
average daily traffic volumes	1.285		1.312	
peak hour traffic volumes	1.292		1.719	
2x daily traffic volumes (for sensitivity)	1.371		1.864	

multi-level intersections (Type 4) have lower elasticities compared to Type 1; values also differ in the size of the network. High R^2 is calculated throughout the evaluations.

Table 5.3 additionally summarizes the external cost evaluations. Multilevel boulevards have the lowest external costs elasticities. The remaining boulevard types have higher cost elasticities, but without a clear ranking order. Detailed evaluation showed that Type 1 and Type 2 have generally low external cost elasticities but increasing values for increasing traffic flows. Overall, it is observed that some external cost results could be approximated with other functions than polynomial functions of degree 3.

5.5 Sensitivity Analyses and Evaluation

Multiple causes are identified for increasing generalized travel costs in boulevard design, despite the high boulevard capacity. Three situations possibly trigger an undesirable network state.

- Drivers reroute off the boulevard onto parallel roads as soon as the speed decreases compared to the parallel routes. Rerouting decreases the original functionality of the boule-

Table 5.3: Comparison of the elasticities ϵ^s for λ = 0.8 and confidence of determination R^2 of all boulevard types; with ϵ^s values for different demand volumes n.

	Size of featureless plane [km^2]			
	2×2		3×3	
Travel cost elasticities	$\min_n\{\epsilon_n^{s,T}\}, \max_n\{\epsilon_n^{s,T}\}$	$\min_n\{R_n^2\}$	$\min_n\{\epsilon_n^{s,T}\}, \max_n\{\epsilon_n^{s,T}\}$	$\min_n\{R_n^2\}$
Type 1: Signal	1.285, 1.371	0.9969	1.312, 1.864	0.9006
Type 2: Signal (pedestrians)	1.195, 1.256	0.9871	0.9425, 1.301	0.8442
Type 3: Red. of conflict points	1.133, 1.247	0.9948	1.302, 1.582	0.9945
Type 4: Multilevel	1.275, 1.328	0.9940	1.222, 1.354	0.9902
Accessibility elasticities	$\min_n\{\epsilon_n^{s,A}\}, \max_n\{\epsilon_n^{s,A}\}$	$\min_n\{R_n^2\}$	$\min_n\{\epsilon_n^{s,A}\}, \max_n\{\epsilon_n^{s,A}\}$	$\min_n\{R_n^2\}$
Type 1: Signal	1.314, 1.381	0.9930	1.360, 1.920	0.8970
Type 2: Signal (pedestrians)	1.197, 1.286	0.9863	0.8908, 1.292	0.8527
Type 3: Red. of conflict points	1.149, 1.246	0.9947	1.303, 1.611	0.9950
Type 4: Multilevel	1.281, 1.343	0.9937	1.271, 1.382	0.9898
External costs	$\min_n\{\epsilon_n^{s,E}\}, \max_n\{\epsilon_n^{s,E}\}$	$\min_n\{R_n^2\}$	$\min_n\{\epsilon_n^{s,E}\}, \max_n\{\epsilon_n^{s,E}\}$	$\min_n\{R_n^2\}$
Type 1: Signal	1.663, 1.901	0.9970	1.782, 2.917	0.9734
Type 2: Signal (pedestrians)	1.634, 1.900	0.9957	1.758, 2.509	0.9557
Type 3: Red. of conflict points	1.801, 1.827	0.9863	1.772, 2.212	0.9953
Type 4: Multilevel	1.494, 1.771	0.9973	1.252, 1.638	0.9787

vard and its center road. Rerouting off the boulevard increases average travel costs of all drivers up to 9% due to the unused capacity of the empty boulevard, and the congested boulevard crossings and parallel roads.

- Long boulevards separate urban space in two halves. This separation increases travel time considerably if the crossings have long waiting time or low capacity. Especially the reduced number of crossings at boulevards (50% in our example compared to a regular grid) increases the chances of bottlenecks. Moreover, the feeder roads to approach the boulevard crossings get congested as well. Especially the high intersection density of the feeder roads near the boulevard increase delays additionally. Cars might drive around the boulevard to avoid congestion, if capacity of the intersections and feeder roads is insufficient.

- Drivers crossing the boulevard increase the delay for cars driving on the boulevard, due to the adaptive green times of signals on the boulevards. Due to adaptive green times, crossing flows increase their green time and at the same time reduce green time of the flows on the boulevard. This effect increases overall travel time on the boulevard, and increase chances of rerouting onto parallel roads.

Multiple solutions tackle the issues above. The boulevard axis needs to retain high flows during both uncongested and congested network states. Signals have longer turn delays due to the cycle characteristics. Therefore, travel speed has to be higher on the center road with signal settings maintaining the desired high flows, compared to the parallel minor roads. Drivers might reroute onto parallel roads as soon as congestion is high enough on the boulevard, to reach an equilibrium state in their route choice. Therefore, capacity should be rather high on boulevards, to reduce delays and rerouting on parallel roads, shown in many boulevards worldwide (Jacobs et al., 2002). Similarly, free flow speeds on parallel roads might be reduced even more to prevent rerouting.

The functionality of a boulevard might be reduced through asymmetric travel demand, constructions, accidents, etc. Statistical analysis can estimate reliability and redundancy of the urban area considered (e.g. Bernard and Axhausen, 2007). The evaluation showed that mainly the capacity of the signals are the limiting factor in boulevard design. High capacity signalized intersections reduce the chance of a breakdown of the boulevard axis. The capacity should be large enough to supply a certain redundancy. Road capacity is not as limited as signal capacity. Multiple and diverging approaching lanes can increase signal capacity for high flows.

Green waves reduce travel time on boulevards. However, it is found that green waves are not as influential as other infrastructure changes in the case of boulevards. Green wave only reduces uniform delay, which is low at high flows and with adaptive green times. Therefore, total travel costs merely decrease when implementing green wave synchronisation.

The network sections adjacent to the boulevard are critical and relevant for the performance of the entire network. Flows crossing the boulevard reduce overall performance. If e.g. terrain barriers force traffic flows to cross the boulevard, the on- and off flows at the intermediate intersections increase overall travel time and therefore reduce the flows on the boulevard itself. And if the flows of the boulevards are delayed, its major functionality is diminished.

The share of long-distance through traffic is ignored, which would be relevant for inbound or outbound traffic. The boulevard is assessed from a city perspective, and did not consider external influences like long-distance travel flow. Additional lanes could eventually cater for higher through traffic demand.

The following cost-benefit estimate holds for an approximately linear correlation of the boulevard length within the application range (see above) and travel costs ($t_{absolut} \propto l_{Boulevard}$), and a low and conservative $\epsilon^{s,\, travel\, cost}$ value. The benefit to cost ratio $\frac{b}{c} > 1.0$ is reached after $\sim$8 years, when assuming the costs above, maintenance (VSS, 2008), lifespan, and discounted costs (VSS, 2006a), but ignoring land acquisition. For a time horizon of 100 years, the costs for land acquisition should not exceed 10'000 [sFr/$m_{\text{boulevard}}$] to reach a $\frac{b}{c} > 1.0$. This low value is mainly due to discounted benefits and ongoing maintenance costs.

Summing up, multiple issues occurred during modeling and evaluation, which are valuable for future design recommendations and the improvement of shape grammar rules. This additional information is added in the form of shape grammar rules including application specifications summarized with the other shape grammars in Chapter 8.

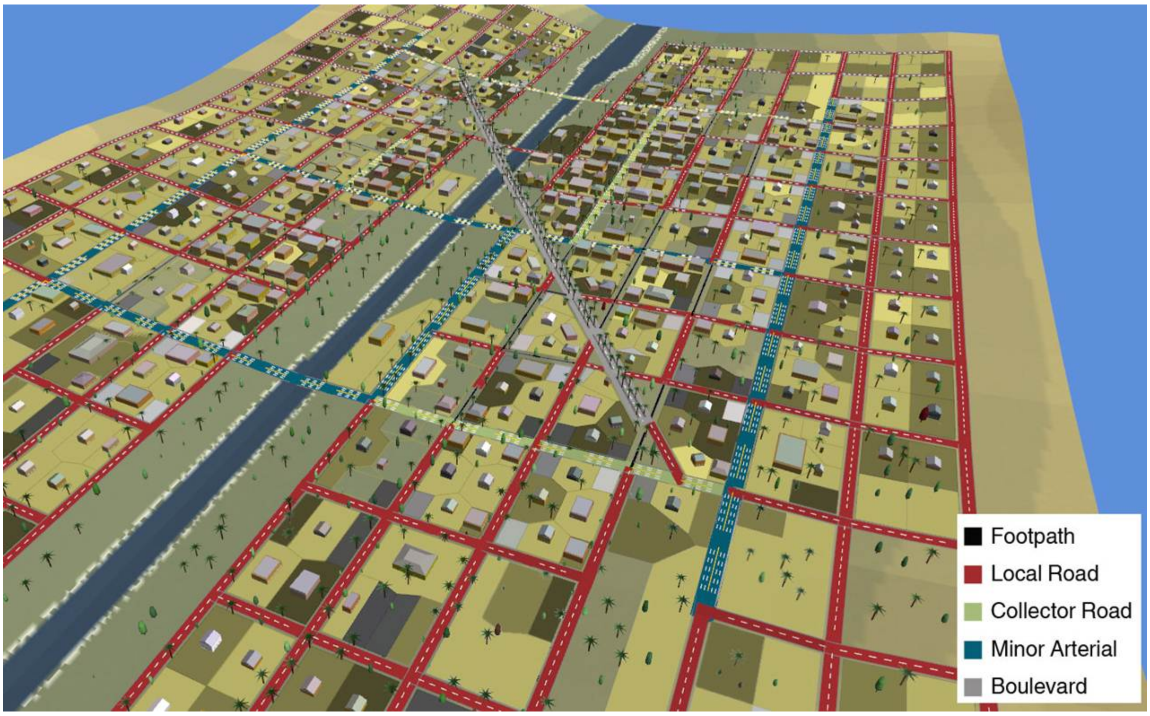
5.6 Implementation in an Urban Simulation Software

Figure 5.4 shows how a diagonal boulevard design can be implemented in an urban simulation software tool for visualization purposes. Figure 5.4 depicts a screenshot of a 3D rendering software, as described and applied in e.g. Vanegas et al. (2009a). Moreover, additional grammar rules can be applied, such as hierarchical road type distribution.

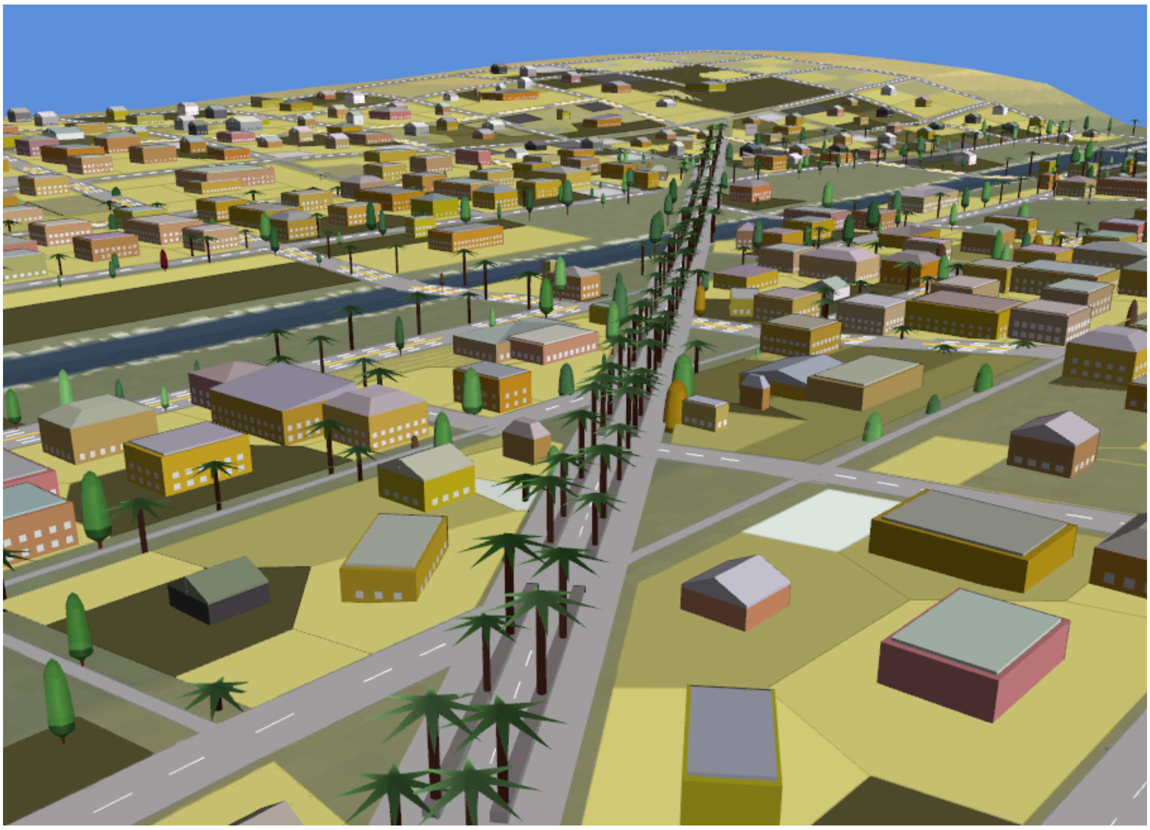
Figure 5.4 shows the potential of rule based modeling. Street types are allocated according to a hierarchical rules (Figure 5.4(a)). Figure 5.4(b) shows the potential of simulating and designing the buildings. Within the software, urban densities can be adapted and buildings are rebuild instantly according to the changes. Overall, the immediate changes in the simulated built environment allow a more participatory design approach, e.g. with different stakeholder involvement (e.g. Jacobi et al., 2009; ESRI, 2012; Synthicity, 2013).

Figure 5.4: Visualization of a diagonal urban boulevard in a 3D rendering

(a) with different street types.



(b) in a close up with different parcel and building types.



Source: Vitins et al. (2013) p.16.

Chapter 6

Network Topology Evaluations and Road Hierarchies

The previous chapter focussed on the evaluation of specific shape grammars and the corresponding requirements and constraints and addressed research question 1. It could be shown that specific shape grammar rules can be evaluated with study design 1. However, only a certain type of rules can be evaluated and even parameterized with study design 1 due to restrictions in the evaluation methodology; e.g. topological insights, which often require consideration of the entire network, are too complex when employing study design 1. Therefore, this chapter focuses on topology evaluation, and therefore also applies the IACGA algorithm described in Chapter 4.

After an introduction into the reliability analyses conducted (Section 6.2) and description of the technical assumptions (Section 6.3), this Chapter focuses on densities (Section 6.4) and network topology evaluations (Section 6.5). Road types and corresponding network designs are discussed in the following Section 6.6 and 6.7. Table 6.1 lists the grammar rules evaluated in this chapter. Sections 6.4 and 6.5 are based on research question 2 and study design 2. Section 6.6 and 6.7 cover research question 3 and study design 3.

6.1 Overview and Work Flow

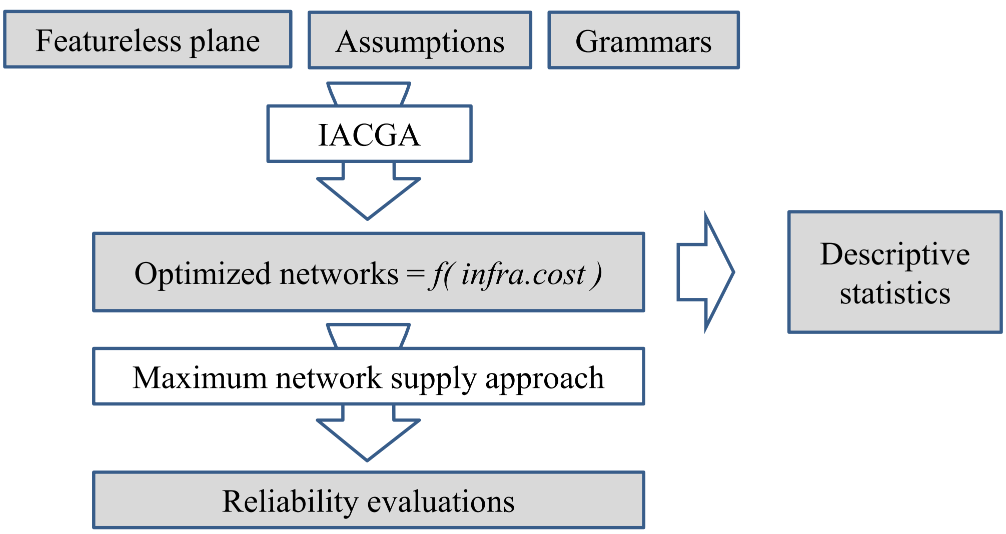
The overall methodologies to generate and evaluate grammars are described as study designs in Section 3.1. Three different study designs are proposed, referring to the research questions and differing therefore in their approaches. Figure 6.1 recapitulates the general work flow of study designs 2 and 3 (Sections 3.1.3 and 3.1.4) and summarizes the general applied methodology. The work flow starts with assumptions regarding the design of the networks (e.g. parcel shape or objective function), and eventually the exogenous determination of shape grammars, which

Table 6.1: Overview of the shape grammars evaluated in this chapter (highlighted).

Study design	Shape grammar	Section
1	Boulevard design	5
2	Network element densities	6.4
2	Network meshedness	6.5
2	Number of arms per intersection (cardinality)	6.5
3	Road type distribution	6.7
3	Intersection type choice (isolated intersections)	7.1
3	Intersection type choice (intersections in networks)	7.2, 7.3
0	General theoretical justification	2.4

might be applied during the optimization (upper part of Figure 6.1). Then, the design algorithm (IACGA) designs and optimizes the networks based on the assumptions and eventually the grammars. A specific optimized set of networks is obtained based on a specific road density, which is again determined beforehand. The optimized networks serve for detailed descriptive statistics and reliability evaluations (lower part of Figure 6.1), which obviously also refer to the independent parameters, such as road density.

Figure 6.1: General work flow to obtain network and urban design characteristics and grammars.



6.2 Reliability Evaluation

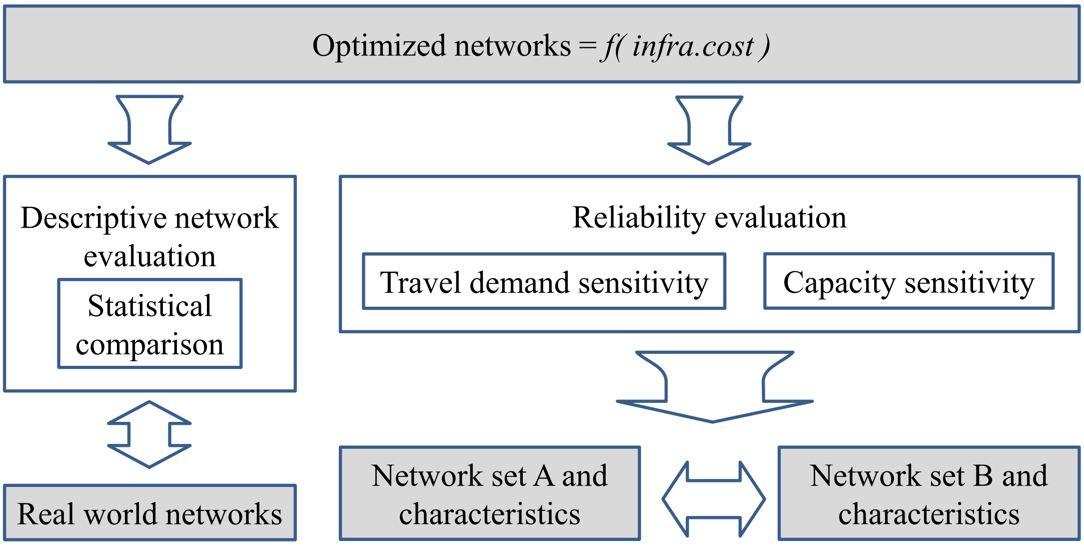
Transport networks are complex and interdependent, e.g. with information and energy supply networks. Reliability is steadily increasing in priority especially in transport systems, due to their limited capacity, in parallel with their crucial function as a backbone for our economic system. One important approach to increase reliability is the adjustment and transformation of infrastructure to absorb events on the demand and supply side in the short and long term. Hence, our transport system faces two major tasks: The system should be as efficient and productive as possible in the steady state, while at the same time reliable and robust to short and long term changes.

Currently, cost-benefit analyses (CBA) are applied widely in practice. CBA is designed to compare a few scenarios. However, focussing on only few scenarios is risky due to uncertainties and interdependencies with other unknown factors, which both could influence the results. The question arises if it is possible to design infrastructure as robust as possible to account for eventualities in the future. Examples are changes in urban densities, such as higher or lower growth rates, or changes in infrastructure funds and infrastructure expenditures. A major advantage of the modeling approach is the possibility to account for various changes, on both the supply and demand side. Models allow to design abstract scenarios about all kinds of potential future developments, without much additional costs. In addition, models allow different scenario evaluations based on different objective functions, as shown in Section 5.

Advances in technologies and changes in infrastructure expenditures can induce changes on either the demand or supply side. In the following, changes are modeled for infrastructure expenditures (supply side). Networks with different densities are used to account for variations on the supply side. Moreover, urban densities and therefore also travel demand can potentially change, and are difficult to predict for the future (demand side). The maximum supply approach is applied for this purpose, explained in Section 3.3, to account for variations on the demand side. It is believed that the proposed approaches contribute to identify the effect and leverage of each grammar.

