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space against the machine

Understanding spatial relationships through geocomputation

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Professional environment

The author of this dissertation has been employed as a PhD research fellow at the Department of Computer Science, Electrical Engineering (Institutt for datateknologi, elektroteknologi og realfag (IDER)) at the Western Norway University of Applied Sciences (Høgskulen på Vestlandet (HVL)) and is enrolled in the PhD program Computer Science: Software Engineering, Sensor Networks and Engineering Computing at HVL.

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Scientific oath

I, Remco de Koning, acknowledge that I am a part of an international community of researchers. I will practice my activities in line with the recognised standards for good research practice. I shall conduct my research honestly, truthfully and factually and show respect for humans, animals, and nature. I shall use my knowledge and skills to the best of my judgement for the good of humanity. I shall not allow interests based on ideology, religion, ethnicity, prejudice, or material advantages to overshadow my ethical responsibility as a researcher.

Acknowledgements

It was a rainy Tuesday evening in the fall of 2013. I was visiting my favourite bar in Delft to listen to the weekly live jazz jam session when I ran into my former university teacher Akkie van Nes. She had just obtained a position as full professor at Høgskolen i Bergen in Norway and was looking for someone who could help at the growing department of Civil Engineering. Moreover, she would need a full-time PhD-candidate if the research project she was applying for would be granted. I had graduated the year before and had been unable to find a decent job in my field. I did not hesitate and signed up for Norwegian classes at the Norske Sjømannskirken in Rotterdam that same week. That seemingly accidental encounter turned out to be a life-changing event: I emigrated on January 4th, 2016. I express my deepest gratitude to you for enabling me to start a new life in Norway. You are not only a great colleague, professor and supervisor, but a close friend.

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This dissertation is dedicated to you and anybody I did not personally mention such as relatives and friends, roommates and PhD fellows, co-authors and consortium partners, coordinators and assistants, and others I collaborated with. Tusen takk!

Prologue

I have always been fascinated with human civilisation and cities as a pinnacle of human achievement over time in particular. I played with LEGO as a kid and liked to draw fictional city plans on large pieces of paper. My video games of choice as a teenager were city builder simulations. I studied at the faculty of Architecture at Delft Technical University where I learned that indeed my interest lay not in the building scale but in the larger context. The graduation track Spatial Planning and Strategy at the department of Urbanism allowed me to pursue my passion to understand why the built environment looks the way it does, how it works and how to improve it given the fact it does not perform very well with regards to sustainability indicators. Although the technological advances now known as 'smart' solutions looked promising to me, too, I learned over time that their contribution to flattening the curve on the consumption of raw materials, space and energy would be limited to using machines to gain knowledge. This became the starting point of my doctoral studies.

The title of this dissertation reflects the interplay between efforts to spatially model the third-dimensional world on steadily more advanced computing machines and the limitations and trade-offs inherent therein. It is also a tribute to Bill Hillier's 1996 book *Space is the machine*, a seminal work on spatial theory and human behaviour. Furthermore, the title is a metaphor for the conflict between civil liberties and institutionalised technocracy, which envisions space – and human society – as a machine, and accordingly attempts progressively to coerce human society. Finally, it refers to the automobile (*macchina* in Italian) in public space, which this dissertation investigates, and, of course, to one of the most influential bands of the 1990s.

Sammendrag

For å oppnå bærekraftig utvikling kreves det bedre, bevisbasert støtte for hvordan byer fungerer og hvordan man kan bruke eksisterende data for å planlegge dem bedre. Denne avhandlingen foreslår nye tilnærmingsmåter for identifisering av de komplekse sosio-romlige relasjonene mellom bystrukturer og -former i forhold til fortettingsmønstre og transportenergibruk ved bruk av romlig analyse. Avhandlingen foreslår innovative metoder for å analysere komplekse, store digitale datasett og arbeidsflyter for å fremme brukervennlig tilgang til passende geodataprogrammeringsverktøy.

Teorier om romlige strukturer og urban morfologi kombineres for å sammenligne bystrukturer og -former, bygningstetthet, arealbruksblanding og transportenergibruk i to middelsstørre byer, Bergen i Norge og Zürich i Sweits. Forskningen analyserer hvordan bevegelsesmønstre, bygningstetthet og funksjonsblanding påvirkes av den romlige konfigureringen av nettverket av rom, det vil si hvordan veier, gater og plasser forholder seg til hverandre. Funnene tyder på en korrelasjon mellom romlig konfigurasjon, bygningstetthet og arealbruksmønstre, og mellom energieffektivitet i transport og områder med høyere tetthet. Den nye metoden for romlig analyse ved bruk av Space Syntax på en GIS platform gir diagnostiske innsikter i hvordan bærekraftige og rettferdige byer kan realiseres.