Figure 6.2 depicts the general evaluation approach. The optimized networks are compared with real world networks and their characteristics (left side of Figure 6.2). The reliability evaluations take different road and intersection capacities into account. Additionally, the evaluations vary in travel demand levels (right side of Figure 6.2).

Figure 6.2: Overview of the different topology evaluation methods.



6.3 Technical Assumptions

In the remaining chapter, networks are designed, optimized and evaluated regarding their characteristics. The networks are designed on featureless planes to not bias the outcome, and are based on the methods of the IACGA (Section 4.5). The networks designed with the IACGA are based on the configuration below:

- According to Cardillo et al. (2006), the average length of links in a network is between 30[m] and 130[m] in dense urban areas, similar to Courtat et al. (2011). A default value of 100[m] is assumed for each block size. More specifically, the connectors to the block access the actual links in the middle (see also Figure 4.3) to model the connection of the block to the network. The connector therefore cut the link length down to 50[m]. However, independent of the access links, the overall link lengths are within a realistic range.

- Strano et al. (2012) evaluated historical network development and observed a transformation towards rectangular and quadratic block shapes (Figure 3.2(c)), similar to the findings of Courtat et al. (2011) for a specific city center. In their 20 case studies, Cardillo et al. (2006) found very few 5 or 6 arm intersections. Therefore, rectangular blocks are assumed in the following. The comparison patterns have the same dimensions.

- All the following optimized networks are designed with 104 demand generating nodes and 432 candidate links in a defined area of 1.0×1.0 [km^2].

- Travel demand is assigned to the network with the user equilibrium (Appendix A), based on the BPR function (U.S. Bureau of Public Roads, 1964), Dijkstra (Dijkstra, 1959), and Frank and Wolfe (Frank and Wolfe, 1956). Turn delays are calculated based on the formulae and parameters of the HCM (Transportation Research Board, 2010).

- Travel demand is calculated according to the micro census (Swiss Federal Statistical Office (BFS), 2010) assuming a four story perimeter block development with courtyards. Trip distribution is adjusted so that the flows are distributed inside the specified perimeter. Long-distance trips would require entry and exit points at the perimeter, which automatically would generate bottlenecks at high densities and high travel demand. Therefore, high shares (90%) of the trips are distributed on the generated networks (Swiss Federal Statistical Office (BFS), 2012), 10% of the trips leave and enter the study area by default on the designated four corners (Figure 4.3). Based on this setting, critical saturated flows can be achieved within the perimeter, and bottlenecks are avoided at the perimeter border and periphery. It is therefore possible to evaluate saturated networks and characteristics, and avoid specific bottlenecks. Through traffic infrastructure is separately evaluated in the case of boulevards (Section 5).

- The IACGA designs networks according to the assumptions above. The designed networks are based on a gridiron structure, even though the IACGA does not depend on gridirons (e.g. Section 4.5.4). However, in the remaining chapter, a gridiron is proposed, which is based on the assumptions above, similar to Figure 4.3, and similar to Levinson and Huang (2012), Yerra and Levinson (2005) or van Nes (2003). Figure 4.3 shows a full grid and potential variation of the grid structure, subject to the condition that all demand generating nodes (centroids) are connected to the same network.

6.4 Network Element Densities

Network element densities of various optimized networks are evaluated in this section designed with the IACGA and based on the assumptions above. The optimized networks vary in both road density d_r and intersection type choice. First, densities of intersections are evaluated, as well as graph faces d_F (regions bound by edges), and the circumferences of the faces l_F, based on road density d_r (Figure 6.3). A face F is defined as a region within a planar graph enclosed by edges without any crossing edge. Two adjacent faces are counted as two faces. The outer face does not count. The road density d_r is the network length divided by the area of the study side [km/km^2]. This method is similar to e.g. Cardillo et al. (2006) who also applied a density measure to evaluate real world network patterns, and overcomes the shortage of detailed but often unknown infrastructure costs. d_r varies between a lower bound of 9 [km/km^2] and an upper bound of 15 [km/km^2]. The lower bound results are due to the required connectivity, the upper bound due to the fact that denser gridiron networks have very similar topologies and travel times and are therefore ignored.

Multiple optimized networks are designed with the IACGA and the above assumptions for sensitivity. Various budget limits are used to account for different road densities d_r. However, due to the heuristic characteristics of the IACGA, final network densities can vary, and therefore, the optimized networks are not continuously spread over d_r.

Overall, Figure 6.3 shows linearity between road density (R^2 = 0.840) and intersection density (R^2 = 0.959) as well as d_F. Figure 6.3 depicts the average face circumference of the network, which is not decreasing linearly with increasing density. The face circumference l_F decreases in inverse proportion to the total road density d_r: $l_F = f\left(d_r^{-1}\right)$ (R^2 = 0.892).

Figure 6.3: Intersection and face densities.

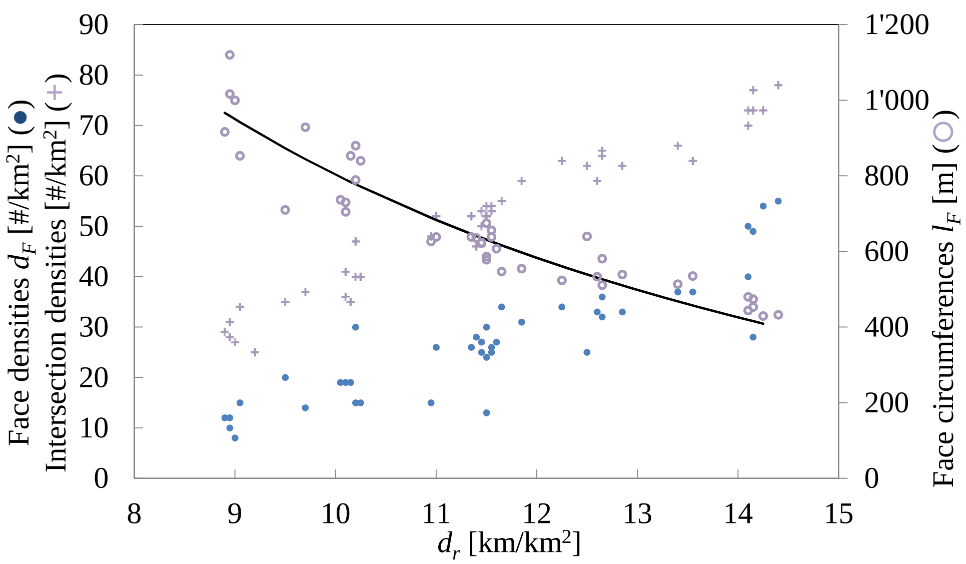
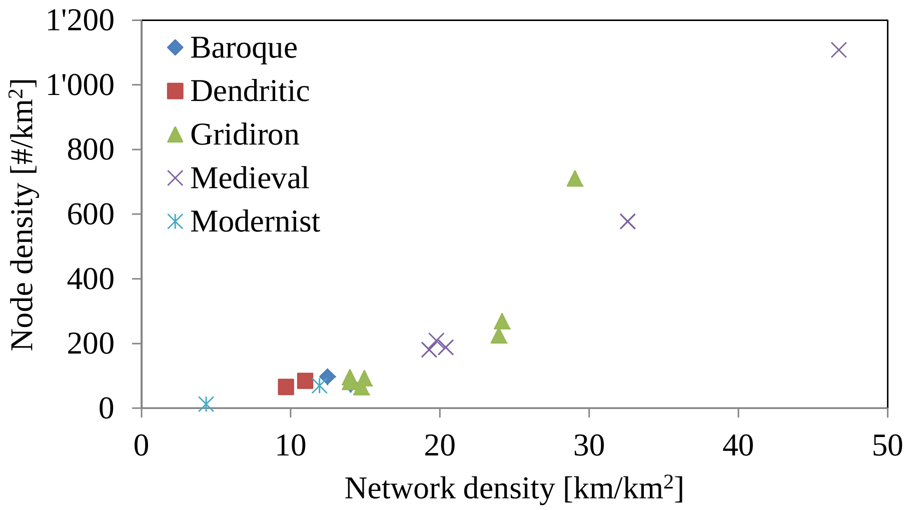


Figure 6.4 shows the intersection density distribution of real world networks in Cardillo et al. (2006), again as a function of network density. Figures 6.4 shows an almost linear relation between network and intersection density within their classification, with minor clusters (dendritic and gridiron networks), even though the specific networks are not from the same city or country. Some of the real-world networks (Figure 6.4) have proportionally higher intersection densities compared to the networks, which are artificially generated (Figure 6.3), probably due to more detailed real-world networks which include smaller local roads and driveways and dense medieval network patterns.

Cardillo et al. (2006) further elaborated on measures for road network topology. Table 6.2 compares descriptive statistics of Cardillo et al. (2006), who are referring to Jacobs (1993), with the result of the optimized networks. $p_{c=1}$ refers to deadend densities, $p_{c=3}$ and $p_{c=4}$ to 3 and 4 arm intersections, respectively (c for cardinality). The upper half of Table 6.2 summarizes data of Cardillo et al. (2006). The lower half of Table 6.2 shows the evaluation of the optimized networks.

The upper part of Table 6.2 shows low dead end densities for gridiron and medieval networks, compared to baroque, modernist and dendritic networks. However, baroque, modernist and

Figure 6.4: Intersection densities of real world networks based on networks of Jacobs (1993).



Source: Cardillo et al. (2006).

Table 6.2: Densities of intersections with different cardinalities including standard deviation σ.

Network Design	$p_{c=1}$	$\sigma_{c=1}$	$p_{c=3}$	$\sigma_{c=3}$	$p_{c=4}$	$\sigma_{c=4}$	Evaluated cities [#]
Summary of real-world network assessments based on Cardillo et al. (2006):							
Gridiron	0.158	0.0837	0.369	0.131	0.450	0.0741	6
Medieval	0.138	0.0702	0.645	0.0951	0.195	0.0568	6
Baroque	0.235	0.00817	0.399	0.193	0.321	0.179	2
Modernist	0.388	0.112	0.378	0.191	0.204	0.0771	2
Dendritic	0.431	0.0462	0.464	0.0149	0.0890	0.0294	2
Optimized networks:							Evaluated networks [#]
without turn delay	0.163	0.0718	0.625	0.0877	0.211	0.0828	16
with signals	0.168	0.039	0.641	0.119	0.191	0.132	10
right-of-way	0.176	0.0916	0.562	0.132	0.262	0.169	15
with roundabouts	0.168	0.0506	0.612	0.104	0.220	0.0723	17

dendritic network evaluations have low sample sizes (number of networks evaluated) but still cover a 1×1 [mile^2] area. The opposite is valid for $p_{c=3}$ except medieval networks, which have generally high $p_{c=3}$ values. In the lower part of Table 6.2, the $p_{c=1}$, $p_{c=3}$ and $p_{c=4}$ values are similar regardless of the implemented intersection types for optimized networks. There are two potential reasons for this outcome: Either the IACGA designs networks resulting in this specific $p_{c=1}/p_{c=3}/p_{c=4}$ ratio, or intersection types choice has a minor effect on the number of arms. The following sections provide further insight on this. Compared to the data of Cardillo et al. (2006), the distribution of the optimized networks resembles the distribution of the real-world medieval networks most regarding the $p_{c=1}$, $p_{c=3}$ and $p_{c=4}$ values.

6.5 Network Topology and Meshedness Coefficient M

Network topology is especially relevant for reliability, robustness and resilience issues (e.g. Erath, 2011; Helbing, 2013). Regarding these aspects, redundancy is an important factor. Redundancy can reduce congestion, lower travel times and improve reliability in case of network failures. Faces and blocks are elements of redundant networks, in contrast with tree networks. In tree networks, a missing network link causes two subtrees and therefore a separation of the originally covered network area in two separated subareas.

Multiple measures exist for topology evaluation, which differs from network element and density measures (e.g. Levinson and Huang, 2012). The meshedness coefficient M accounts for redundancy and is evaluated in this section. The coefficient M (also in Buhl et al., 2004; Courtat et al., 2011) is a sensitive graph topology measure which is defined as $M = F/F_{max}$, where F is the number of faces of a network graph, and F_{max} the maximum possible number of faces in a maximally connected planar graph ($F_{max} = 2N - 5$), proportional to the number of nodes N (see Cardillo et al. (2006) p.5 or Equation (6.1)). Compared to network element densities (nodes, links), and node degree, M focuses on the topology of networks by accounting for the face densities.

$$M = \frac{F}{2N - 5} \tag{6.1}$$

6.5.1 Descriptive Statistics for Meshedness M

The upper half of Table 6.3 shows values of M for multiple real world network patterns (Cardillo et al., 2006) (n = number of evaluated networks). M differs considerably between the different patterns. The networks of New York, Savannah, and San Francisco for example have values of $M >$ 0.3, while Irvine and Walnut Creek have $M <$ 0.1 (Table 6.3). The lower half of Table 6.3 shows values of M for optimized networks as above. These networks were designed with different urban densities and therefore infrastructure costs, and optimized for low generalized user costs. Despite different intersection types, high values of M are achieved through the optimization process, including low standard deviation σ. There is evidence that networks with high M values correlate with low user costs. A graph based efficiency analysis showed similar results for the real-world networks (Cardillo et al., 2006).

Four rigid and simplistic network patterns are proposed based on an oblong or square block shape for future comparison with the optimized networks. Figure 6.5 visualizes the four distinct patterns, of which three patterns serve as reference networks below. The distinct patterns differ in the number of arms at intersections (Figures 6.5(a)/6.5(b)/6.5(c) vs. 6.5(d)), road densities (Figure 6.5(a) vs. 6.5(b) vs. 6.5(c)), and different intersection densities (all patterns). The offset grid is similar to the H-alley and T-alley layout in the American Planning Association (2006).

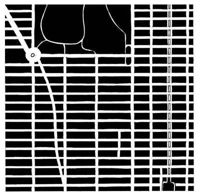
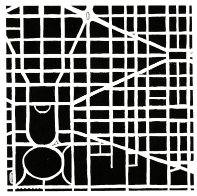
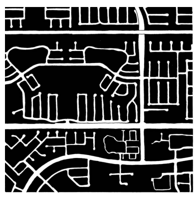
Figure 6.6 shows the distribution of the high meshedness values M of the optimized networks as a function of the road density d_r. The reference networks refer to the networks described in Figure 6.5. There is a minor correlation between network density and M. Again, due to the heuristic foundation of the IACGA, final network densities can vary, and therefore, the optimized networks are not continuously spread over d_r.

6.5.2 Urban Density Sensitivity and Reliability

Two approaches are proposed for sensitivity testing of the experimental network designs and results. In a first approach, travel demand is estimated according to specific spatial densities, and travel costs are determined according to the travel demand. In a second approach, the supply side is evaluated by maximizing urban densities, for reliability evaluation, as already explained in Section 3.3. Results of the first approach are discussed in the following, whereas results of the second approach are discussed in Section 6.5.3.

The designed networks based on the IACGA are evaluated according to different urban density levels, which correspond to different demand levels. An increasing urban density is assumed, as this is the case in many cities worldwide. Therefore, total travel time differences Δt^{tot}, the dependent variable, are estimated in the case of increasing population and job densities d_{pop} and d_{jobs}. d_{pop} and d_{jobs} are increased by a factor of 2.0 to account for more saturated road networks. Factor 2.0 is assumed as a reasonable growth rate. However, growth of urban densities can be even higher, depending on the economic growth and development (e.g. Schaefer et al., 2009). The growth leads to higher travel times, and a certain travel time difference $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$. The advantage of $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$ calculations is the reduced influence of overall road density d_r, compared to e.g. a more direct evaluation of the designed networks. The disadvantage is the growth factor (in this case 2.0), which is obviously unknown to planners.

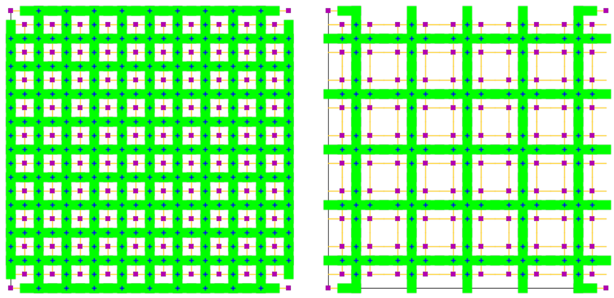
Table 6.3: Characteristics of example networks (1×1 [mile^2]) as well of the optimized networks.

Design	Examples	M	σ	n	Example network
Real world networks:					
Gridiron	Barcelona, Los Angeles, New York, Richmond, Savannah, San Francisco	0.291	0.0435	6	 Manhattan
Medieval	Ahmedabad, Cairo, Bologna, London, Venice, Vienna	0.229	0.0374	6	 Venice
Baroque	New Delhi, Washington	0.224	0.0695	2	 Washington
Modernist	Brasilia, Irvine (1)	0.116	0.0310	2	 Brasilia
Dendritic	Irvine (2), Walnut Creek	0.049	0.0350	2	 Irvine
Sources: Cardillo et al. (2006), Jacobs (1993).					
Optimized networks:		M	σ	n	
without turn delays		0.259	0.0450	15	
with signals		0.265	0.0411	11	
right-of-way		0.266	0.0728	15	
with roundabouts		0.264	0.0258	16	

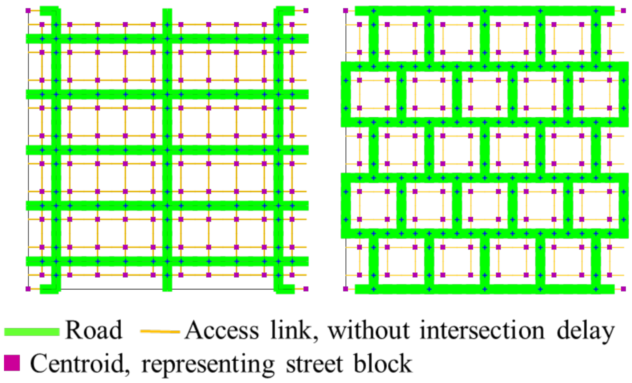
In addition to the changes in d_{jobs} and d_{pop}, three scenarios are developed to account for changing capacity on the supply side. Road and intersection capacities are increased to evaluate

Figure 6.5: Four distinct road network patterns serving as reference networks, and their densities (1×1[km^2] in size and 104 demand generating nodes).

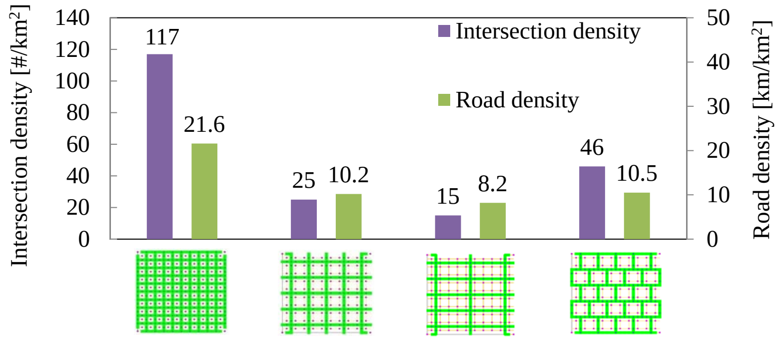
(a) Dense gridiron, block size 100×100[m^2]. (b) Reduced gridiron, block size 200×200[m^2].



(c) Oblong gridiron, block size 300×200[m^2]. (d) Horizontal offset grid, block size 200×200[m^2].



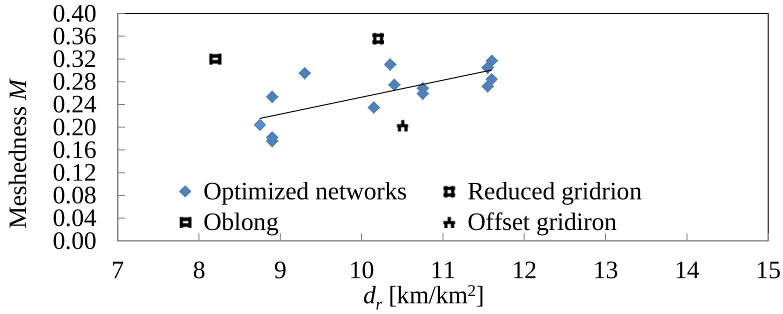
(e) Road and intersection densities of each network pattern of Figure 6.5(a) – 6.5(d).



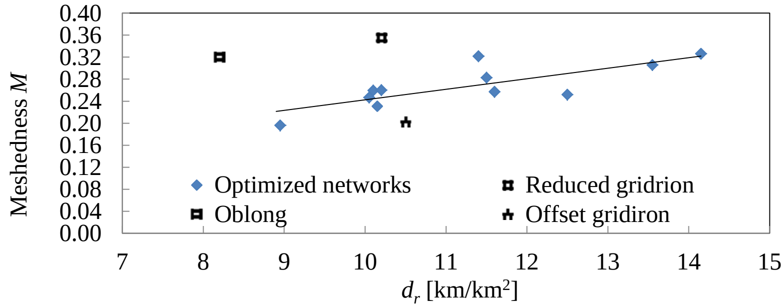
their effect on network design. The underlying road and intersection capacity assumptions are shown in Table 6.4. Capacities for scenario 0 are determine according to the norms (see also Table 6.12). Scenario 0 models low road capacities, especially on collector and local roads due to on-street parking and traffic calming. Scenario 1 and 2 have larger road and intersection capacities, respectively, e.g. due to additional lanes. Intersection capacities are increased by adding an additional approaching lane at signals and right-of-way intersections and an additional circulating lane at roundabouts. The underlying turn delay calculations are still based on

Figure 6.6: Meshedness coefficients M by network type versus road density d_r.

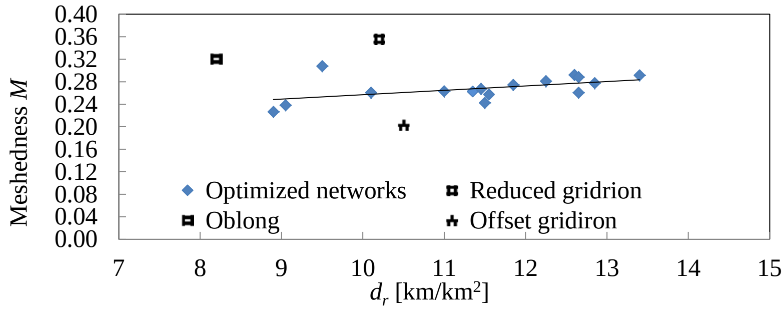
(a) Networks without turn delays.



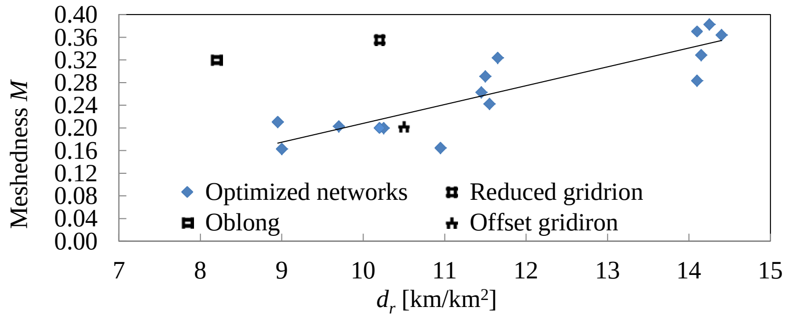
(b) Networks with signalized intersections.



(c) Networks with roundabouts.



(d) Networks with right-of-way controlled intersections.



the HCM (Transportation Research Board, 2010). The networks are designed with the IACGA, but only in Scenario 0. For scenarios 1 and 2 the networks are adapted only with the designated capacities.

Eight independent variables are statistically evaluated for significant influence on the dependent

Table 6.4: Road and intersection capacities of the different evaluated scenarios.

	unit []	Scenarios 0	1	2
Minor arterial	Capacity [veh./h]	1’200	**2’400**	1’200
Collector		800	**1’600**	800
Local road		500	**1’000**	500
Signal control	Approaching lanes [#]	2	2	**3**
R. of w. control		2	2	**3**
Roundabout		2	2	**2+2**$^{(*)}$

$^{(*)}$: 2 incoming lanes and 2 circulating lanes

variable $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$, namely d_r, $p_{c=1}$, $p_{c=3}$, $p_{c=4}$, M, d_F, l_F, d_i (intersection density) and multiple intersection types. Therefore, a stepwise linear regression is proposed. Table 6.5 shows the results, including the variation inflation factor (VIF) accounting for multicollinearity. 38 optimized networks are evaluated in total for each scenario (432 candidate links and 104 demand generating nodes).

Table 6.5: Regression results of optimized networks with $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$ as dependent variable.

Scenario (Table 6.4)	Parameter	Significance	Standardized coefficient (β)	Variance inflation factor (VIF)
0	Meshedness M	0.018	-0.301	1.002
	Dummy right-of-way	0.008	-0.371	1.193
	Dummy signal	0.006	0.392	1.193
Significance (ANOVA): 0.000				
Adj. R^2: 0.439				
1	Meshedness M	0.008	-0.308	1.002
	Dummy right-of-way	0.026	-0.276	1.193
	Dummy signal	0.000	0.557	1.193
Significance (ANOVA): 0.000				
Adj. R^2: 0.551				
2	Network density d_r	0.001	-0.458	1.357
	Meshedness M	0.042	-0.251	1.310
	Dummy signal	0.000	0.418	1.060
Significance (ANOVA): 0.000				
Adj. R^2: 0.588				

The stepwise regression excludes $p_{c=3}$, and $p_{c=4}$, mainly due to correlation with network density and due to the optimized design of the networks. Additionally, face density d_F is excluded due to strong correlation with M, including the corresponding standard deviation. M has a negative and significant influence on $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$, independent of the scenarios. Also signal have a significant but positive influence on $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$. Right-of-way intersections have a negative influence, but only at scenario 0 and 1. These findings are in line with the evaluation of the isolated intersections (see later in Figure 7.1). Additionally, in scenario 2 it is expected that roundabouts lead to about equal delays compared to right-of-way intersections. Moreover, d_r influences $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$ negatively, but only in scenario 2. However, there is a minor multicollinearity expected between d_r and M, disabling evidence on the amount of influence. Standardized β coefficients for signals is > 0 because the right of way intersections and roundabouts are able to cope with the traffic flows more efficiently when doubling the population and job densities for $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$.

There is a lack of evidence of the potential influence of $p_{c=3}$ and $p_{c=4}$ on network design. In a principal component analysis, only one component has an initial eigenvalue > 1.0. Therefore, a significant relationship is not found between $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$ and $p_{c=3}$ and $p_{c=4}$. Low influence of $p_{c=3}$ and $p_{c=4}$ on efficiency might be expected when considering the statistics of the real world networks of Cardillo et al. (2006), summarized in Table 6.2. Cardillo et al. (2006) showed different $p_{c=3}$ and $p_{c=4}$ values for network of medieval and gridiron type, even though both types have a high efficiency (Table 6.2, and Cardillo et al. (2006) Figure 3). Ewing and Cervero (2010) found a negative correlation of 4 arm intersection density and VMT. However, also road density correlates to the same extent, and potentially indicates multicollinearity. It therefore remains uncertain if 3 or 4 arm intersections are more efficient.

It seems that in the evaluations of $\Delta t^{tot}_{2\cdot(d_{pop}+d_{jobs})}$ the networks are not saturated which is probably due to the rather low travel demand. A reason is the positive influence of the signals in Table 6.5, which contrasts the results of the isolated intersection delays and the low turn delays of signals at high flows (see later in Figure 7.1). The following Section 6.5.3 therefore deals with higher flows, and corresponding effects on the networks and user costs.

6.5.3 Maximum Network Supply Approach

At an initial planning stage, planners might not be knowledgeable about future densities. Authorities aim at maximum level of service for economic reasons. Therefore, it is interesting to analyze how much urban density one network could supply without unacceptable travel time increase ($\Delta t^{x\%}$). The main idea was already discussed in Section 3.3. An upper bound is assumed for a travel time change (+20% in the following $\rightarrow$ $\Delta t^{20\%}$), which is achieved by gradually increasing densities of population and jobs (d_{pop} and d_{jobs}). The aim is to determine how high we can proportionally increase d_{pop} and d_{jobs} within a given area, but without unacceptable increase in travel time $\left(\Delta d_{pop,jobs}\left(\Delta t^{x\%}\right)\right)$. It is expected that certain dependencies exist on different network topologies, and eventually intersection types. Table 6.6 shows the regression results for $\Delta d_{pop,jobs}\left(\Delta t^{20\%}\right)$. 38 optimized networks are evaluated for each scenario (432 candidate links and 104 demand generating nodes). Again, a stepwise linear regression is proposed with eight independent variables, namely d_r, $p_{c=1}$, $p_{c=3}$, $p_{c=4}$, M, d_F, l_F, d_i (intersection density) and multiple intersection types. The demand model is kept simple, and no feed back on travel demand is implemented due to the reasons explained in Section 3.4.2.

Table 6.6: Regression result of optimized networks for $\Delta d_{pop,jobs}\left(\Delta t^{20\%}\right)$ as a dependent variable.

Scenario (Table 6.4)	Parameter	Significance	Standardized coefficient (β)	Variance inflation factor (VIF)
0	Meshedness M	0.009	0.286	1.310
	Network density d_r	0.000	0.409	1.357
	Dummy signal	0.000	0.665	1.060
Significance: 0.000				
Adj. R^2: 0.688				
1	Meshedness M	0.011	0.273	1.310
	Network density d_r	0.000	0.434	1.362
	Dummy right-of-way	0.000	0.493	1.197
	Dummy signal	0.000	0.707	1.266
Significance: 0.000				
Adj. R^2: 0.705				
2	Meshedness M	0.000	0.621	1.002
	Dummy right-of-way	0.011	-0.307	1.193
	Dummy signal	0.043	0.239	1.193
Significance: 0.000				
Adj. R^2: 0.586				

As shown in Table 6.6, d_r and M contribute significantly to high supply in scenario 0 and 1. Again, low multicollinearity is expected between d_r and M. Additionally, the implementation of signals is significant, which also fits with Figure 7.1 later on. Right-of-way intersections only have a positive significant influence in scenario 1, but less so than signals. The positive influence of right-of-way intersections suggests that roundabouts might have higher delays with increasing densities. In scenario 2, right-of-way intersections have a negative influence, indicating that capacities of right-of-way intersections cannot increase to the same extent than at roundabouts and signals. Right-of-way intersections are therefore less efficient with additional lanes and increasing flows, which also matches with further results on intersection type choice.

In Table 6.6, Scenario 2 shows significant values for M, signal and right-of-way. Additionally, d_r is significant even after the stepwise linear regression. However, the standardized β value of d_r is negative in combination with M, which seems unreasonable. M and d_r are slightly correlating, as shown in scenario 0 and 1. Therefore, d_r is excluded in Table 6.6 in scenario 2 due to low standardized β and lower significance compared to M.

6.6 Road Types, Costs and Hierarchies

Road type choice depends on multiple aspects, such as road relevance and investment decisions. The following sections describe road types, including a short review of current norms, followed by the methodology on road type choice and the description of the results (Section 6.7). The following sections refer to research question 3 and study design 3.

Roads differ in their characteristics, such as designated speed, capacity, and number of lanes. Road types standardize road design through consistent characteristics, and therefore support users and their cognition, improve safety, and facilitate funding by authorities for construction and maintenance. Moreover, road types have distinct functions, e.g. collector roads, and might be embedded into different environments, such as urban or rural networks.

A hierarchical order of road types within road networks enhances planning and the design. Homburger and Kell (1981) classified road types according to their access and movement function, similar to AASHTO (2004) p.7. Table 6.7 describes the classification and hierarchy applied in the Swiss norm. In the US, the official classification separates between urban and rural

Table 6.7: Road types in Switzerland.

Link type	Level	Function	German translation
Highway	international to regional	major carrier for through traffic	Hochleistungsstrasse (HLS)
Expressway	national to intermunicipal	major carrier for connection purposes	Hauptverkehrsstrasse (HVS)
Arterial	regional to intermunicipal	minor carrier for connection purposes	Verbindungsstrasse (VS)
Collector	municipal	collecting traffic	Sammelstrasse (SS)
Local	district	access	Erschliessungsstrasse (ES)

Source: VSS (1994b).

roads and therefore differs from the Table 6.7. In the US, the class of arterial roads includes multiple different subclasses, which range from freeways (principle arterial street) to intracommunity streets (minor arterial street). Details can be found in AASHTO (2004) and ITE (2008). Table 6.8 describes the classification in the USA.

Table 6.8: Road types in the USA.

Class		Subclasses	
A	Principle arterial street	1	Freeway
		2	Interstate (only in urban classifications)
		3	Others
B	Minor arterial street		–
C	Collector street	1	Major (only in rural classifications)
		2	Minor (only in rural classifications)
D	Local street		–

Source: after AASHTO (2004).

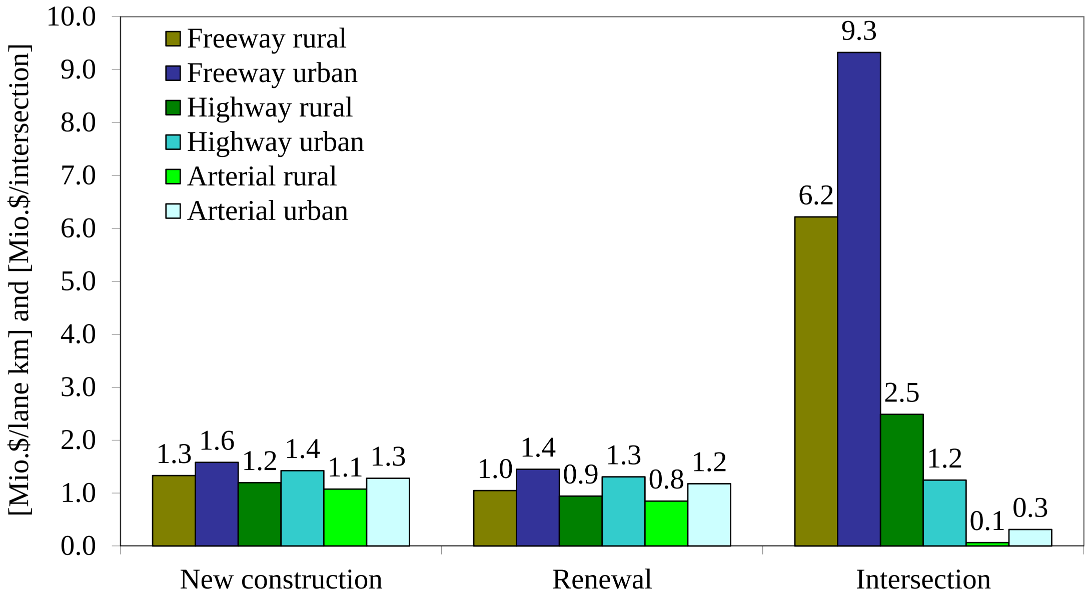
Table 6.9 compares the transport related attributes of speed and lanes for each road type. The transport related attributes are derived from Spacek (2009) for Switzerland and FGSV (1996) for Germany. An open problem is the distinction between average speed and speed limits; handbooks often refer to the designated speed. In the US speed limits vary between States, making countrywide conclusions difficult. Another issue is the stated capacities of roads. FGSV (1996) and FGSV (2008a) list capacities for various road times starting from 3'000 [vehicle/day] for a local road until freeways for up to 100'000 [vehicle/day]. However, capacities depend on many different design and driver attributes. Therefore, Table 6.9 excludes capacity numbers.

Average infrastructure costs for the different road types are difficult to obtain from the literature. One reason might be the complex expenditures at construction sites, e.g. for land use, terrain corrections, etc. (e.g. Flyvbjerg et al., 2002). Another reason might be the missing database required for comparison, and the very variable costs between construction sites. Figure 6.7 is based on one of the few references found for the US, and shows average infrastructure costs for urban and rural areas of various street and intersection types. As expected, considerable differences occur between links in urban and rural areas. The costs of the major arterial roads are considerably higher compared to the next lower level, the collector roads, because major arterials historically function as major carriers, compared to the collector roads which only carry local traffic. For local streets, no reasonable values were found so far. The costs of intersections are higher between the different levels of hierarchies, compared to the cost differences of road types. This is due to over-and underpasses and larger radii for curves at freeway and highway nodes. Costs tend to increase over time because the cheaper projects tend to be built first (Gaetzi, 2004).

Table 6.9: Definition of road types and differences between Switzerland, Germany and the U.S..

Original name	Country	Max. speed [km/h]	Lanes [#]
Erschliessung	Switzerland	30	2
Local road	USA	~25-50	2
Wohnstrasse	Germany	30	2
Sammelstrasse	Switzerland	40	2
Collector road	USA	~25-50	2
Sammelstrasse	Germany	30/50	2
Verbindung	Switzerland	50	2
-	USA	-	-
Verbindungsstrasse	Germany	50	2
HVS innerorts	Switzerland	50	2/4
Urban arterial	USA	~50	2/4
Einfahrtsstrasse	Germany	50	2/4
HVS ausserorts	Switzerland	70	2/4
Rural arterial	USA	~90-100	2/4
Bundesstrasse	Germany	100	2(4)
HLS	Switzerland	120	4-8
Freeway	USA	~110	4+
Autobahn	Germany	130+	4-8

Figure 6.7: Detailed infrastructure costs in the USA (2000 US $).



Source: Jack Faucet Associates (1991), Litman (2011) and Alam et al. (2005).

6.7 Hierarchical Road Type Distribution in Road Networks

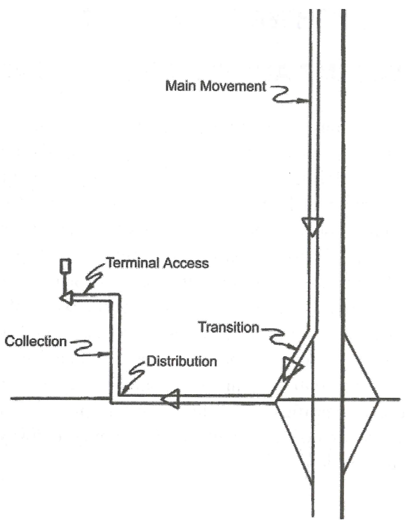
6.7.1 Background

Road type distribution describes the distribution of road types within a given network graph of nodes and edges, without any topological changes. Different and predefined road types are assigned to the network graph according to predefined rules, e.g. rules can describe if an arterial road can be crossed by a local road. Or, rules assign narrow roads with sideways, speed bumps and parking areas for residential access, as opposed to wider roads assigned for interurban connections with less parking, less and smoother curves and higher designated speed limits.

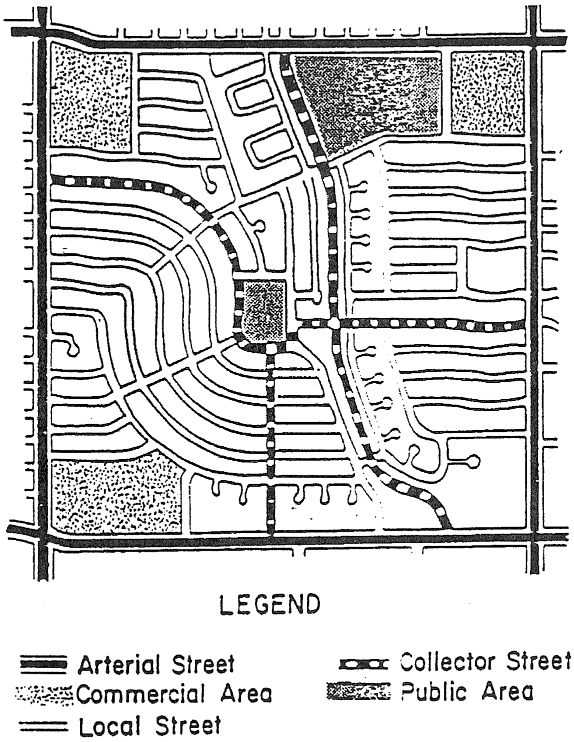
A variety of rules for road type distribution already exists in the literature. LeCorbusier (1955) explicitly proposed a hierarchical design. Alexander et al. (1977) proposed a hierarchical road layout to avoid through traffic (rule 49). Marshall (2005) proposed hierarchical rules for network design and includes intersection types. Yerra and Levinson (2005) evaluated the formation of a self-organizing hierarchical road network. Multiple norms of different countries propose road type distributions. As an example, Figure 6.8 depicts a road type distribution of AASHTO (2004).

Figure 6.8: Examples of hierarchical road type distribution.

(a) AASHTO (2004) p.2.

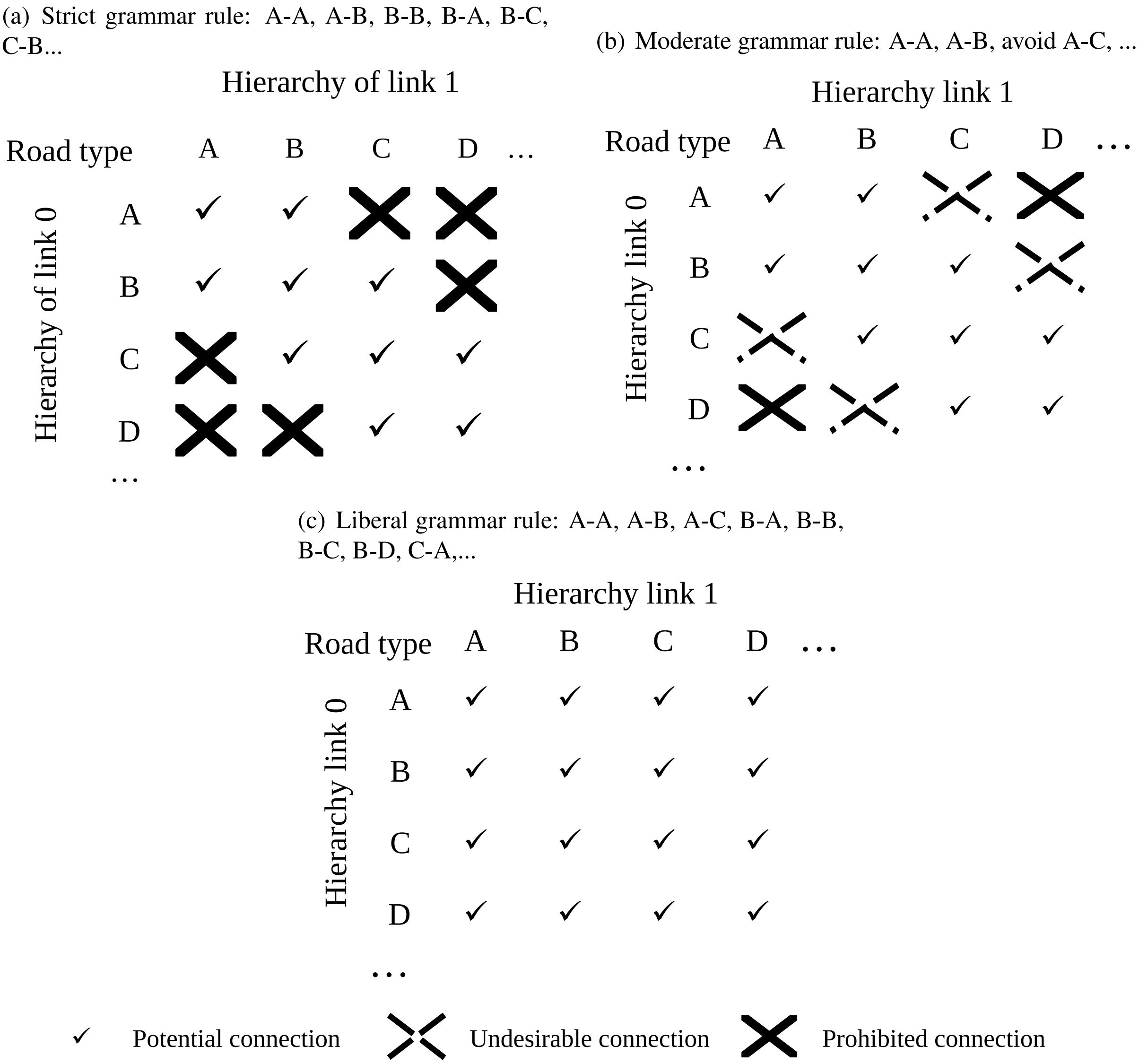


(b) AASHTO (2004) p.6.