Denne avhandlingen bidrar med i) ny data av romlige sammenhenger på makroskala og mikroskala; ii) en systematisk evaluering og forståelse av byer i ulike kontekster; og iii) automatisert arbeidsflyt for geodataprogrammering for innsamling, forberedelse og sammenligning av romlige data, for å demonstrere hvordan grafiske datamodeller kan bistå fagfolk og beslutningstakere innen stedsplanlegging uten omfattende dataferdigheter. Det er allikevel viktig å være klar over begrensningene ved overdreven tillit til digitale modeller kontra den ekte verden. Fornuftige tolkninger av innsiktene ovenfor kan gi nyttig støtte for overvåking og evaluering i planleggings-, design- og politiske prosesser.

Abstract

Achieving sustainable development requires better evidence-based support for how cities work and how people could use existing data to better plan cities. This dissertation proposes novel approaches for the identification of the complex socio-spatial relationships of urban structures and forms in relation to densification patterns and transport energy usage using spatial analysis. The dissertation proposes innovative methods to analyse complex and large digital datasets, and workflows to improve user-friendly access to appropriate geocomputational software tools.

Theories on spatial structures and urban morphology are combined to compare structures, forms, building density, land use mix and transport energy usage in two medium-sized cities, Bergen, Norway and Zürich, Switzerland. The research analyses how movement patterns, building density and land use mix are affected by the spatial configuration of the network of spaces, i.e. how roads, streets, and squares relate to each other. Findings indicate a correlation between spatial configuration, building density and land use patterns, and between transport energy usage efficiency and higher density areas. The novel method of spatial analysis with Space Syntax on a GIS platform allows diagnostic insights into how sustainable and equitable cities can be realised.

The dissertation contributes i) new data of spatial relationships on the macroscale and the microscale; ii) a systematic evaluation and understanding of cities across different contexts; and iii) automated geocomputational workflow for collecting, preparing and comparing spatial data, to demonstrate how graphical computer models can aid spatial planning professionals and decision-makers without extensive computer skills. Nonetheless, it is important to be aware of the limitations of overreliance on digital models versus the real world. Sensible translations of the above insights can provide useful support for monitoring and evaluation in planning, design and policymaking processes.

Samenvatting

Om duurzame ontwikkeling te bereiken is betere, op feiten gebaseerde kennis vereist over hoe steden functioneren en hoe mensen bestaande data kunnen gebruiken om deze beter te plannen. Dit proefschrift stelt nieuwe aanpakken voor om door middel van ruimtelijke analyse de complexe socio-ruimtelijke relaties van stadsstructuren en -vormen te identificeren in relatie tot verdichtingspatronen en transportenergieverbruik. Er worden innovatieve metoden voorgesteld om complexe, grote digitale datasets te analyseren, en workflows om toegang tot geschikte geocomputationele softwaretools te verbeteren.

Theorieën over ruimtelijke structuren en stedelijke morfologie worden gecombineerd om structuren, vormen, bebouwingsdichtheden, functiemix en transportenergieverbruik te vergelijken in twee middelgrote steden, Bergen in Noorwegen en Zürich in Zwitserland. In het onderzoek wordt geanalyseerd hoe bewegingspatronen, bebouwingsdichtheid en functiemix beïnvloed worden door de ruimtelijke configuratie van het netwerk van ruimtes, dat wil zeggen hoe wegen, straten en pleinen zich tot elkaar verhouden. De bevindingen wijzen op een correlatie tussen ruimtelijke configuratie, dichtheid en gebruikspatronen, en tussen de efficiëntie van het energieverbruik van vervoer en dichter bebouwde gebieden. De nieuwe ruimtelijke analysemetode met Space Syntax op een GIS-platform geeft diagnostische inzichten in hoe duurzame en rechtvaardige steden kunnen worden gerealiseerd.