Regarding a hierarchical road design, both restricted and relaxed recommendations can be found in the guidelines. A strictly hierarchical layout leads to a network with joined links which only differs in one level of hierarchy level at most. If the recommendations are more liberal, joined links can differ in more than one level of hierarchy. An overview is given in Figure 6.9 about different hierarchical road type designs.

Figure 6.9: Abstract hierarchical road type distribution.



6.7.2 Guidelines

Multiple guidelines provide shape grammar rules for hierarchical road type distribution. A selection is provided in Table 6.10. The guidelines listed in Table 6.10 differ in their recommendations for a hierarchical structure within network design. Based on Figure 6.9, both restricted and liberal recommendations are found in the guidelines. More specifically, the guideline of Switzerland recommends a strong hierarchical design, but does not list any detail about the pattern in practice. The opposite is found in the handbook "Transport in the Urban Environment" of England (IHT, 1997) which gives advice on street appearance, but no advice on hierarchical structures in network layouts and transitions.

Table 6.10: Overview of the norms and corresponding hierarchies, referring to Figure 6.9.

Country	Classification	Number of hierarchies	Description and special focus	Reference
Switzerland	strict	5	Transport and settlement divided type approach	VSS (1994b)
USA	moderate	5-6	Land-use related, extra transitions	ITE (2008), AASHTO (2004)
Germany	liberal	5	Rural and urban subdivision, functional levels	FGSV (2008b)
England	–	–	–	IHT (1997)

6.7.3 Methodology

Multiple guidelines on hierarchical road design were discussed in the previous sections. In the following, a methodology is proposed to model specific hierarchical rules to evaluate their effects. The rules are defined consequently as well as their practical application in a given road network.

6.7.3.1 Proposed Road Type Hierarchies

The share of the road types, e.g. the share of collector road length, needs to be defined in advance. Table 6.11 describes the existing road type share in the USA, which is used as an assumption for further evaluations. Table 6.12 refers to the implemented link types. They are defined according to the characteristics of the different road types. One lane is implemented in the base networks and 3 different types. Local roads have rather low capacities, which conforms with the German norm. However, capacities also change for reliability analysis (Section 6.5.2).

Figure 6.10 proposes four shape grammar rules r_0 – r_3 which can be separated into two classes. The first class defines if the network is continuous with only one subnetwork of the highest road hierarchy, and subsequently one network of the other hierarchies, including the upper hierarchies in each case. Grammar rules r_0 and r_1 are continuous, r_2 and r_3 are discontinuous.

Table 6.11: Share of road types in the USA.

	Share of road type [%]	
	urban	rural
Principal arterial system	5 - 10	2 - 4
Minor arterial system	10 - 15	4 - 8
Collector road system	5 - 10	20 - 25
Local road system	65 - 80	65 - 75

Source: AASHTO (2004) p.10,12.

Table 6.12: Implemented road types.

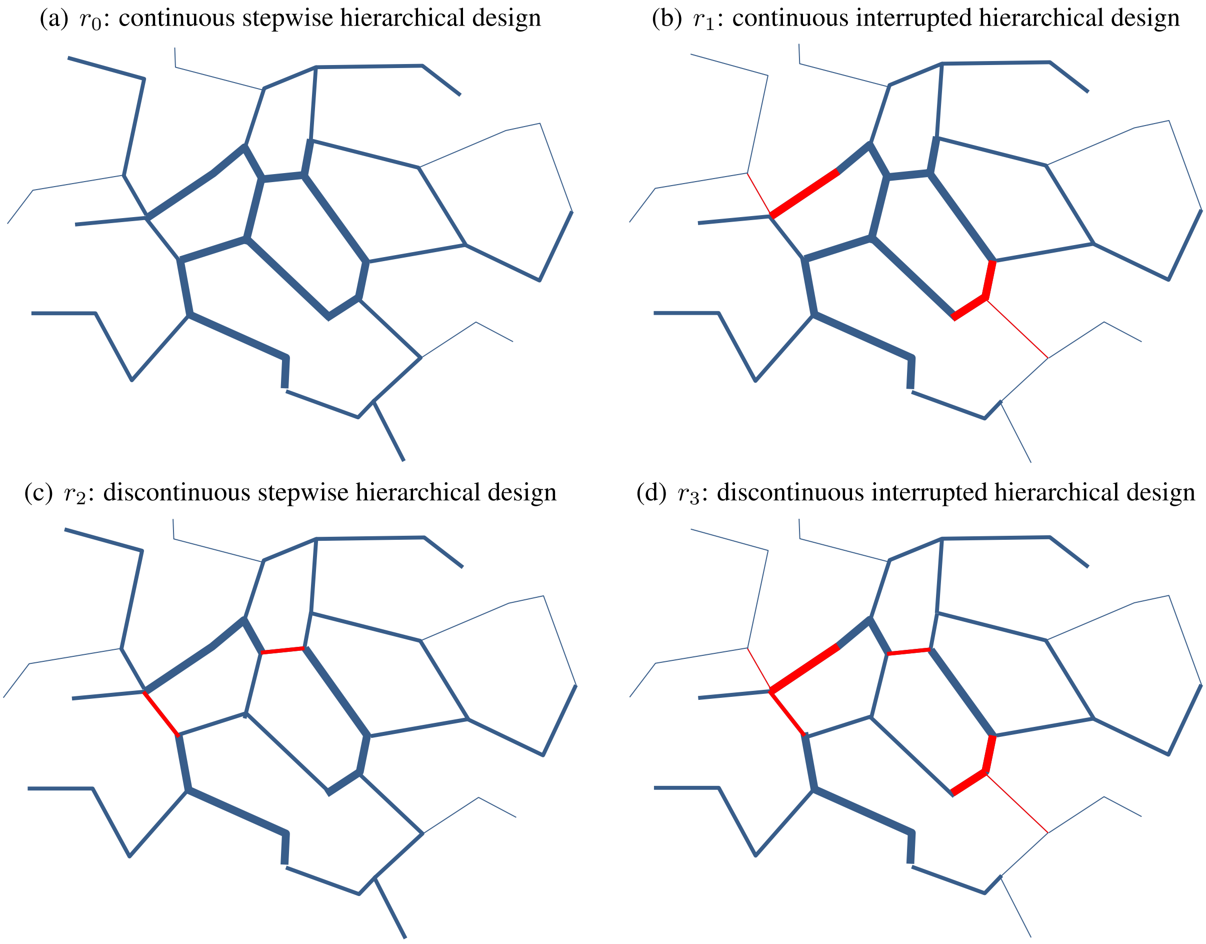
Road type	Hierarchy	Max. capacity [veh./h/lane]	Free speed [km/h]
Minor arterial system	A	1.200	68
Collector road system	B	800	46
Local road system	C	500	28

The second class defines if the types of two adjacent roads differ in at most one hierarchy, referred to as stepwise hierarchical distribution in the following. r_0 and r_2 fulfill the definition of a stepwise hierarchical distribution, r_1 and r_3 have an interrupted hierarchical distribution. Table 6.13 defines the same rules more formally.

6.7.3.2 Technical Implementation

The rules are applied in different road networks designed with the network design algorithm (Section 4.5). The distribution of discrete road types within a given network graph is a discrete problem. The problem formulation becomes a mixed integer problem in combination with an assignment problem (Section A.2). Mixed integer problem are often $\mathcal{NP}$-hard, which means that the problem is only solvable in exponential time (Garey and Johnson, 1979; Zimmermann, 2008). Similar problems occurred in other research related to road type distribution. E.g. Yerra and Levinson (2005) distributed road types iteratively. Due to the complexity, a straightforward greedy algorithm is proposed to solve the distribution problem. Due to the complexity, the algorithm is a heuristic and therefore does not guarantee to find the global optimum.

Figure 6.10: Proposed hierarchical shape grammar rules.



Red links indicate the disruption and discontinuity, respectively.

Given the convex search space of a standard user equilibrium with predetermined road types, the solution is unique for the standard user equilibrium and can be determined with one of the well-known optimization techniques (e.g. Sheffi, 1985). An example convex search space is provided in Figure 6.11(a).

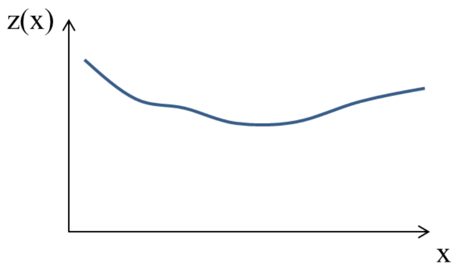
Algorithm 2 describes the greedy algorithm formally. It starts with a regular demand assignment, and changes road types subsequently. For this, the marginal user costs are calculated for each road link and road hierarchy, but only based on the actual flows. It is assumed that road links with the highest marginal cost gains are most relevant for hierarchy changes (Figure 6.11(b)). This procedure is iteratively repeated until the total travel time cannot be improved anymore (Figure 6.11(b), 6.11(c), 6.11(d)).

Table 6.13: Hierarchical rules, given a graph $G(e, v)$ with increasing hierarchies h assigned to each edge i: $e_i \rightarrow e_{i,h}$, and connecting nodes $e_i = (v_{i0}, v_{i1})$.

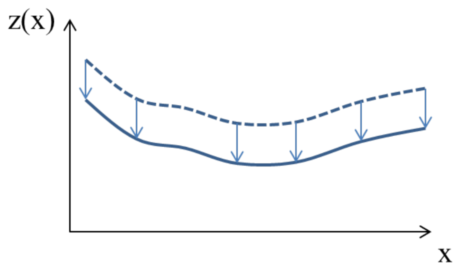
Rule	Continuous	stepwise	Rules
r_0	yes	yes	$G_n(v, e_n)$ is connected $\forall\ h \in H \wedge e_n = \{e_h, ..., e_H\}$ $\wedge\ \lvert h_0 - h_1 \rvert \leq 1\ \forall\ e_{i,h_0}, e_{j,h_1}$ with $\{v_{i0} \vee v_{i1}\} = \{v_{j0} \vee v_{j1}\}$
r_1	yes	no	$G_n(v, e_n)$ is connected $\forall\ h \in H \wedge e_n = \{e_h, ..., e_H\}$
r_2	no	yes	$G_n(v, e_n)$ is connected $\forall\ h \in H \wedge e_n \subseteq \{e_{h,...,H}\}$ $\wedge\ \lvert h_0 - h_1 \rvert \leq 1\ \forall\ e_{i,h_0}, e_{j,h_1}$ with $\{v_{i0} \vee v_{i1}\} = \{v_{j0} \vee v_{j1}\}$
r_3	no	no	$G_n(v, e_n)$ is connected $\forall\ h \in H \wedge e_n \subseteq \{e_h, ..., e_H\}$

Figure 6.11: Greedy algorithm for optimized road type distribution with flows x and total travel time z(x).

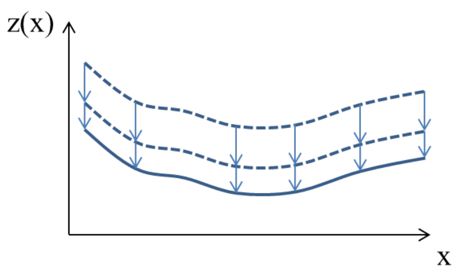
(a) Convex function of a standard user equilibrium.



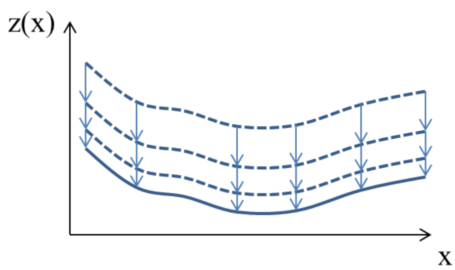
(b) Step 1, after first road type redistribution.



(c) Step 2, after second road type redistribution.



(d) Step 3.



6.7.4 Results of Grammar Rules for Hierarchical Road Type Distribution

Rules r_0 and r_1, which are defined above, are implemented in the design algorithm. Rules r_2 and r_3 actually never occurred due to the rather monocentric characteristics of the underlying featureless plane and model assumptions and the distribution of the population and travel de-

Algorithm 2 Greedy algorithm for optimized road type distribution.

Start
1. Define network, and an initial road type distribution of one specific road type.
2. Iteration n = 0.
repeat
1. Calculate user equilibrium.
2. Distribute the road types:
- According to the corresponding shape grammar rule
- such that high hierarchies are assigned to links with high marginal cost gains.
3. $n = n + 1$.
until Road type distribution is constant between iteration n and $n - 1$.
End

mand pattern (Section 6.3). In a multicenter area (approach r_2 and r_3), flows are needed to be determined between the centers. Flows depend on the distance costs, which would needed to be determined, and which complicated assumptions and evaluations. Therefore, approaches r_2 and r_3 are not further pursued here.

Table 6.14 shows the user cost differences for the different hierarchy distributions. The assumptions of Section 6.3 are applied. The upper part of Table 6.14 shows the differences of the rules in the standardized patterns (see Figure 6.5). The lower part of Table 6.14 lists the effects of the hierarchies in optimized network designs applying the IACGA (study design 3). p shows the result of a t-test analysis. n is the total number of networks designed (85 demand generating nodes, 360 candidate links).

The results in Table 6.14 show similar user costs of networks designed with r_0 compared to networks designed with r_1. Regarding the upper part of Table 6.14, almost identical user costs result with both rules r_0 and r_1 (indicated with $\sim$). Even though the user costs seem identical, the resulting network patterns designed with r_0 and r_1 are not exactly identical regarding the road type distribution, which can be verified when looking at the concrete distribution within the networks. The differences in user costs and also travel time might depend on the travel demand patterns. Therefore, different demand levels are examined. However, at low and high travel demand patterns, user costs never exceeded a difference of $> 0.5\%$ between r_0 and r_1. Even lowering the relative gap value (*rg*, see also Appendix A.5)) did not change the outcome and did not cause higher user cost differences. Summing up, when evaluating the patterns, applying r_0 and r_1 leads to almost identical results regarding the user costs.

In case of the lower part of Table 6.14 and the applied rules in the IACGA, rules r_1 leads to slightly lower travel costs compared to networks designed with to the more strict hierarchical rules r_0. The results of the optimized networks show evidence that a certain trade-off might remain at the implementation of a strict hierarchical network, compared to a more liberal road type distribution. It seems that a hierarchical network is more structured in its design, but has a slightly lower efficiency regarding generalized user costs. However, the differences are small, and it can be stated that in this case, the efficiency of a non-hierarchical and hierarchical network is very similar. Vitins et al. (2012b) showed similar results based on an evaluation on the objective function implemented in the IACGA.

Table 6.14: Hierarchical road type distribution (r_0) in different networks, and their difference to networks without a strict hierarchical distributions (r_1).

Patterns	Block size [m]			Difference in user costs $r_1 - r_0$ [%]
Dense gridiron	100			~0.0
Lese dense gridiron	200			~0.0
Offset gridiron	200			~0.0
		n	p (t-test)	
Optimized networks:		8	0.02	-5.0

Chapter 7

Intersection Type Choice

Intersection type choice is a complex decision within network design. Intersections and topology are intimately linked to each other. Therefore, network complexity is gradually increased in the following subsections to foster the understanding of the network components and their potential interactions. Generally, study design 3 (Section 3.1.4) is applied to compare different intersection types within road networks. Isolated intersections are compared first (Section 7.1), followed by the reference network patterns (Section 7.2) and the evaluation and comparison of the optimized networks (Section 7.3). Table 7.1 gives an overview of the shape grammars evaluated in this thesis and this section. Certain evaluations about intersections are already completed in the previous chapter (Section 6.5.2 and 6.5.3) due to their strong dependence on topology. However, this chapter emphasize in particular intersection type choice.

Table 7.1: Overview of the shape grammars, and envisaged grammars in this chapter (highlighted).

Study design	Shape grammars	Section
1	Boulevard design	5
2	Network element densities	6.4
2	Network meshedness	6.5
2	Number of arms per intersection (cardinality)	6.5
3	Road type distribution	6.7
3	Intersection type choice (isolated intersections)	7.1
3	Intersection type choice (intersections in networks)	7.2, 7.3
0	General theoretical justification	2.4

The research questions of Section 2.7 are refined in this chapter for intersection type choice. The following more detailed questions are derived from research question 3 in Section 2.7, and the follow up on its main idea, in addition to study design 3 (Section 3.1.4). In the following, the first research question focuses on insolated intersections, whereas the second research question focuses on intersections within entire networks.

What is the influence of variable traffic flows on isolated intersections?

Variable traffic flows are ubiquitous in urban areas due to fluctuating daily demand. Sensitivity to turning flow volumes is therefore essential for an optimized intersection type choice. The question concerning the effect of variable traffic flow is in line with study design 2 and 3, which evaluate network scenarios under various conditions, such as flows. Multiple intersection types are needed to be evaluated for variable flow.

Do rigid patterns or adaptive networks reduce turn delays and overall travel time?

Intersection type choice influences topology and vice versa. Quantitative evaluations should take place not only for one specific network pattern. More adaptive networks should be designed and compared with specific network patterns.

7.1 Turn Delays at Isolated Intersection Types

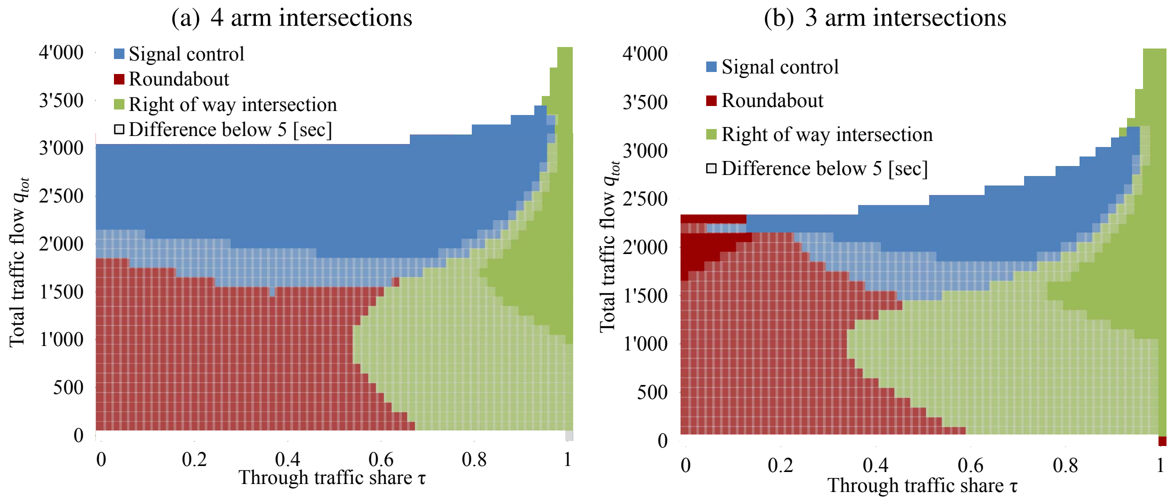
Turn delays are calculated as described in Section 3.5.3, in the Appendix B and in the HCM (Transportation Research Board, 2010). The through traffic measure τ defines increasing through traffic on a designated through traffic direction, divided by the sum of all turning flows (definition in Section 3.5.2). Figure 7.1 depicts the chosen intersection types with the lowest total turn delays but identical turning flows under various conditions of τ and total flows $q_{tot} = \sum_n q_n$. An upper bound of 90 [sec] omits very long turn delays, which often result in queue spill-over effects in dense urban areas, which are not simulated here. Intersection types with delay time differences less than 5 [sec] are in brightened colors.

Figure 7.1 shows that at low total flows ($<$ 1’500 [veh./h]), total turn delays are similar at right-of-way intersections and roundabouts. Roundabouts have slightly lower total turn delays at equally distributed turning flows. Right-of-way intersections have lower turn delays at asymmetric turn flows, due to minor delays for through traffic on the east-west axis. Signals have higher delays at total flows $<$ 1’500 [veh./h]. At moderate flow volumes ($\sim$ 1’500 [veh./h] – 2’000 [veh./h]), there is a shift in minimum delay from roundabouts / right-of-way controlled intersections to signalized intersections.

At high flows ($>$ 2’000 [veh./h]), 3 arm intersections differ from 4 arm intersections:

- At 3 arm intersections, roundabouts have the lowest total turn delays at equally distributed turning flows ($0.1 < \tau < 0.9$). Signalized intersections have lower turn delays

Figure 7.1: Intersection type choice based on the lowest total turn delays.