Dit proefschrift draagt bij met i) nieuwe gegevens over ruimtelijke relaties op macroschaal en microschaal; ii) een systematische evaluatie en kennis van nederzettingen in verschillende contexten; en iii) een geautomatiseerde geocomputationele workflow om ruimtelijke data te verzamelen, prepareren en vergelijken, om te demonstreren hoe grafische computermodellen planologen en besluitvormers zonder uitgebreide computervaardigheden kunnen helpen. Desalniettemin is het belangrijk zich bewust te zijn van de beperkingen van digitale modellen ten opzichte van de echte wereld. Zinnige interpretaties van de bovengenoemde inzichten kunnen helpen plannings-, ontwerp- en beleidsvormingsprocessen te monitoren en evalueren.

List of publications

Publications used in this thesis:

Paper A1:

de Koning, R. E., Roald, H. J. & van Nes, A. (2020a): A Scientific Approach to the Densification Debate in Bergen Centre in Norway. Sustainability, Vol. 12:21, 9178. Available at: https://doi.org/10.3390/su12219178

Paper B1:

de Koning, R. E., Tan, W. G. Z. & van Nes, A. (2020b): Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities. Sustainability, Vol. 12:19, 8146. Available at: https://doi.org/10.3390/su12198146

Paper B2:

de Koning, R. E., van Nes, A., Roald, H. J. & Ye, Y. (2017): Strategies for integrated densification with urban qualities. Combining Space Syntax with building density, land use, public transport and property rights in Bergen city. *In:* HEITOR, T., SERRA, M., SILVA, J. P., BACHAREL, M. & CANNAS DA SILVA, L., eds. Proceedings of the 11^{th} International Space Syntax Symposium, 3^{rd} - 7^{th} July, Lisbon, Portugal: Instituto Superior Técnico, Departamento de Engenharia Civil, Arquitetura e Georrecursos, #56, 863-879. Available at: http://www.11ssslisbon.pt/docs/proceedings/papers/56.pdf

Paper C1:

de Koning, R. E., Heldal, R. & Tan, W. G. Z. (2022): Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: the cases of Bergen, Norway, and Zürich, Switzerland. Data in Brief, Vol. 42:108290. Available at: https://doi.org/10.1016/j.dib.2022.108290

Other publications:

de Koning, R. E. & van Nes, A. (2017): "Mind the Mindemyren": a new spatial analysis tool for linking building densification strategies to public transport and street network accessibility in Bergen city in Norway. In: ANTUNES FERREIRA, J., SIMÕES, J. M., SOFIA, M., MARQUES DA COSTA, E., CABRAL, J., LOUPA RAMOS, I., BATISTA E SILVA, J. & BAPTISTA-BASTOS, M., eds. AESOP Annual Conference, 11th - 14th July, Lisbon, Lisbon: AESOP, 2246-2255. Available at: https://www.researchgate.net/publication/318826912_Mind_the_Mindemyren_A_new_spatial_analysis_tool_for_linking_building_densification_strategies_to_public_transport_and_street_network_accessibility_in_Bergen_city_in_Norway

de Koning, R. E. & van Nes, A. (2018): Morphological analysis of settlements in the Arctic: a comparative analysis of four settlements with diverging ideologies on Svalbard. ISUF 2018 XXV International conference: Urban Form and Social Context: from traditions to newest demands, 4-11 July 2018, Krasnoyarsk: Siberian University. Available at: http://resolver.tudelft.nl/uuid:9c1bb2b4-040b-4bce-8eb2-23e72a07e219

de Koning, R. E. & van Nes, A. (2019a): How two divergent ideologies impact the location of functions in relation to spatial integration in Arctic settlements: Space Syntax analyses of settlements closest to the North Pole. Proceedings of the 12th International Space Syntax Symposium, 8th - 13th July, Beijing, China, #405-2. Available at: http://www.12sssbeijing.com/upload/file/1562662202.pdf

de Koning, R. E. & van Nes, A. (2019b): Urban Space and Energy Usage. 12th International Space Syntax Symposium, 2019-07-08 - 2019-07-13, Peking. Available at: http://www.12sssbeijing.com/upload/file/1562661198.pdf

Maiullari, D., Romero, M. M., de Koning, R. E., van Timmeren, A., van Nes, A. & Schlueter, A. (2019): SPACERGY: Space-Energy Patterns for Smart Energy Infrastructures, Community Reciprocities and Related Governance. TU-Delft. https://hdl.handle.net/11250/2641879