Areas with total delay $>$ 90 [sec] are blank, delay time differences $<$ 5 [sec] are in brightened colors.

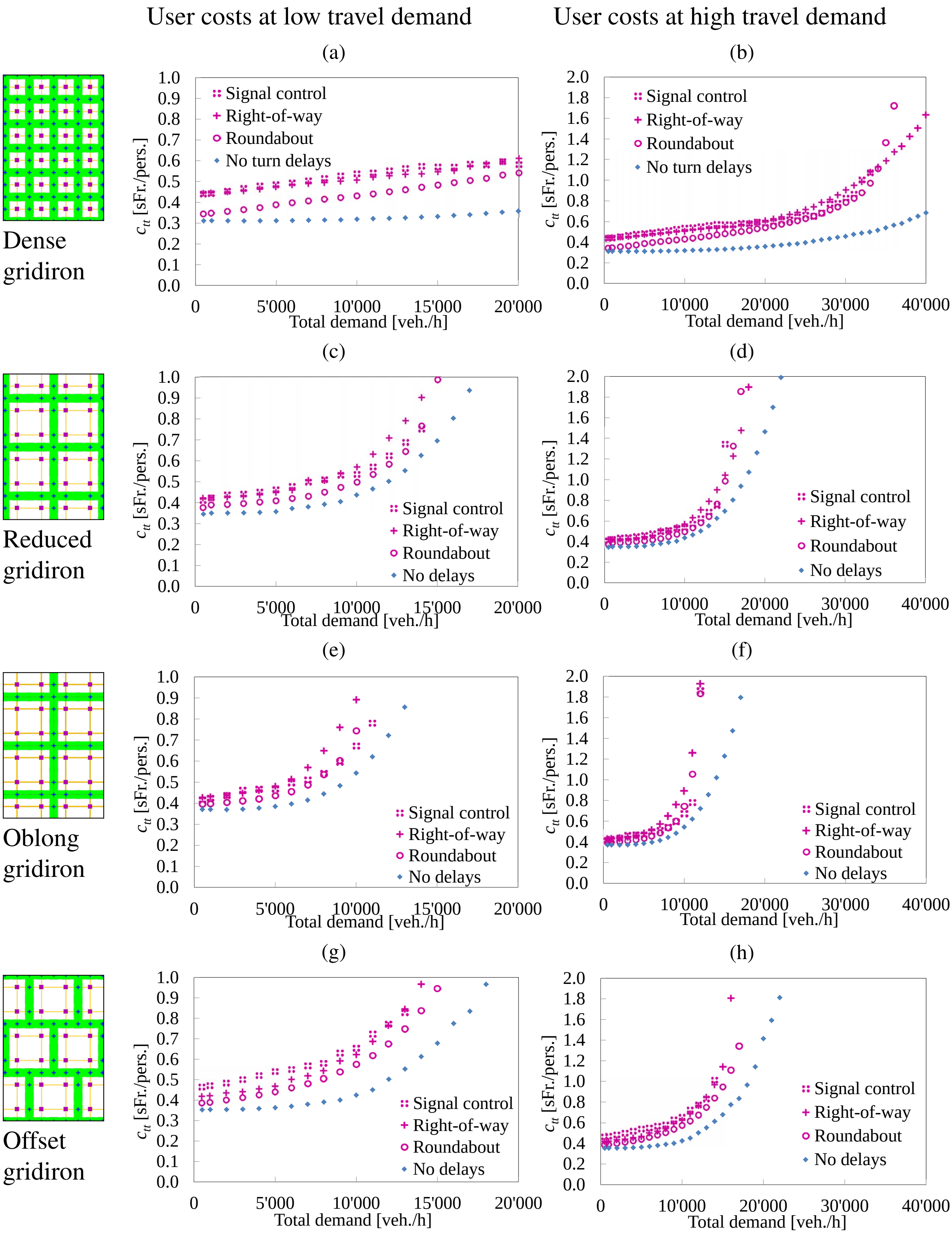
at more asymmetrically distributed turning flows. Signalized intersections have adapted green and cycle times but still slightly higher turn delays compared to 4 arm intersections due to less efficient phase allocation. At very high τ values, right-of-way intersections achieve the lowest delays, which is plausible due to their priority.

- At 4 arm intersections, signalized intersections have the lowest delays for $\tau < 0.9$. Phase allocation at signals is more efficient at 4 arm intersections, and therefore, higher demands can be accommodated compared to 3 arm intersections. Similar to 3 arm intersections, right-of-way intersections achieve the lowest delays at high τ values.

7.2 Travel Time and Turn Delay Sensitivity in Road Network Patterns

Figure 7.2 visualizes the monetarized travel time c_{tt} per person (Hess et al., 2008) and travel demand sensitivity for the distinct network patterns (Figure 6.5). The left side of Figure 7.2 refers to the network patterns, identical to the patterns in Figure 6.5. Different travel times are calculated for the network patterns. The subfigures in the middle and right column differ only in the interval of the x-axis and y-axis. Subfigures in the middle visualize c_{tt} values for lower total travel demand, whereas the right subfigures visualize c_{tt} values for higher total travel demand. Total travel demand originally relies on the empirical data in Section 3.4.2. However, demand is changed to assess the robustness of the networks. A hierarchical road type distribution is applied (r_1), based to the results in Section 6.7, and due to the necessary right-of-way rules at right-of-way intersections.

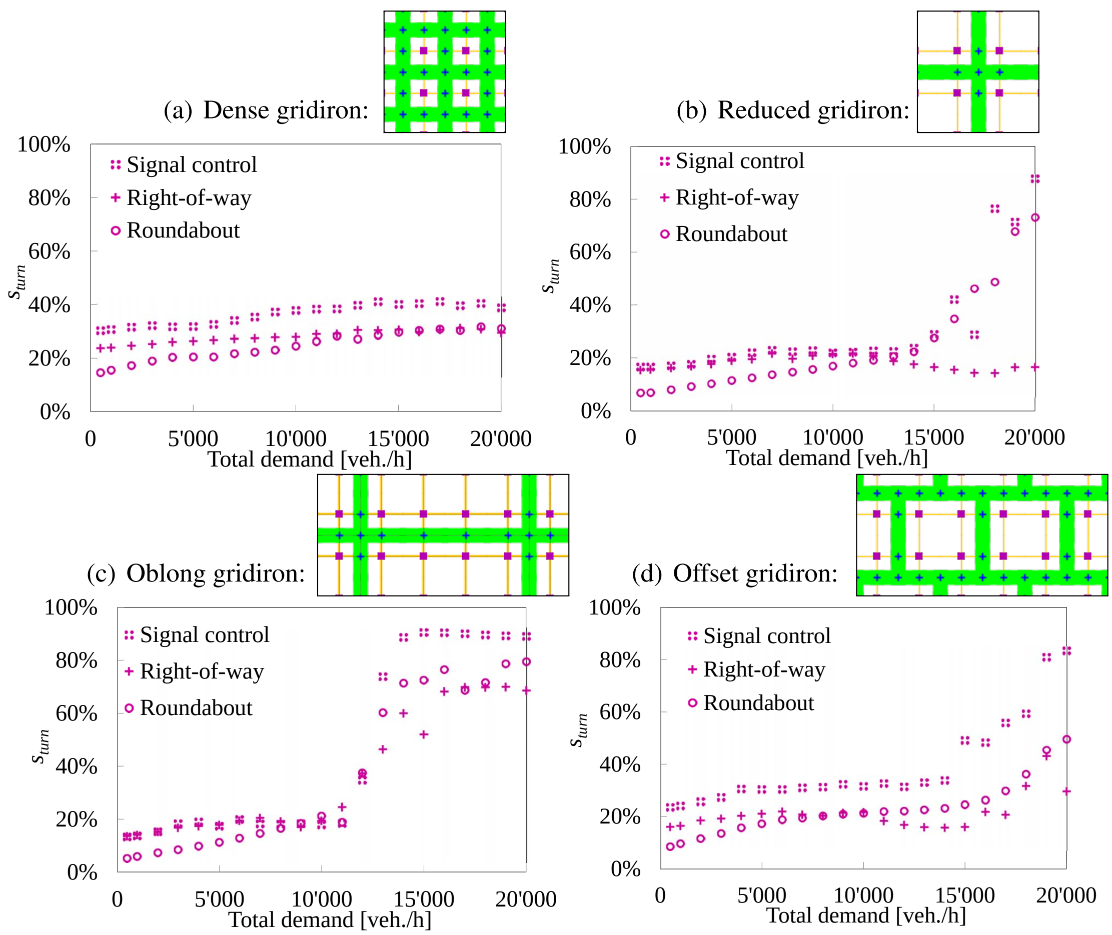
Figure 7.2: Total monetarized travel time c_{tt} [sFr./pers.] of different network patterns and intersection types.



Overall, the differences when accounting for turns are considerable compared to results which ignore turn delays. These differences indicate the significance of turn delays in network modeling. The results in Figure 7.2 reveal network saturation with a disproportionate increase in travel times at about 11'000 to 33'000 [veh./h]. Figures 7.2(a) – 7.2(h) show that in general, denser networks accommodate higher travel demand better compared to less dense networks, which is not surprising. The reduced gridiron (Figure 7.2(d)), and the offset grid (Figure 7.2(h)) have similar densities (see Figure 6.5(e)) and also similar c_{tt} values. Slightly lower c_{tt} values are expected in the reduced gridiron (Figure 7.2(d)), however, detailed evaluations below shed more light regarding the delays. Regarding intersection type comparison, Figure 7.2 shows higher c_{tt} values at low demand in networks with signals. Roundabouts have lower delays, which is consistent with the findings above (Figure 7.1).

Figure 7.3 depicts the relative share s_{turn} [%] of turn delays related to total travel time. Vehicles spend more time at intersections if s_{turn} is higher (closer to 100%) compared to time spent on roads. Travel time is not monetarized in this evaluation.

Figure 7.3: Share of turn delays s_{turn} at intersections in relation to total travel time.



Overall, Figure 7.3 shows that signalized intersections generally have relatively high s_{turn} values, compared to other intersection types due to uniform turn delays, as supposed before. This holds especially at high intersection densities (Figure 7.3(a) and 7.3(d)). All subfigures in Figure 7.3, except for the dense gridiron (Figure 7.3(a)), display disproportional increases of s_{turn} at increasing travel demand. This disproportional increase indicates that in general, intersections are saturated at a certain traffic flow. Compared to Figure 7.2, saturation at intersections is more abrupt in Figure 7.3.

The dense gridiron results in the most stable s_{turn} values (Figure 7.3(a)). At higher volumes, generally lower s_{turn} values are calculated due to the denser infrastructure. However, high s_{turn} shares can be observed even at low demand. The reduced gridiron (Figures 7.3(b)) and the offset pattern (Figure 7.3(d)) display similar s_{turn} values. The results in Figure 7.3(b) contrasts with those in Figure 7.3(d) regarding signal light delays. There is evidence that signal lights achieve relatively low delays either with low intersection densities or with 4 arm intersections. More evidence is necessary at this point.

The dependency of road and intersection density is highlighted in Figure 7.4 in the case of signal lights. Figure 7.4 shows a comparison of a dense gridiron with capacities according to scenario 0 (Table 6.4), and a less dense networks, but with doubled capacities for roads and the signal light (combination of scenario 1 and 2). Figure 7.4 shows that the less dense gridiron generates lower costs at low and moderate travel demand compared to the denser gridiron. At even higher travel demand, the less dense network gets congested, as it can be seen due to the disproportionate increase in travel time. The reason for lower costs are due to increasing intersection delays, which exceed the potential additional costs for detours at the less dense gridiron.

Figure 7.4: Total monetarized travel time c_{tt} [sFr./pers.] of two network patterns (Figure 6.5(a) and 6.5(b)).

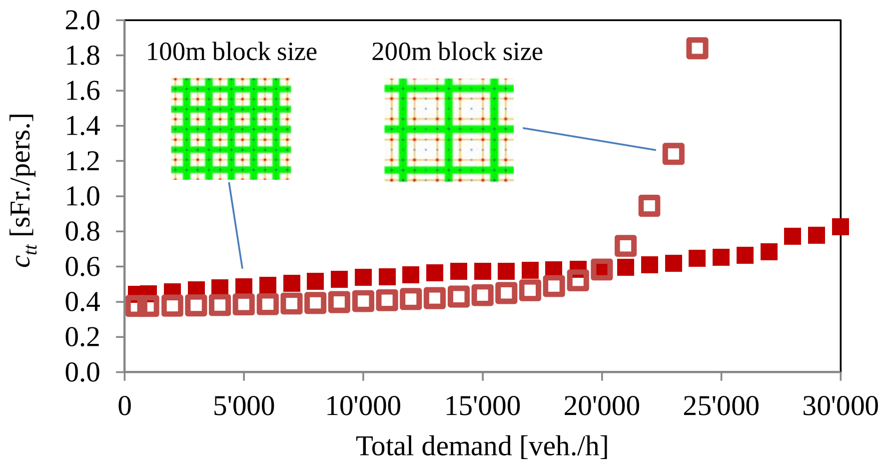


Figure 7.5 shows multiple network patterns with decreasing road densities (d_r), and corresponding monetarized travel times changes (c_{tt}). Road and intersection capacities are the same in all patterns, therefore, network saturation takes place at lower demand compared to Figure

7.4. Figure 7.5(a) shows the c_{tt} changes when ignoring turn delays. Decreasing road length leads to increasing c_{tt} values at low and high demand patterns. However, the outcome considerably changes when considering signal lights and corresponding turn delays (Figure 7.5(b)). At low travel demand, overall c_{tt} decreases at decreasing road densities d_r until 10–12 [km/km^2] which corresponds to 45% – 55% of the density of a dense gridiron of 100 [m] block size. Assuming the demand of a four story perimeter courtyard development with $\sim$3'000 [veh./h] (peak hour, estimated from the Swiss micro sensus (Swiss Federal Statistical Office (BFS), 2010)), the urban (population and job) density can increase in more than double and road density can still be low (40% of the dense gridiron) to achieve low travel time values. It is also remarkable that a road density of 8–14 [km/km^2] (40% – 65% of a dense gridiron) is enough for most demand patterns.

7.3 Comparison of Optimized Networks and Rigid Patterns with Economic Measures

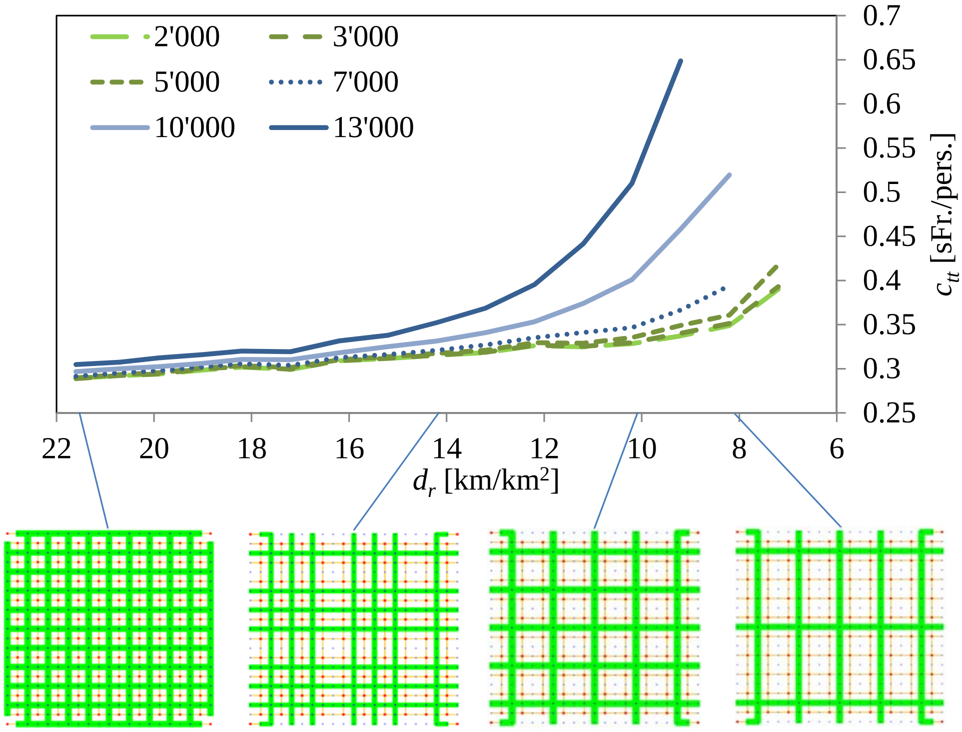
The presented network design algorithm IACGA allows assessments, which lead beyond evaluations of rigid patterns. Figure 7.6 depicts the total monetarized travel time (c_{tt}) per person of optimized networks with different road density values d_r, and rigid networks patterns. The rigid patterns get a rough estimate for a density estimation. It can be assumed that road density is proportional to infrastructure costs, which allows to ignore the transformation from road density to real infrastructure costs. The optimized networks are designed with the IACGA (Section 4.5). Again, c_{tt} is evaluated because it is the major influential component in a cost-benefit analysis, beside infrastructure costs. Demand is determined according to the densities d_{pop} and d_{jobs} based on a four story perimeter courtyard development (Section 3.4.2). Figure 7.6 focuses on the comparison between reference patterns and optimized networks at similar infrastructure costs. The three reference patterns (Figure 6.5(b), 6.5(c), 6.5(d)) are visualized in Figure 7.6 for comparison. The road infrastructure costs are visualized as d_r [km/km^2].

The results visualized in subfigure 7.6(a) ignore the influence of turn delays, unlike the subfigures 7.6(b) – 7.6(d). For certain transport modes and networks, ignoring turn delays might be still reasonable, especially for transport modes with low speeds, such as pedestrians. Modes with low speeds travel longer on links relative to waiting time on nodes (e.g. pedestrian or bicycle networks). Obviously, adding infrastructure decreases travel cost in most cases. Therefore, the slope of the regression is rather steep, compared to the subfigures 7.6(b) – 7.6(d).

Figure 7.6(b) displays the costs of rigid patterns and optimized networks with signals. The two gridiron patterns differ in travel time from the offset pattern with 3 arm intersections. The results show evidence that the signalized intersections achieve especially low turn delays

Figure 7.5: Monetarized travel time c_{tt} [sFr./pers.] depending on the network density d_r at different demand levels (2'000-13'000 [veh./h]).

(a) Ignoring turn delays.



(b) Including only signal lights.

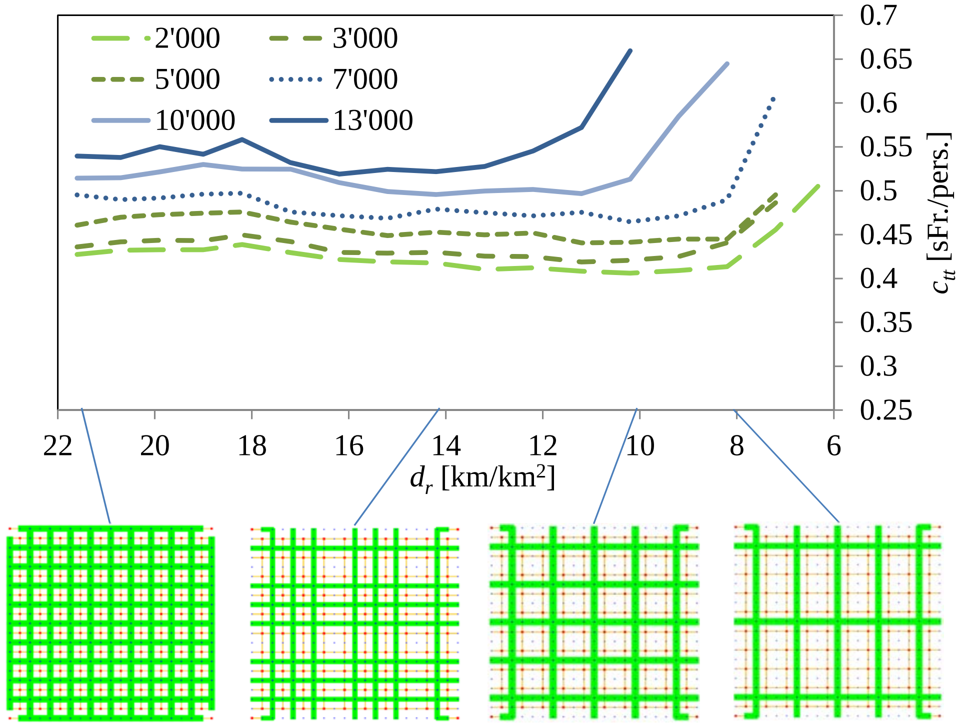
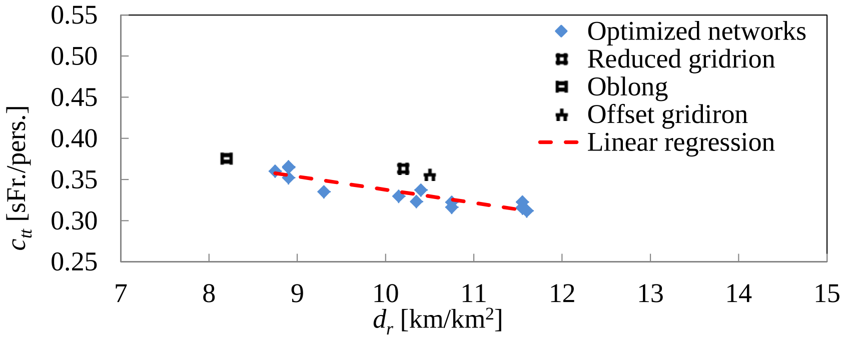
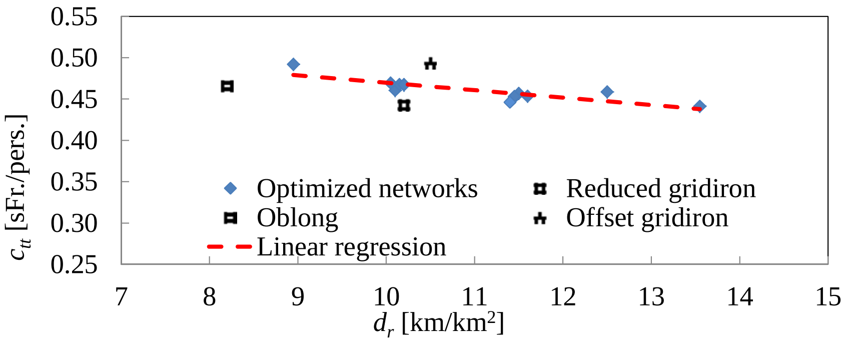


Figure 7.6: Comparison of optimized networks and rigid reference patterns regarding generalized costs c_{tt} [sFr./pers.].

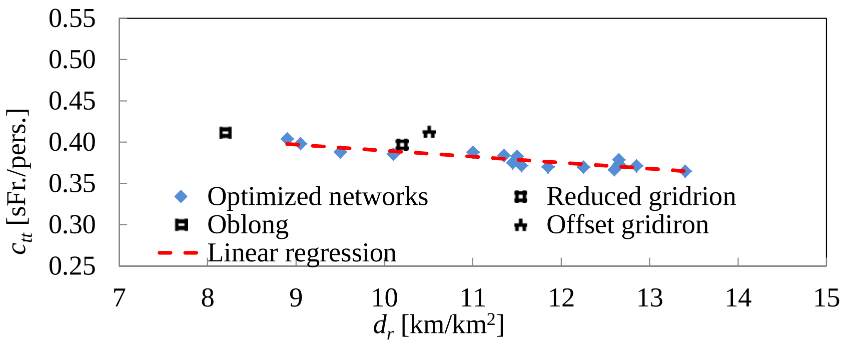
(a) Networks without turn delays.



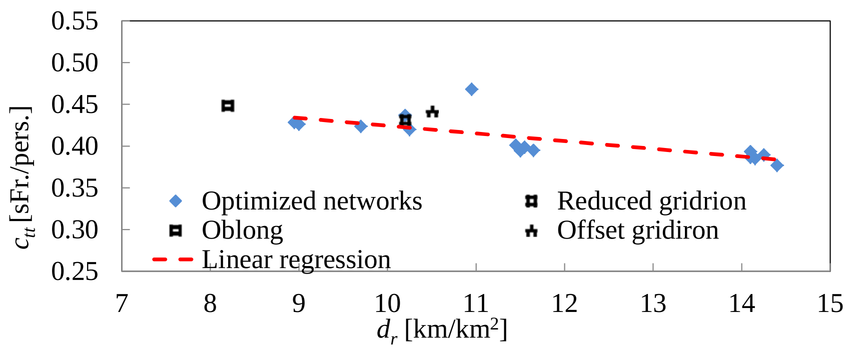
(b) Networks with signalized intersections.



(c) Networks with roundabouts.



(d) Networks with right-of-way controlled intersections.



Demand is calculated according to the assumption in Table 3.5.

in gridiron networks with relatively low intersection densities. The uniform average delay at signals favors networks with lower intersection densities. An additional reason might be the more efficient phase allocation at 4 arm intersections, compared to 3 arm intersections. This evidence supports with above findings (Figure 7.1).

Figure 7.6(c) visualizes c_{tt} values of distinct patterns and optimized networks with roundabouts. Distinct patterns result in similar costs compared to the optimized patterns. Figure 7.6(d) depicts the costs of patterns and optimized networks for right-of-way intersections. Optimized networks achieve equal costs compared to rigid patterns. The linear regression approximation shows steeper marginal costs than roundabouts (see below for more details).

Overall, Figure 7.6 shows that networks with right-of-way intersections and roundabouts have lower c_{tt} values compared to signals, which is in line with the above results. This is valid for a relatively low travel demand, due to the considered and rather low d_{pop} and d_{jobs} (Section 3.4.2). Figure 7.6 shows that the performance of gridiron patterns can be achieved with optimization algorithms except in the case of network patterns with signals. However, the optimized networks do not necessarily have a gridiron topology.

Linear regression is applied to define the marginal generalized cost savings $\frac{\delta c}{\delta d}$ and elasticities $\frac{\delta c}{\delta l}\frac{\bar{l}}{\bar{c}}$ of the optimized networks in all subfigures of Figure 7.6. l is the length of the network and proportional to density d_r due to the identical size of the perimeter. Linearity is assumed as an approximation. Here, the question is answered of how much generalized travel costs can be saved when adding additional road length. The answer is based on the optimized networks, and the optimized allocation of the road length.

The first line in Table 7.2 refers to the marginal generalized cost savings related to the road network length. Marginal generalized cost savings differ considerably between the subfigures for undersaturated networks. The second line in Table 7.2 shows the elasticity values for all intersection types. Right-of-way intersections have highest elasticity values, and relatively high marginal cost values. Adding road length on networks with embedded right-of-way intersections increases generalized cost savings more than when adding roads in networks with signals. There is evidence that at signalized intersection, increasing capacity reduce user cost more than additional road length (Figure 7.4 and 7.5).

Table 7.2: Estimated marginal generalized cost savings at undersaturated networks vis-à-vis elasticity values, both related to network length.

	No turn delays	Signal lights	Roundabouts	Right-of-way control
Marginal generalized costs $\frac{\delta c}{\delta l}\left[\frac{sFr}{km}\right]$	-0.032	-0.015	-0.013	-0.016
Elasticity $\frac{\delta c}{\delta l}\frac{\bar{l}}{\bar{c}}\left[\,\right]$	-0.384	-0.171	-0.166	-0.180
R^2	0.796	0.739	0.842	0.745
Average share of intersection delay [%]	0.0	23.1	12.2	9.93

Chapter 8

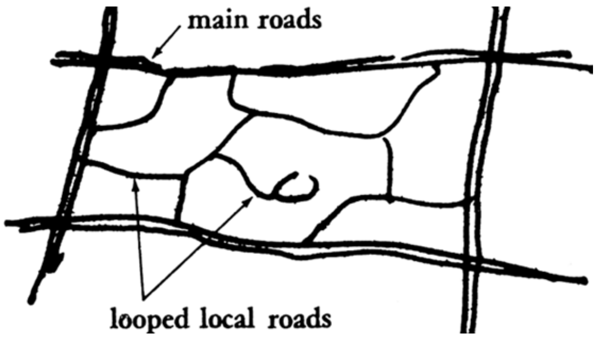
Shape Grammar Set

Grammars can be formulated in many different ways. Many geometry based grammar rules are visualized directly in geometric plans, e.g. Stiny and Mitchell (1978). The rules are described in the basic form $\alpha \rightarrow \beta$ (Section 2.1.4 or Stiny and Mitchell, 1980). Section 2.5 already pointed in the direction of a more descriptive approach, similar to Alexander et al. (1977, e.g. Figure 8.1), which is implemented below and contrasts a rigid plan based approach. Even though the plan based approach would be more straightforward, and maybe clearer, the descriptive approach accounts for the complexity of the grammars and the characteristics of the results to be achieved. Especially the complexity of the urban design and the interdependence of the grammars hamper a straightforward geometric rule description.

As it will be shown in Section 8.5, network design and topology depends on the modes and their characteristics, as well as the surrounding urban densities. Therefore, absolute geometric lengths and angles can not be provided in most grammars. E.g. meshedness cannot be characterized with absolute lengths. Still, it is found that meshedness is a relevant characteristics, and significant regarding reliability. Therefore, also no geometric drawing similar to e.g. Stiny (1985) can be found in the following.

Chapters 5 – 7 described design recommendations based on the evaluation results. This chapter summarizes the results according to the rule – semantic format proposed in Figure 2.4 and explained in Section 2.4, and therefore focusses on grammar rules and application specification. Sections 8.1 – 8.4 refer to road network design, related to cars. Sections 8.5 – 8.6 opens up the discussion to other modes and the corresponding design consequences.

Figure 8.1: A grammar about looped local roads as a result of a descriptive approach.



Source: Alexander et al. (1977) p.263.

8.1 Boulevard Design

This research suggests the following rules for boulevards, based on the evaluation in Chapter 5:

Rule 1: Boulevards should have a minimum length to achieve noticeable travel cost reduction and accessibility increases: The minimum length is 2–3 blocks. Longer boulevards reduce travel costs and increase accessibility further. The target is $\geq$3 blocks for boulevards in larger networks, and far higher average travel distances.

Rule 2: Boulevards with signals situated at the center road have the highest travel cost and accessibility elasticities $\epsilon^{s,T}$, $\epsilon^{s,A}$. Therefore, it is recommended to implement signals in boulevard junctions.

Rule 3: Travel speed on the boulevards has to be higher than on the parallel roads, even under congested network conditions. So the planners have to design networks such that speed on the main boulevard center road never drops below. This rule affects the overall urban design context. It can imply capacity and speed reductions on parallel roads e.g. through on-street parking, traffic flow guidance, turn restrictions etc. It also leads to design consequences on the center road, stated in the following rule.

Rule 4: The capacity of the center road has to be high enough to accommodate the flows. At least two center lanes in each direction are advisable. The consequence of insufficient capacity on the center road would be rerouting onto parallel roads.

Rule 5: Boulevards reduce generalized travel costs of urban traffic if the major intersections at the center road provide enough capacity and low turn delays for the flows. This holds also for the crossings of the boulevard, which can be bottlenecks for crossing traffic. At least 3 approaching lanes for the major intersections are advisable.

Rule 6: Boulevards have a benefit to cost ratio of $\frac{b}{c} > 1.0$ only if the land prices are relatively low for land acquisition. Obviously, boulevards as proposed above should be planned in an early stage of urban design. If not, additional economic studies and effects (e.g. Venables, 2007) have to be considered, which are beyond a standard cost-benefit procedure.

The above rules were derived with specific assumptions and evaluation methods. The application specifications are described in Section 5.1 and 5.3 in detail. The major application specifications are summarized in Section 8.7.

8.2 Topology

Major insights gained are the density- and flow-related trade-offs between network design and urban densities. Higher urban densities and therefore travel demand lead to significantly different network user costs depending on topology characteristics and intersection types. The following recommendations are based on the results above, which aim for efficient network topologies with low travel times and generalized travel costs:

Rule 7: A high meshedness coefficient M was found in all travel cost – efficient networks, both in optimized and existing real-world networks, as well as in less dense and denser networks with low and high traffic flows. Therefore, $M \geq 0.2$ is a sound advice for efficient networks. Obviously, this rule accounts for the general topology of a network, and is less specific compared to e.g. a recommendation for the number of arms. Examples of networks with high meshedness are shown in Figure 8.2, quantitative evaluation can be found in Cardillo et al. (2006).

Rule 8: Deadend density $p_{c=1}$ should be low in both optimized and existing road networks. This recommendation is based on the descriptive statistics of all efficient networks.

Rule 9: It is unclear whether 3 or 4 arms are more efficient regarding delays. Additional information is needed related to the scenario and specific example application.

Rule 10: Higher network road density d_r improves network efficiency in the case of ignoring or low turn delays which obviously depend on the travel mode. Exceptions are the Braess paradox (Braess, 1969) and intersection types with high turn delays, e.g. signals (described in Section 8.5).

In summary, it becomes clear that the efficiencies of the proposed reference networks are high regarding generalized travel costs, especially the gridiron network, which has high M values and low $p_{c=1}$ values, and a low intersection densities.

8.3 Road Type Distribution

The distribution of the hierarchy levels is crucial within the network. A hierarchical network is found to be efficient regarding user and infrastructure costs. This is true when comparing hierarchical network designs with network designs based on optimized road type distribution, but without necessarily a hierarchical structure. Very prescriptive hierarchies have a somewhat reduced efficiency (∼0 – 5%) compared to less strict hierarchical designs, depending on the network topology.

Rule 11: The road type choice is essential for efficient network design. A straightforward hierarchical road type distribution is leading to an efficient network design regarding total generalized travel costs. An optimization of the road type distribution within a given network based on the proposed algorithm is leading to the same or only slightly higher efficiency. Hierarchical and optimized approaches are therefore similar with regards of their final user costs.

8.4 Intersection Type Choice

Intersection type choice depends on the expected traffic flows.

Rule 12: Signals are more efficient for increasing urban densities and travel demand. However, signal delays are relatively high at low demand, leading to higher travel times.

Rule 13: Signals have lower turn delays at 4 arm intersections. Therefore, overall travel delay is low for a combination of gridiron networks with signals (see Chapter 6 and 7).

Rule 14: Right-of-way intersections have low turn delays at low flows, especially for high through traffic shares and overall low travel demand. Intersection density seems less relevant for right-of-way intersections.

The above results support gridiron networks with signals, especially in combination of rectangular block shapes. A hybrid approach is plausible at this point: Signals can be turned off during off-peak periods, and only turned on in peak hours.

There is evidence that signals accelerate traffic flow at high urban densities and traffic flows. To achieve low delays, signals have to be optimized regarding cycle and green time and the number of approaching lanes. Planners can consider signalized intersections due to spill-over effects at high traffic flows.

8.5 Topology Design Conflict

Travel time, speed, turn delays depend on network topology and design and urban densities. Slow modes, e.g. pedestrians, spend less time on intersections compared to time traveled on links. Slower modes of transportation can have shorter turn delays, as is the case e.g. with bicycles. Higher values of marginal travel cost savings correlate with relatively low turn delays. Increasing road density therefore would generally provide higher returns for modes with low turn delays. Slow modes can benefit most from a dense network topology and higher intersection densities and even a high 3 leg intersection share. The situation changes when considering faster modes, e.g. cars, and higher turn delays. Especially in dense urban areas, fast modes with high turn delays profit from lower intersection densities and high road and intersection capacities. Similar findings might hold for transit networks. We can find dense bus networks with short headways and changing times which contrast with long distance networks, but with longer headways and longer stopover times. In summary, modes with different travel speeds require different network topologies with different densities, which is notable and which has consequences on the design of city layouts.

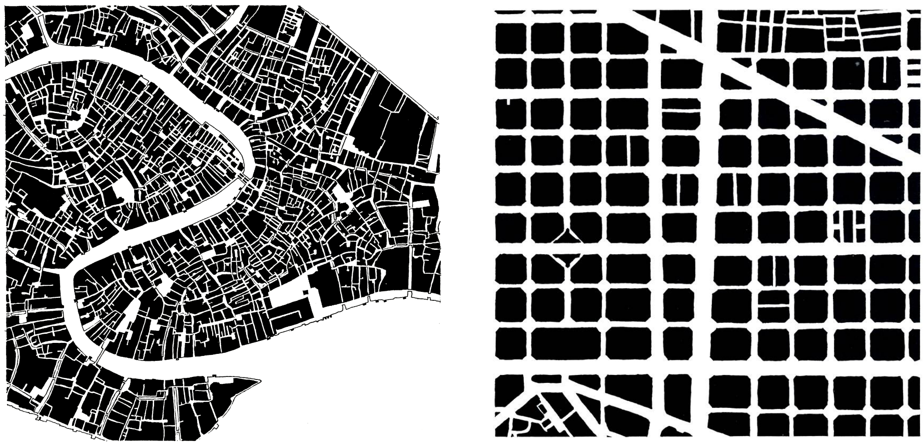
The specifications of the grid and block size are important, hence simply recommending a "gridiron" design is insufficient. Therefore, application specifications (semantics) are required to further improve travel costs and economic efficiency. The intimate link of rule and corresponding specifications is in line with the theory of language, as is described in Section 2.4. Urban densities, e.g. population and jobs, influence traffic substantially. The findings show that road networks with low capacity intersections are recommended for low urban densities and low flows and hence low turn delays. In this case, network density might be even high, and is therefore subject to the infrastructure investment strategy due to the low urban density. However, in the case of higher urban densities, less dense road networks are recommended with high road and intersection capacities. This sounds contradicting, but provides lower overall travel costs due to overall low turn delays. In the case of slow modes such as pedestrians, dense networks are still recommendable at high urban densities, as described above.

The transformation of road networks at increasing urban densities is not intuitive, but often necessary due to the increasing travel demand. Changing network densities or changing from one mode to another is therefore most challenging, as it can be seen in the development of transportation through history. Growing urban systems have to be redesigned over time as densities increase, travel modes change, and new needs must be met. Figure 8.2 compared two completely different topologies, obviously designed at different eras for different modes, but which can be found similarly in other cities as well.

The definition and evaluation of potential solutions for the mentioned transformation are outside the scope of this research. Figure 8.3 shows a possible basic solution by cutting down road

Figure 8.2: Two different network topologies yet with the same spatial dimensions (1×1 [mile^2]).

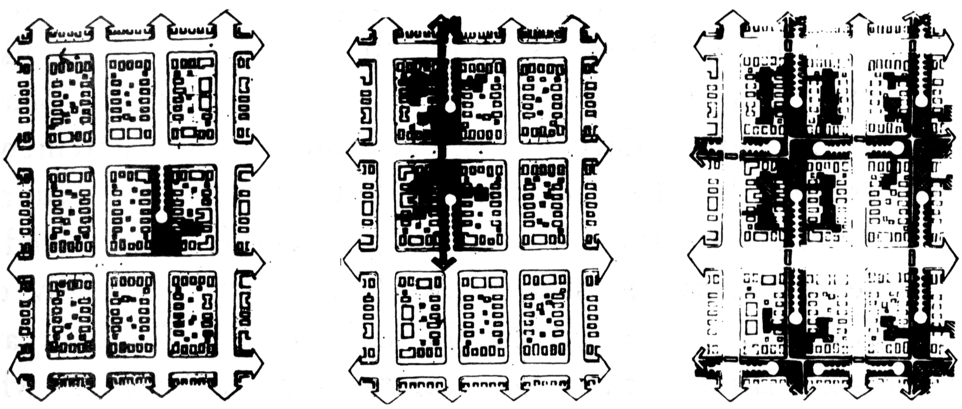
(a) Venice (b) Barcelona



Source: Jacobs (1993) p.249, 208.

length, proposed by Alexander et al. (1977). However, it requires more elaboration with regards to modes, block size and capacity adaptation, which seems to be ignored in Figure 8.3. Figure 8.3 is based on the most widely applied gridiron; additional research would be required for other layouts. Nonetheless, the basic idea is clear and indicates that a reduction of intersection density is needed to increase efficiency in car oriented networks.

Figure 8.3: Redesign of an urban grid network by closing down specific streets (indicated by dark road segments).



Source: Alexander et al. (1977) p.273.

8.6 Consequences of the Topology Design Conflict

Efficiency, here user costs, depends very much on the topology. It can be assumed that the topology affects to a considerable extent the travel times and thus the choice of travel mode. Known examples are lollipop networks, which are less efficient, e.g. for walking; this is in contrast to medieval networks, which are especially efficient for walking. Further insights are less obvious, but reasonably based on the results above. Medieval networks and gridirons might be efficient regarding topology measures (Cardillo et al., 2006), but this changes when looking from a transport planning perspective. At high urban densities, gridirons outperform medieval structures regarding car travel cost because of low intersection density and efficient 4 leg intersections and often lower road densities coupled with higher road and intersection capacities. Consequences are higher walking shares in medieval networks, and higher car traffic shares in gridirons.

8.7 Application Specifications for Shape Grammar Rules in Section 8.1 – 8.6

As suggested in the theory of grammar development (Section 2.4), the assumptions corresponding to the stated rules above have to be defined for completeness of the design grammars. So planning experts know about the origin of the grammar rules above, the underlying fundamental theory and the applied methods:

Application specification 1: The following elasticities were estimated for boulevards with signals at the center road:

- $\epsilon^{s,\ travel\ cost} \simeq 1.3 – 1.9$, with higher $\epsilon^{s,\ travel\ cost}$ values at higher flows (e.g. peak hours).
- $\epsilon^{s,\ accessibility} \simeq 1.3 – 1.9$, with higher $\epsilon^{s,\ accessibility}$ values at higher flows.
- $\epsilon^{s,\ external\ costs} \simeq 1.6 – 2.9$, with higher $\epsilon^{s,\ external\ costs}$ values at higher flows.

Application specification 2: The results are based on a static model with detailed intersection delay formulae from the HCM (Transportation Research Board, 2010), but ignoring spillover effects of possible queues.

Application specification 3: Urban densities of a medium dense urban neighborhood are assumed in the base scenario (15’068 [pers/km^2] and 6’685 [jobs/km^2]). Travel demand is estimated based on the Swiss micro census (Swiss Federal Statistical Office (BFS), 2012) in a simple and straightforward way with uniform demand distribution (Table 3.5), but including peak hour and reliability analysis. Due to the general uncertainty in planning and travel demand estimation, it is regarded as relevant to apply a comprehensive reliability approach to gain information about changing travel demand and its effects.

Application specification 4: The results account for changes on the demand and supply side. Various urban densities are tested for robustness, as well as for changing infrastructure investments.

Application specification 5: Pedestrians, trucks, bicycles, public transportation are not considered in the evaluation.

Application specification 6: The road lengths are based on average empirical data, as well as parcel shapes.

Application specification 7: Through traffic and through axes are not considered above. However, the boulevard grammars (Section 8.1) give some insights.