Roald, H. J. & de Koning, R. E. (2019): A knowledge driven approach to urban transformation: Densification strategy of Bergen, Norway. AESOP annual congress 2019, 2019-07-09 - 2019-07-13, Venezia. Available at: http://hdl.handle.net/11250/2620269

List of figures and tables

List of abbreviations

Abbreviation	Meaning
AADT	Annual Average Daily Traffic
AI	Artificial Intelligence
DSR	Design Science Research
DUS	Daily Urban System
EC	European Commission
FSI	Floor Space Index
GIS	Geographical Information System
GSI	Ground Space Index
GUI	Graphical User Interface
HCI	Human-Computer Interaction
IT	Internet Things
LCNC	Low-code-no-code
LiDAR	Light Detection and Ranging
MAUP	Modifiable Areal Unit Problem
MATSim	Multi-Agent Transport Simulation
ML	Machine Learning
MXI	Mixed-Use Index
OSR	Open Space Ratio
OSM	OpenStreetMap
PSS	Planning Support System
RCL	Road Centre Line
SDG	Sustainable Development Goal
SST	Space Syntax Toolkit
SVV	Statens Vegvesen (The Norwegian Public Roads Administration)
UES	Urban Ecosystem Service
VGA	Visibility Graph Analysis

Contents

Part I: Introduction

Non scholae sed vitae discimus

1. Introduction

The domain of urban planning and design is concerned with the question of how cities should be organised. To answer this question, new insights are needed into how cities work. This dissertation aims to provide insights into understanding cities through its spatial structures and forms as the driving force for a variety of social and (socio)economic phenomena. Specifically, the dissertation seeks to understand how the spatial properties of the built environment influence the distribution of building densities and land uses (understood as non-residential functions for commerce or public service) and generate patterns of movement (people travelling from an origin to a destination) between these land uses. These phenomena are expressed through spatial relationships. A spatial relationship specifies how some physical object (e.g. a building) or non-physical phenomenon (e.g. an activity) is located in space in relation to some reference object. Such relationships can be made explicit by analysing their spatial configuration with software tools for processing spatial information. This dissertation proposes an approach for identification of the above spatial relationships between structure, form, building density, land use mix, and movement patterns. The approach builds upon theories of urban structures and urban morphology aided by appropriate geographical information processing software, i.e. the process of geocomputation: “the art and science of solving complex spatial problems with computers” (de Smith *et al.*, 2007, p. 383). The aim of this approach is to improve spatial analysis in Geographical Information Systems (GIS) by building executable models with the use of a Visual Programming Language (VPL), a software program that lets users manipulate elements graphically rather than through text. Moreover, this dissertation demonstrates the ability to use open-source data to conduct spatial analysis. The models will help in aligning data inputs and analytical processes for gaining insights into relations between spatial structure, movement patterns and socio-economic activity in cities. The research is done by comparing the cities of Bergen, Norway, and Zürich, Switzerland. The choice of focusing on these cities is justified by the fact that they offer insights into spatial relationships through a variation in social activities and energy and mobility infrastructure. This dissertation proposes that understanding spatial relationships through spatial analysis via geocomputational software tools can generate better insights into how sustainable development can be met, and what the consequences are for spatial planning research, policy and practice (Jiang and Claramunt, 2002).

In this dissertation, the main research question is:

Which spatial relationships, as expressed through densification patterns and transport energy networks, are identified through spatial configuration analyses with software tools for geocomputation?

To reach a greater understanding of how these phenomena take place given certain spatial conditions and how socio-economic and transport patterns function in cities, two expressions of spatial relations will be examined, namely i) its densification patterns and ii) its transport and energy networks. This will be explored by applying spatial analysis methods to spatially expressed data via geocomputational software.

1.1. Scope of research

This dissertation will explore how urban structures and spatial relations in cities contribute to influence the distribution of density of the built mass and land uses, and how it affects the way people use these structures regarding mobility and activity patterns. The field of research that concerns itself with this subject is urban design and planning. Spatial analysis research relies on handling increasingly complex, large datasets. The degree to which this information can be successfully processed and meaningfully interpreted thus plays a key role in the degree to which knowledge can be gained. Most of this information is in the form of digital data, which ordinarily requires a certain level of skills and expertise in programming to process. The younger generation of urban design and planning experts have been taught basic spatial analysis and programs during their university education, but most are not commonly trained in programming. More advanced, specialised skills are often obtained through "real-world project experience" in the industry, not in academia (Radermacher *et al.*, 2014, p. 299). However, business organisations that employ technically skilled data scientists experience gaps in managers' domain knowledge of data technologies for interpreting outcomes and understanding how the technology can be used to gain new insights or a competitive edge (Mikalef and Krogstie, 2019). Therefore, user-friendly access to appropriate and intuitive geocomputational software tools for handling spatial data is invaluable both to industry and non-industry researchers.