Application specification 8: The boulevard is modeled in a gridiron network, of $2 \times 2[\text{km}^2]$, and $3 \times 3[\text{km}^2]$, respectively.

8.8 Potential applications of the proposed shape grammars

In general, grammars can be applied differently depending on the rules, application specifications and the intended developments and specific scenarios. A large variety of applications can be found in literature. When looking at the existing literature, e.g. Stiny (1985) defined and applied grammars differently compared to Alexander et al. (1977). Stiny (1985) applied well-defined forms and shapes for his proposed building plans, whereas Alexander et al. (1977) suggested a descriptive approach with example layouts of cities, neighborhoods and buildings to design new or also improve existing developments. Grammars can serve different purposes. They can be applied to improve existing infrastructure, such as existing networks and urban neighborhoods, or they can be applied to design new networks and urban developments. They can affect the whole transport network design, or only single and isolated network elements such as intersections or road segments. Also within this research, the proposed grammars can serve different purposes and different applications.

The grammars defined and evaluated above are subdivided in Table 8.1 and 8.2 based on their potential future applications and design purposes. Table 8.1 and 8.2 show the potential implementations of the proposed grammar rules in practice, subject to their main design purposes (Table 8.1) and the required space and time requirements (Table 8.2). Table 8.1 and 8.2 therefore further specify the potential applications of the proposed grammars.

Table 8.1 subdivides the proposed grammar set above in a subset of grammars for network improvements and in a subset of grammars for the design of new urban networks. One has to add that the grammars suitable for improving existing developments can be applied for the design of new urban developments as well. For example intersection type choice is relevant in existing networks and in the design of new networks.

Table 8.1: Main purpose of the defined shape grammars.

Improvement of existing networks	Design new or extending existing urban development
Boulevard intersection types and vehicle routing (rule 2, 3)	Boulevard length (rule 1)
Boulevard capacity (rule 4, 5)	Boulevard investment decision (rule 6)
Road capacity (rule 11)	Network meshedness (rule 7)
Intersection type choice (rule12, 14)	Intersection cardinality(rule 8, 9)
Mode separated networks (topology design conflict)	Network density (rule 10)
	4 leg signal crossings (rule 13)

Table 8.2 contains information about the spatial and temporal requirements of the proposed grammars during implementation. Regarding the spatial requirements, some proposed grammars might be applied on a local scale, e.g. when improving intersection type choice. However, some grammars might also be applied on a more global scale, and therefore affect the design of the whole network. Obviously, shape grammars for a local scale are also valid and can be implemented within the design of the entire network. Beside the affected spatial area, the implementation of certain grammars might require different time spans for implementation. Mostly, grammars for small scale applications can be planned with and implemented in a shorter amount of time, compared to more global grammars, which affect entire network design.

While certain grammars like the design of a boulevard or rules about intersection type choice are straightforward in their design recommendation, other grammars like the proposed high meshedness value are less intuitive and more complex in their application. It can be shown that even complex recommendations can be applied and considered during the design of networks. An example is provided in the case of the meshedness rule (rule 7). Rule 7 and Table 8.1 recommend that new networks should be designed based on topologies with high meshedness values. This rule can be verified during the planning and design process of new networks, based on the meshedness definition (Equation (6.1)). However, even existing networks can be evaluated regarding their meshedness values. The meshedness value can be evaluated for a predefined area within a city based on Equation (6.1), similar to e.g. Cardillo et al. (2006). Areas with low meshedness values can be determined and reasons for the low meshedness values can be found depending on the predefined area and existing network topology. It is therefore possible to evaluate existing networks regarding the rather complex and specific meshedness values for improvement and modification purposes.

Table 8.2: Spatial and temporal requirements of the proposed shape grammars during implementation.

Time requirements for implementation		Spatial requirements within a given network: local	regional	global
	Short term	Intersection type choice (rule 12, 14)	Boulevard intersection types and routing (rule 2, 3) Boulevard capacity (rule 4, 5)	
	Medium term	4 leg signal crossings (rule 13)	Mode separated networks (topology design conflict)	Road capacity distribution (rule 11)
	Long term		Boulevard length (rule 1) Boulevard investment decision (rule 6) Intersection cardinality (rule 8, 9)	Network meshedness (rule 7) Network density (rule10)

Chapter 9

Summary and Discussion

This thesis provides an overview of shape grammars in transportation planning and cognate fields, covering academic literature and existing guidelines. It is clear that shape grammar rules are applied widely in planning. However, methods to define grammars and to determine the effect of shape grammar applications are less established. Therefore, methods are suggested and applied to crystalize and evaluate shape grammars for urban transport networks. This chapter focuses on the methods and results applied above from a more global perspective and summarizes the major achievements, pros and cons. The research questions (Section 2.7) are discussed for this purpose, as well as the applied study designs and underlying methods. Some ideas for future research are proposed in addition.

9.1 Research Questions

9.1.1 Research Question 0

Research question 0 looked at the theory of shape grammars. The fundamental idea of shape grammars in fields such as architecture, geometry or computer sciences matches the idea of shape grammars for urban network design. Grammars are defined as rules and corresponding application specifications. Design rules (syntax) are insufficient to determine shape grammars. Application specifications (semantics) are needed to further specify the applications of rules and to increase the effectiveness after implementation. The application specifications describe the conditions under which the rules can be applied in practice, and therefore should support the practitioners in the application. It could be shown that the characteristics for meaningful applications can be determined for specific rules.

On the one hand, the rules and application specifications can be very detailed as shown e.g. in the case of boulevard design. On the other hand, rules can be determined for more global design recommendations, such as network meshedness. Also for more global recommendations, application specifications are required for more effective implementation. This could be shown in the case of gridiron networks and the influence of urban densities and travel demand.

It could be shown that it is possible to determine shape grammar rules for planning purposes. Due the complexity of the network design problem (Braess, 1969; Johnson et al., 1978), exact numbers are not possible for the effectiveness of specific shape grammar rules. This is a major drawback, but cannot be solved due to the remaining complexity of the problem. However, the achieved results about the application specifications improve the understanding for the application of rules. In the future, more insights are needed especially in the application specifications of the rules.

9.1.2 Research question 1

Research question 1 aimed at the straightforward evaluation of specific shape grammar rules. In the proposed study design, scenarios are compared with and without shape grammars according to a specified objective function (study design 1). This approach is effective, but is only applicable for straightforward and specific rules. Moreover, application specifications are needed and might be specific for only certain network specifications. Limitations arise at study design 1 when evaluating global rules, such as the number of arms per intersection.

Exemplarily, different boulevard types are evaluated directly in gridiron networks regarding three objective functions. Shape grammar rules are derived, as well as application specifications for improved effectiveness. Crucial insights are gained during the process of modeling and evaluation, which serve as fundamental knowledge for shape grammar rules.

9.1.3 Research question 2

Research question 2 aims at the definition of new shape grammar rules for network design. New rules can be determined based on optimized networks and statistical evaluations, especially general rules for the entire network (global rules). The determination of optimized networks is therefore a critical component within the proposed method in study design 2. Artificially generated and optimized networks are cumbersome due to the large search space. However, real-world networks are biased due to history and therefore problematic as well for statistical evaluations.

A network design algorithm is proposed to design optimal road networks. Beside other criteria, the meshedness coefficient M is statistically evaluated based on optimized networks. It is found that high M values are conductive for low generalized travel costs.

9.1.4 Research question 3

Compared to research question 2, research question 3 implements global network design rules in the generation and optimization of networks (study design 3). After the design of the networks, networks are evaluated and compared statistically. Is is shown that it is possible to design optimal networks including global design rules. However, similar issues arise as in research question 2, especially because of the complexity of the network design and the large search space during design and optimization. Evaluation of intersection type choice and hierarchical distributions of road types are conducted based on study design 3. Statistical evaluation showed substantial results, however, again complexity of network design remains an issue.

In summary, the research questions and corresponding study designs are able to evaluate a broad range of different shape grammar rules. Future issues can arise regarding the complexity of shape grammar rules, in combination with the complexity of transport networks and of their performance.

9.2 Methods Applied

Beside the definition of shape grammars and the applied study designs discussed above, various methods are suggested and applied in this thesis. Interesting results are gained with the maximum network supply approach (Section 3.3), which is a measure for network reliability under various urban densities and therefore travel demands. The promising method assesses the maximum increase in travel demand a network can cater for without unacceptable travel time increases. The suggested approach to measure the capacity maximum of networks is successfully implemented here. Relevant network design characteristics could be determined statistically. This measure can be relevant for future planning, where the urban densities and travel behavior might change.

Moreover, the importance of turn delays is highlighted in this thesis. Turn delays contribute considerably to overall travel time and generalized costs. Turn delays are often ignored in planning and modeling. It could be shown that turn delays are large, and that intersection type choice is relevant for urban planning already in an initial state. Especially the capacities of intersections are most relevant, in combination with the road capacities and network topology.

The network design algorithm (IACGA) is extensively discussed, including advantages and disadvantages. The IACGA is especially designed and suitable for the design of entire road networks. The IACGA allows the design of lager networks, but also the statistical evaluation of many different networks. It overcomes issues of the standard GA and ACO, and therefore is able to cope with reasonable large search spaces. Some issues have to be addressed regarding search space and calculation time. Search space increases considerably when adding new dimensions, such as road types, or intersection types. Eventually, future development in hardware can overcome the computational burden of these issues in future applications.

Due to its heuristic nature, and the enormous search space, the IACGA does not guarantee to find the optimal solution. However, it could be shown that the IACGA outperforms the reference networks in the case when ignoring turn delays, in the case of roundabouts and right-of-way intersections. However, with signals, the gridiron reference network generates the lowest turn delays. This is most probably due to the increased overall complexity of the design, the more complex phase optimization for signal delay calculations, and the very specific and efficient design of a gridiron reference network.

Due to the high complexity and large search space, separate evaluations of network elements are recommended in the future to reduce search space. In this way, as is shown in this research, results become clearer than when multiple network elements are optimized at the same time. And, the final definition of shape grammars and the increased fundamental knowledge in network design will make future optimization calculations unnecessary.

9.3 Conclusion

Methods for the definition and evaluation of shape grammars are developed and applied in this thesis. The approaches aim at increased understanding and final reduction of the complexity of transport networks. The proposed novel methods enable to estimate the effect of rules, which so far were based mostly on intuition and on scant systematic testing. Therefore, shape grammar rules can be applied more effectively. Overall, valuable insights are found for shape grammars applications in general, for topology design and intersection type choice.

It is remarkable that high meshedness is observed even for networks with low road density and therefore low infrastructure costs. This might be due to the travel demand pattern, which is distributed over the whole model area. This is a reasonable assumption, since people want to increase accessibility and therefore want to have access to many attractive nodes nearby. Treelike network topologies which correlate with deadend density are observed less in the results. Trees are often designed to minimize costs (Steiner tree). However, it seems that slightly higher network densities leads to meshed topologies very quickly when optimizing user costs.

No significant difference whatsoever could be found between the distributions of 3 and 4 arm intersections in optimized networks. However, regarding isolated intersections, signals generate the lowest turn delays at 4 arm intersections due to phase allocation. Regarding the differences between intersection types, signals can accommodate high flows at lower delays, compared to roundabouts and right-of-way intersections, which have lower turn delays at low flows.

It is concluded that topology, intersection types and capacities strongly interact. At lower urban densities and transport demand, right-of-way intersections and roundabouts are most efficient regarding generalized costs. At higher urban densities and transport demand, signals are more efficient regarding generalized costs. Again, topologies with high meshedness values contribute to lower costs and also higher reliability.

Moreover, gridirons are found to have generally low travel costs especially at high urban densities and travel demand. It is found that lower total road length, in combination with high capacities at intersections (signals) and roads achieve lower total travel costs, compared to higher total road length, but lower capacities. However, in the former case, capacities have to be high enough to avoid congestion. This can be observed already in larger cities, where traffic concentrates on designated axes. However, through and local traffic are often mixed which complicate evaluation in real world networks.

There is evidence that different modes with different speeds and turn delays require different network topologies. As stated above, automobiles require relatively high capacities at roads and intersections, and therefore have opposite needs than slower modes, such as pedestrians and bicycles. Pedestrians and bicycles have lower delays at intersections, especially relatively to the travel time on the links. They get around on denser networks with lower travel costs. It is found that elasticities $\frac{\delta c}{\delta l}\frac{\bar{l}}{\bar{c}}$ on user costs c in dependence on network density l are higher in networks without or with low intersection delays compared to networks with high turn delays.

Along this line, similarities can be found between the modeling results and historical developments of networks. The emergence of different major travel modes since the medieval times created different networks. This is due to the requirements of these major modes, especially capacity and speeds. In the medieval times pedestrians, the few horses and carriages needed less space and capacity on roads and especially on intersections, compared to the public transportation era around 1900 and especially the car age after 1950.

The modeling results of this thesis are compared with empirical data from different network types worldwide (e.g. Cardillo et al., 2006; Strano et al., 2012). It is remarkable that the theoretical findings complement the empirical data. As an example, high meshedness and specific efficiency measures depend on each other which is in line with empirical findings (e.g. Cardillo et al., 2006).

Exemplarily, different boulevard types are discussed as well as hierarchical road network design. New findings on the effect of both designs are determined, especially the effect of overall generalized costs, accessibility and external costs for boulevards. Detailed rules and application specifications are stated specifically for boulevard design. Both rules and specifications increase the overall understanding, and might improve future urban designs. Regarding the hierarchical road network design, it is found that a hierarchical network does not or only slightly reduce generalized costs, compared to other road type distributions depending on topologies. It seems that hierarchical network design would automatically evolve when optimizing the road type distribution.

Through traffic is very site-specific and is ignored in the above evaluations. Boulevards, which are also evaluated, are able to accomodate through traffic to a certain extent by adding additional capacity on the axis. In the boulevard evaluation, it is shown that any disruption of the through traffic affects overall traffic and increases overall travel costs. Especially the capacity of both the signals and roads have to be high enough on the through axis. Moreover, the often reduced number of crossing roads can create bottlenecks, especially in combination with signals and optimized phases. High capacities on both the through axis and and crossing roads are required.

9.4 Outlook

Further research is needed to increase the understanding of network design, and to overcome various issues in growing urban agglomerations. Potential future approaches are listed below.

- The conducted literature overview for shape grammars uncovered a large set of shape grammars originating from various fields. They might be not labeled as such, but still can be applied in planning. An overview and synchronisation of all grammars would generate a large and encompassing set of grammars for urban and transport planning. Therefore, a straightforward and cross-disciplinary notation is necessary to facilitate applications.
- Growth processes of urban agglomerations are ignored in this research. Even though different densities are evaluated, the transformation needs additional knowledge from a less dense to denser agglomerations, and vice versa.
- Transit networks and lines are addressed in the literature review, but not further considered in this research. Future research is required to address public transportation.
- Regarding the evaluation of rules, microsimulations and more detailed travel demand simulations are required for sensitivity, testing especially for signals.
- Advances in signal timing and demand assignment (macro and micro) would increase the detailed understanding and evaluation of urban networks.
- Transport networks and new transport technologies have co-evolved over time. For future evolution of technologies, it might be possible to define the most efficient networks

regarding the future developments and their characteristics. Therefore, adaption and recommendations can be made for these technologies.

In summary, network design remains a complex task. However, its contentious character can be reduced by increasing knowledge and extracting characteristics and rules for best practice in network design. Applications of shape grammar rules become more straightforward when applying previously evaluated shape grammar rules and when considering application specifications.

Chapter 10

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Appendix A

Technical Description of the Static Demand Assignment with Interrupted Flows

A.1 User Equilibrium (UE) Formulation Excluding Dependent Turn Delays

The standard user equilibrium (UE) is formulated below with the notations of Sheffi (1985) and Lee and Machemehl (2005). However, the problem description is only valid in the case of turn delays independent of any other flows $x_{i \neq a}$. This assumption is valid when e.g. the turn delays are constant or only depend on the flow considered. This assumption is not valid for more detailed turn delay calculations including semi-compatible movements at signal controlled intersections or turning movements at uncontrolled intersections..

$$\text{minimize} \quad z(x) = \sum_a \int_0^{x_a} t_a(\omega) d\omega \tag{A.1}$$

$$\text{subject to} \quad a = \sum_p \sum_q \sum_k X_k^{pq} \rho_{a,k}^{pq} \;\; \forall a \quad \Big\} \text{ Link flow definition.} \tag{A.2}$$

$$\sum_k X_k^{pq} = r_{pq} \quad \Big\} \text{ Flow conservation constraints.} \tag{A.3}$$

$$X_k^{pq} \geq 0 \quad \} \text{ For meaningful flow values.} \tag{A.4}$$

$$\text{whereas} \quad \frac{\partial t_a(x_a)}{\partial x_a} > 0 \;\; \forall a \quad \Big\} \text{ Costs are increasing with increasing } x_a. \tag{A.5}$$

$$\frac{\partial t_a(x_a)}{\partial x_b} = 0 \;\; \forall a \neq b \quad \Big\} \; t \text{ is independent of other link flows.} \tag{A.6}$$

x_a:	Flow on link a.
$t_a(\omega)$:	Performance function of link a.
X_k^{pq}:	Flow on path k connecting OD pair p-q.
$p,\ q$:	Origin and destination of demand matrix.
k:	Link path connecting origin p and destination q.
X_k^{pq}:	Flow on path k connecting OD pair p-q.
$\rho_{a,k}^{pq}$:	Indicator variable $\begin{cases} 1, & \text{if link } a \text{ is on path } k \text{ between OD pair } p\text{-}q, \\ 0 \text{ otherwise.} \end{cases}$
r_{pq}:	Demand between origin p and destination q.

The standard UE has a unique minimum if $t_a(\omega)$ is differentiable and therefore the Hessian is positive definite (Sheffi, 1985, p.66*f*). Additionally, one initial solution is required to guarantee that the problem is solvable at all.

The condition of a differentiable $t_a(\omega)$ is normally fulfilled in transportation applications due to the fact that most volume delay functions are differentiable. The BPR (U.S. Bureau of Public Roads, 1964) for example has the form $t_0 \cdot \left(1 + a \cdot \frac{q}{q_{max} \cdot c}\right)^b$ and therefore is differentiable.

The condition that $t_a(\omega)$ is independent of all other flows $\left(\frac{\partial t_a(x_a)}{\partial x_b} = 0\right)\ \forall a \neq b$ is valid in the standard UE without detailed turn delay calculations. This condition allows a simple reduction of the Hessian matrix to a diagonal matrix, with all non-diagonal values = 0 (Sheffi, 1985, p.67). Therefore, a unique minimum solution of the UE problem above exists and can be determined in an iterative manner, e.g. with a Frank and Wolfe Algorithm (Frank and Wolfe, 1956).

A.2 User Equilibrium (UE) Formulation including Turn Delays

The static assignment with intersection delays differs in theory from the static assignment without delays. In the case of detailed turn calculations, the time spent at intersections (turn delay) depends on some or all incoming flows form all other roads. Therefore, the case of dependent turn delays needs the following adaption in the objective function (notation of Sheffi, 1985, p.215):

$$\text{minimize} \quad z(\mathbf{x}) = \int_{\mathbf{0}}^{\mathbf{x}} \mathbf{t}(\boldsymbol{\omega}) d\boldsymbol{\omega} \tag{A.7}$$

subject to Eqs. (A.2) to (A.5)

The major changes to the UE formulation without turns are in the performance function $t_a(\boldsymbol{\omega})$ and in the absence of the constraint $\frac{\partial t_a(x_a)}{\partial x_b} = 0\ \forall a \neq b$ (Equation (A.6)). The absence of the constraint $\frac{\partial t_a(x_a)}{\partial x_b} = 0\ \forall a \neq b$ is due to the fact that turn delays depend on other link flows, e.g.

conflicting opposite flows.

The major consequence of the absence of Equation (A.6) is the more complicated calculation of the Hessian. The Hessian of the above function now has values for off-diagonal elements $\neq 0$. Therefore, it is unclear if the Hessian is still positive definite, as in the UE without turns, and it is unclear if a unique solution still exists for the above optimization problem. If the Hessian is not positive definite, the problem may not have a unique solution (Sheffi, 1985).

A.3 Convergence of the UE including Turn Delays

The problem description in Section A.2 can be simplified when it is assumed that all the **x** are known and fixed at a given iteration (Sheffi, 1985). The assumption does not fix all the values, just the relation to other links (off-diagonal values). This assumption leads to the following *subproblem* of the general problem above, but with identical constraints (Equation A.8).

$$\text{minimize} \quad z(x) = \sum_a \int_0^{x_a} t_a(x_1^n, ..., x_{a-1}^n, \omega, x_{a+1}^n, ..., x_A^n) d\omega \tag{A.8}$$

$$\text{subject to} \quad \text{Eqs. (A.2) to (A.5)}$$

Still it remains unclear, if an equilibrium state can be found. According to Sheffi (1985, p.216*ff*), an equilibrium flow pattern exists, if we can find a solution in iteration k, which holds $\mathbf{x}_a^{k+1} \simeq \mathbf{x}_a^k$. Then, $\mathbf{x}_a^k$ is the equilibrium flow to the optimization problem above. Therefore, we have to find a solution that holds $\mathbf{x}_a^{k+1} \simeq \mathbf{x}_a^k$, for all problems formulated in Appendix A.2.

The equilibrium state is approached using a *streamlined* algorithm (Sheffi, 1985, p.220*ff*). With this, the *subproblem* with fixed **x** is not solved until the convergence is reached sufficiently. It is sufficient to solve the subproblem in only one iteration and then to go back to the original problem (Figure A.1(a)). Further information about the streamlined algorithm can be found in e.g. Florian (1981) and Dafermos (1982).

A.4 Comments on the Frank and Wolfe Algorithm

The Frank and Wolfe algorithm (Frank and Wolfe, 1956) is used widely in transport modeling to solve the above UE formulation. It is applied here due to its tolerance regarding turn delays. Alternative methods exist (e.g. Bar-Gera, 2002), however, the Frank and Wolfe algorithm is sufficient and is fast enough for the required accuracy and network sizes in this thesis.

In this thesis, the golden section method (Sheffi, 1985, p.83) is implemented in the search algorithm to determine the loadings in the successive iteration. An advantage of the golden section method, compared to e.g. the bisection method, is the absence of the derivative of the objective function. The golden section method also was applied in e.g. Lee and Machemehl (2005). Complementary, various advanced search methods exist (Arrache and Ouafi, 2008; Mitradjieva and Lindberg, 2012).

A.5 Comments on the Relative Gap

The relative gap *rg* is based on the link flows and the relative difference to the best lower bound (definition in e.g. Boyce et al., 2004). Convergence is reached with $rg < \epsilon$, which means that $\mathbf{x}_a^{k+1} \simeq \mathbf{x}_a^k$ (Section A.3) for a small enough gap. ϵ is a value < 1.0 and needs to be fixed exogenously. Normally, $\epsilon = 0.1\%$ (e.g. in Boyce et al., 2004).

The *rg* measure is especially crucial since *rg* is able to indicate a stable solution of the UE formulation. However, the interpretation of *rg* requires more clarification, especially due to the different UE formulations. Ignoring turn delays, convex combination methods, such as the Frank and Wolfe method, guarantee to find a solution for the UE formulation arbitrarily close to the unique solution. In this case, *rg* is a measure to estimate the closeness to the unique solution.

The *rg* measure differs in its meaning in the case of detailed turn delays at intersections (Equation A.7). If convergence is not reached in these cases, the algorithm does not find an optimal solution for the UE formulation. Therefore, it is necessary to reach an optimum to ensure convergence. The Frank and Wolfe method is not able to guarantee an optimum anymore.

A.6 Signal Light Optimization in the UE Formulation

In this thesis, signal timing includes the adaption of green times of the phases and of the cycle time. Regarding the control of multiple signals within a network, the control can be coordinated in arterial intersection control, closed network control and area wide system control, e.g. green wave setting. Aiming at an integrated approach, signals and flows have to be both optimized simultaneously within a network.

In a straightforward approach, signal timing optimization alternates with traffic assignment. This approach seems reasonable at first glance (Figure A.1(b)). However, Smith (1979) and Dickson (1981) showed that this procedure is not guaranteed to converge. The core of the problem is the difference between the user equilibrium flow pattern and the system optimizing flow which minimized total turn delays (Sheffi and Powell, 1983). Sheffi and Powell (1983) state that the problem formulation, including signal timing, might not have a unique optimum.

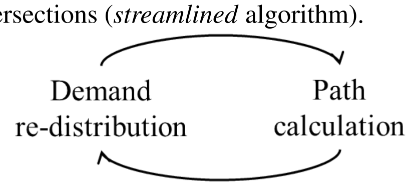
This is due to the lack of a continuously differentiable objective function. Therefore, even though if the solution algorithm converges, it possibly converges towards a local optimum.

However, Sheffi and Powell (1983) found that even though signal timing might differ between different algorithms, the total travel time over the network remains similar with the straightforward approach stated above. Sheffi and Powell (1983) also stated that a straightforward approach is especially suitable, if the system and user equilibrium is similar, e.g. for low traffic levels and for highly congested networks. Lee and Machemehl (2005) found out that the straightforward (streamlined) Frank and Wolfe algorithm, the two global search methods (GA, simulating), and the local search approaches perform differently with different network sizes and total demand. They recommend global search methods especially for variable cycle lengths.

In the following, the simultaneous signal and flow optimization is ignored due to complexity, high calculation time and uncertainty regarding the applied method. Therefore, system wide signal coordination is ignored. The calculations of green and cycle times are kept isolated from other signals in the network.

Figure A.1: Iterative approaches to solve the UE under different delay considerations.

(a) Procedure for UE formulations without turn delays, *right-of-way* and *roundabouts* controlled intersections (*streamlined* algorithm).



(b) Iterative procedure, most popular approach (Lee and Machemehl, 2005).

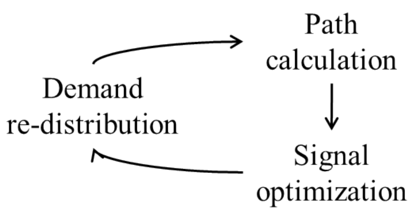
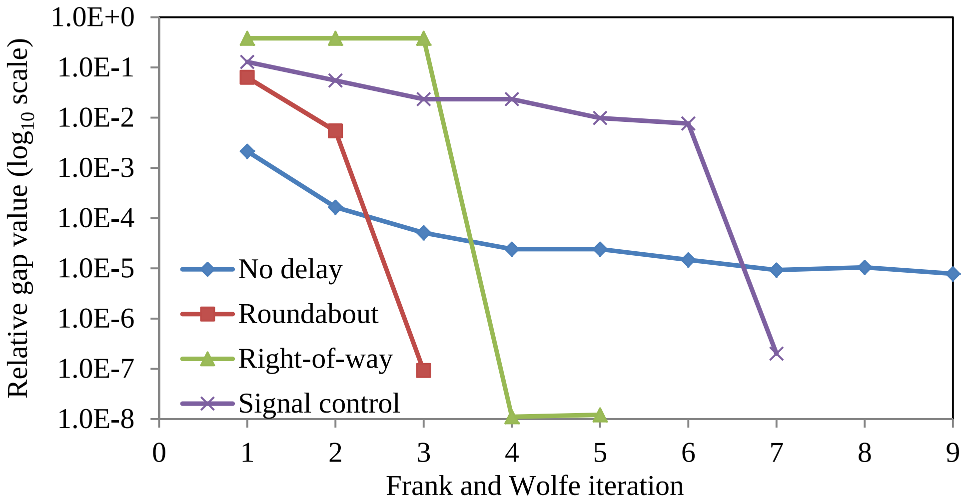


Figure A.2 shows the convergence of the average demand assigned in most of the experiments (see Section 3.4.2 for more details on the assumptions). All assignments converge in a reasonable time, especially when assuming a maximum relative gap of 0.001 for a convergence threshold (Boyce et al., 2004). Different settings with different network patterns and demand flows were calculated for verification, however, convergence could be reached in all the cases. Generally, a higher number of parallel streets increase the number of necessary convergence iterations, compared to a lower number of parallel streets.

Figure A.2: Convergence of the Frank and Wolfe Algorithm (Frank and Wolfe, 1956) for different intersection types and a given network design (Figure 6.5(b)).



Appendix B

Formula for Turn Delay Calculations Based on the HCM

The reader is referred to the HCM (Transportation Research Board, 2010) for all the details. A short discussion is provided in Vitins and Axhausen (2012a).

B.1 Right-of-way controlled intersections

The HCM refers to Brilon and Grossmann (1991) regarding the right-of-way controlled intersections.

The total conflict flow rate $v_{c,x}$ of a movement x is determined for all turns (Equation (B.1)):

$$v_{c,x} = \sum_i v_{c,i} \tag{B.1}$$

$v_{c,x}$: Conflicting flow rate of a movement x.
$v_{c,i}$: Flow rate of single movement i, which is in conflict with movement x.

The potential capacity $c_{p,x}$ of movement x is calculated as shown in Equation (B.2).

$$c_{p,x} = v_{c,x} \cdot \frac{e^{-v_{c,x} t_{c,x}/3600}}{1 - e^{-v_{c,x} t_{f,x}/3600}} \tag{B.2}$$

$v_{c,x}$: Sum of all conflicting flow rates for movement x.
$t_{c,x}$: Critical headway for minor movement x, based on observations.
$t_{f,x}$: Follow-up headway for minor movement x, based on observations.

The potential capacity $c_{p,x}$ is corrected for each road type and rank according to the flows of the other movements, resulting in $c_{m,j}$ (Table B.1).

Table B.1: Calculation of $c_{m,j}$ depending on the turn movement.

Turn movement	$c_{m,j} =$
Major street left turn	$c_{p,j}$
Minor street right turn movement	$c_{p,j}$
Major street left turn	$c_{p,j} \cdot p^*_{0,j} = c_{p,j} \cdot \left[1 - \frac{1-p_{0,j}}{1-x_{i,1+2}}\right]$ with $p_{0,j} = 1 - \frac{v_j}{c_{m,j}}$
Minor left turn movement	$c_{m,j} = c_{p,j} p' p_{0,j}.$ with $p' = 0.65p'' - p''/(p''+3) + 0.6 \cdot \sqrt{p''}$ and $p'' = p_{0,j} p_{0,k}.$

The delay calculations of right-of-way controlled intersections are subdivided in four turn movements (Transportation Research Board, 2010, p.19-7):

- Rank 1 turn movements include through traffic and right-turning traffic approaching on major streets.
- Rank 2 movements include left- and U-turning traffic approaching on major streets, and right turning traffic onto major streets.
- Rank 3 movements include through traffic approaching on minor streets, and left-turning traffic approaching on minor streets (at T-junctions).
- Rank 4 movements include left-turning traffic approaching on minor streets, only at 4 leg intersection.

The delay d_1 for any movement of rank 1 is calculated as shown in Equation (B.3) (Transportation Research Board (2010) p. 19-28).

$$d_1 = \begin{cases} \left(1 - p^*_{0,1}\right) \cdot d_{M,LT} & \text{if } N = 1, \\ \dfrac{\left(1 - p^*_{0,j}\right) d_{M,LT} \left(\dfrac{v_{i,1}}{N}\right)}{v_{i,1} + v_{i,2}} & \text{if } N > 1. \end{cases} \tag{B.3}$$

$p^*_{0,1}$: Proportion of rank 1 vehicles not blocked.
$d_{M,LT}$: Delay due to major left-turning vehicles.
N: Number of through lanes per direction on the major street.
$v_{i,1}$: Major-street through vehicles in shared lane [veh/h].
$v_{i,2}$: Major-street turning vehicles in shared lane [veh/h].

The delay d_{2-4} for rank 2 to 4 movements is calculated as shown in Equation (B.4), number of left turning lanes is one in all calculations in this thesis:

$$d_{2-4} = \frac{3'600}{c_{m,x}} + 900 \cdot T \cdot \left[\frac{v_x}{c_{m,x}} - 1 + \sqrt{\left(\frac{v_x}{c_{m,x}} - 1 \right)^2 + \frac{\frac{3600}{c_{m,x}} \frac{v_x}{c_{m,x}}}{450T}} \right] + 5 \tag{B.4}$$

v_x: Flow rate for movement x.
$c_{m,x}$: Capacity of movement x.
T: Analysis time period [h].

B.2 Signal Controlled Intersections

Four phases are modeled for all calculations. The turn delays d of signalized intersections are based on the general formula (Equation (B.5)):

$$d = \frac{0.5 \cdot C \cdot (1 - g/C)^2}{1 - [min(1, X) \cdot g/C]} \quad + 900 \cdot T \cdot \left[(X_A - 1) + \sqrt{(X_A - 1)^2 + \frac{8kIX_A}{c_A T}} \right] \tag{B.5}$$

d_1: Uniform delay.
C: Cycle length, sum of green times, yellow and red clearance.
g: Green time.
X: Volume to capacity ratio $\left(= \frac{v}{N \cdot s \cdot \frac{g}{C}}\right)$.
v: Volume of incoming lane.
N: Number of lanes.
s: Saturation flow rate [veh./h/lane].
T: Analysis period duration.
X_A: Average volume to capacity ratio.
k: Incremental delay factor.
I: Upstream filtering adjustment factor (= 1 for isolated intersection).
c_A: Average capacity.

Signal controlled intersections can have many different characteristics and parameter settings. The parameters green time and cycle length play a crucial role in the delay calculations of signal lights. The HCM proposes commercial software for certain signal light settings and parameter determination. One of the few strategies, which can be applied without excessive calculations, is based on the volume-to-capacity ratio for critical lane groups (Transportation Research Board, 2010, p. 31-37). This strategy allocates the green time in proportion to the flow ratio of the critical lane group for each phase. Other strategies are known for calculation of green and cycle time. They optimize total delay of all vehicles, or equalize the level of service for all critical lane groups (Transportation Research Board, 2010, p. 31-37). However, they require a more complex delay calculation, which is available mostly in commercial software products. The implemented four phase approach accounts for conflicting opposite flows. The reduced capacity due to the conflicting opposite flows are calculated according to the HCM.

B.3 Roundabouts

The formula for delay calculations in roundabouts is similar to the delay calculations in right-of-way intersections, but is adjusting the yield (Transportation Research Board, 2010, p.21-1). The total delay d is calculated as shown in Equation (B.6) (Transportation Research Board (2010) p. 21-19):

$$d = \frac{3'600}{c_e} + 900 \cdot T \cdot \left[x - 1 + \sqrt{(x-1)^2 + \frac{\frac{3'600}{c_e} x}{450T}} \right] + 5min[x, 1] \tag{B.6}$$

d: Average control delay.

x: Volume capacity ratio of subject lane.

T: Analysis period duration.

c_e: Capacity of subject lane, $\left(= 1130 \cdot e^{f \cdot 10^3 \cdot v_c}\right)$.

f: Correction factor for number of circulating lanes.

v_c: Volume of conflicting circulating traffic.

Appendix C

Structure and Examples of the Simulation Platform

All algorithms for the transport model and the IACGA were implemented in the Java environment (ORACLE, 2014). A few Java software packages were additionally applied for the research conducted (Kronfelder et al., 2010; Apache Commons, 2013; Eclipse, 2014).

The package structure of the simulation platform can be found in Table C.1. The junit tests have a similar structure. Currently, the project is available at the local IVT server:
repos.ivt.ethz.ch/svn/IVT/src/network_generation

Within the ETH Sustainability Summer School (ETH, 2013), the students had access to the simulation platform. Students especially applied the assignment algorithms including turn delays for evaluation purposes. However, they were also able to run shape grammar rules and optimization algorithms. A user interface was designed especially for the Summer School to facilitate the application and reduce programming burdens. An example of the study area of the Summer School is shown in Figure C.1.

Ryser (2013) elaborated in his report on the accessibility of the bicycle network in Zurich. Within his work he used the algorithms and shape file importer of the simulation platform to evaluate the bike network of Zurich. Figure C.2 shows an example map of the bicycle accessibility.

Table C.1: Package structure of the simulation platform.

Package name	Description
analysis	Methods for various evaluations
assignment	Assignment methods including Frank and Wolfe and Dijkstra
demand	Demand matrix methods
grammars	Network design grammar methods
gui	User interface and visualisation
land use	Land use experiments, including parcels
lib	Library of universal and mainly static classes
network	Network related classes, including intersection delays
spatialAlignment	Spatial redesign experiments
tournament_and_merging	IACGA and GA methods
util	Shape file related and statistical evaluation methods
xml	Import and export methods

Figure C.1: The Singapore case study area for the ETH Sustainability Summer School 2013.

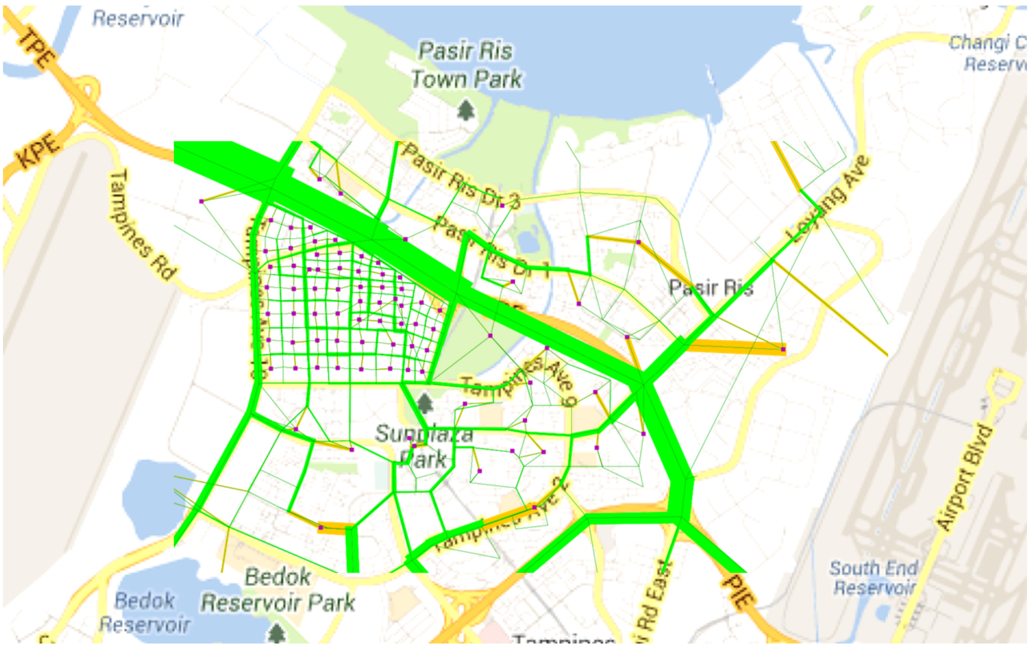
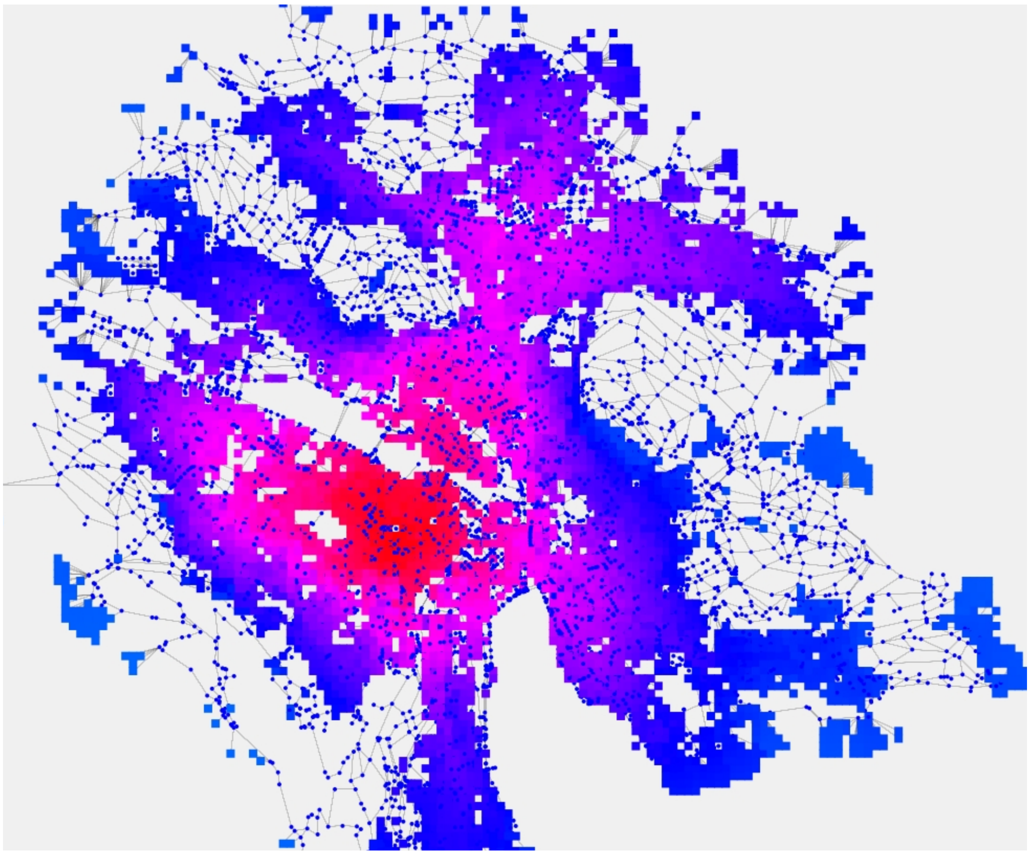


Figure C.2: Bicycle accessibility calculated and visualized for the city of Zurich.



Publication List for the Period of the Dissertation

Vitins, B. J. and K. W. Axhausen (2010) Patterns and grammars for transport network generation, paper presented at the *10th Swiss Transport Research Conference*, Ascona, September 2010.

Vitins, B. J., V. Killer, N. Braun and M. Gmünder (2010) Agglomerationsdefinition Schweiz - Überprüfung der Machbarkeit einer von Pendlerdaten unabhängigen Methode, *Final Report*, Swiss Federal Statistical Office (BFS), ETH Zurich and B,S,S. Economic Consultants, Neuchatel.

Killer, V., B. J. Vitins, N. Braun and M. Gmünder (2010) Agglomerationsdefinition Schweiz - Vertiefte Abklärung der Eignung von Erreichbarkeitsdaten als Substitut für die Pendlerdaten im Rahmen einer Agglomerationsdefinition für die Schweiz, *Final Report*, Swiss Federal Statistical Office (BFS), ETH Zurich and B,S,S. Economic Consultants, Neuchatel.

Vitins, B. J., N. Schüssler and K. W. Axhausen (2011a) Comparison of hierarchical network design shape grammars for roads and intersections, paper presented at the *European Transport Conference*, Glasgow, October 2011.

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Hackney, J. K., B. J. Vitins and B. R. Bodenmann (2013) Market-Clearing Models in FaLC, paper presented at the *13th Swiss Transport Research Conference*, Ascona, April 2013.

Vitins, B. J. and K. W. Axhausen (2014) Shape grammars in transport and urban design, paper presented at the *World Symposium on Transport and Land Use Research*, Delft, June 2014.

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