The field of urban design and planning has developed in several directions in terms of how the city is studied and knowledge is gained. This ranges from considering the city as a collection of (architectural) artefacts to the analysis of urban form, networks, and more recently, various spatial characteristics. **This dissertation seeks to provide insights into how specific spatial relationships in cities function.**

1.2. Understanding spatial relationships

In this dissertation, a spatial relationship is understood as a connection between two or more physical (e.g. objects, geometries) or non-physical (e.g. flows, processes) phenomena with a reference to the physical, third-dimensional world. Through geocomputational modelling and comparing these phenomena, patterns and consistencies can be identified as to whether and how these relate to each other spatially. This can provide evidence for the effect one phenomenon has on the other such as the distribution of built mass and land uses in relation to the spatial layout of the street network (Ye and van Nes, 2014). The field of urban design and planning seeks to increase the understanding of how cities function with respect to densification patterns, transport and mobility, urban metabolism (a framework for studying flows of materials and energy infrastructure) (Zhang, 2013), and economic and social aspects to name a few. This knowledge is considered paramount for designers, policy makers and citizens to make informed, evidence-based decisions about their environment. The modern origins of gaining knowledge of cities can be traced back to the 19th century when cities became an object of study in various disciplines. The most noteworthy contributions of the time are Cerdà's 1859 plan for the expansion of Barcelona and his 1867 text 'The general theory of urbanisation', which revolutionised how cities are analysed and planned as systems and networks of "...streets, buildings and people" (Neuman, 2011, p. 118, 125; Pafka *et al.*, 2020; Soria Y Puig, 1995); the German human-geographical classifications of cities based on the plans that have shaped it (de Oliveira, 2016, p. 157-160); and Sitte's book 'City planning according to artistic principles' in which he set out his urban design principles based on studies of pre-industrial cities (1889). These works inspired new generations of scholars to study cities systematically and to focus on theory building in architecture and urbanism (Moudon, 1997). However, most approaches in the field of architecture and urbanism of the 20th century were fuelled by utopian ideals of how the 'ideal' city should be organised spatially and socially, considering the city as a machine (Le Corbusier, 2007; Mumford, 2002). Urban design and planning became focused on organising and separating functions within a city. Many architects used geometric forms to design the built mass and organise the distribution of places for working, dwelling and leisure (Hall, 2014; Hanson, 1989b; Hillier, 2009).

At that point in history, there had been a lack of empirical support for describing how urban areas function in reality, rather than relying on intuition or past examples to predict how they *should* work. This marked the start of urban morphology developing from the Chicago school neighbourhood classifications based on socio-economic properties in the 1920s and '30s (Burgess, 1925; Hoyt, 2000). Leading scholars from the United Kingdom (Conzen, 1960; Whitehand, 1981), France (Panerai *et al.*, 2004) and Italy (Caniggia, 1976; Caniggia and Maffei, 2001; Muratori, 1960; Rossi, 1984) started to develop descriptive research methods in the '50s to understand how the continuous urban transformation of cities took place based on societal changes throughout history. These scholars conducted systematic research and developed frameworks for identifying and classifying the physical elements of cities. This yielded various classification systems of these elements on various levels of scale (van Nes and Yamu, 2021a) (see Section 2.1 for more detail). Cullen's visual analysis of the 'townscape' (1961) typifies this era of understanding cities.

From the 1970s, Hillier and his colleagues at the University College London started to develop a new conceptual framework for investigating relationships between society and space. In contrast to the various schools of urban morphology, the Space Syntax approach focuses on the spatial relationships of the urban spaces shaped by the urban artefacts (van Nes and Yamu, 2021a) to "...arrive at spatial descriptions of buildings and cities with the minimum intervention of linguistic concepts" (Hillier, 2009, p. K01:01). Whereas urban form approaches normally give "...a simple functionalist or economic explanation" (de Oliveira, 2016, p. 156) of urban phenomena, Hillier and Hanson (Hillier and Hanson, 1984) argued that a descriptive approach to studying spatial relationships in urban areas would enable "...the consideration of a wider morphological variety to reflect the different relationships between space and society" (de Oliveira, 2016, p. 173). This dissertation recognises that to gain a better understanding of spatial relationships in cities, it is necessary and justified to combine the urban-morphological approach, which studies urban form, with the spatial-relational approach, which studies urban structure.

Most planning authorities in cities aim to develop the territories under their jurisdiction to provide inclusive, healthy, safe and enjoyable spaces that promote prosperity, well-being and self-fulfilment for both current and future generations without causing conflict, disease and suffering or exhausting nature and natural resources (Meadows *et al.*, 1972; United Nations, 1992, 2015, 2017). Regarding space and energy as finite resources, this dissertation supports these aims by focusing on the study of urban structure through spatial theories and methods to identify spatial relationships as expressed through densification patterns and transport energy usage. Space Syntax offers powerful methods for explaining various spatial phenomena since it focuses on the relationships between built form and function rather than the shapes and patterns of urban space (Hillier, 2014). Therefore, no specific meaning or value is associated with these properties. These merely describe how each space relates to all others within a system. As such, natural movement is argued as "...the raîson d'être of the urban grid itself" (Hillier *et al.*, 1993, p. 32) and a direct result of social and economic activity.

Through the theories of spatial combinatorics (Hillier, 1996, p. 216-261), natural movement (Hillier et al., 1993) and natural urban transformation (Ye and van Nes, 2014), various spatial relationships can be explained. The theories provide accurate descriptions of how densification patterns, mobility choices and social behaviour are highly influenced by the spatial structures in which these phenomena take place. Movement patterns, both pedestrian (Hillier et al., 1998; Hillier et al., 1993) and vehicular (Penn et al., 1998; Serra and Hillier, 2017, 2019), are demonstrably linked to configuration. Hence, this dissertation will explore how transport energy usage also may be influenced by spatial configuration of the street and road networks. There is a prevailing assumption that areas with higher building and land use density, such as compact and densely populated urban areas, tend to have more concentrated energy use for transport, resulting in greater energy efficiency (see for example: Banister, 2007; Lefèvre, 2009; Newman and Kenworthy, 2006; Papa *et al.*, 2014; Silva *et al.*, 2018).

The Sustainable Development Goals (SDG) proposed at the 2015 UN climate summit in Paris address the issue of sustainable urban development (United Nations, 2017). Most nations and major cities worldwide have subsequently adopted climate policies that include the goal of making transport more sustainable (see for example: European Commission (EC), 2016; Regjeringen Solberg, 2017). This dissertation argues that to achieve sustainable communities, cities and their inhabitants must consider their spatial configurations in the context of ongoing urbanisation and growth in light of limited resources and conflicting spatial claims. The diverging approaches that emerged as a reaction to how to organise urban areas more sustainably such as 'post-modernism', 'smart urbanism', 'eco-urbanism' or 'new urbanism' (for a discussion, see: Jabareen, 2016), are reactionary to the rigid planning paradigm of modernism, which advocated prioritisation of the car, free-standing buildings in open space and strict segregation of functions (Le Corbusier, 2007). Modernist planning has led to segregated, anti-urban, sprawling cities with high transport energy usage per capita (Carmona, 2021, p. 5). Some of these urban areas now perform the poorest in terms of social, economic and environmental sustainability (Berge *et al.*, 2022; van Ham *et al.*, 2021; van Nes and López, 2013). As part of this increasing pressure on cities and the urgency to reconsider how to organise urban areas with respect to densification patterns and transport energy usage, efforts to increase the knowledge base on how to organise and manage the complex urban structures and processes in more sustainable ways are gaining dependency on efficiently processing substantial amounts of information.

Computer applications have become indispensable when it comes to handling spatial data and geo-information in the field of urban design and planning. A few examples of such applications are Google Earth (Google, 2021), Open Street Map (OSM) (2021), MapInfo (Precisely, 2021), ESRI® ArcGIS CityEngine (ESRI, 2021a) and Trimble eCognition (Trimble, 2021). Most organisations concerned with urban planning, administration, management and policymaking rely on more or less advanced data systems to perform their tasks. Likewise, research fields concerned with the study of urban areas depend on the extent to which data can be modelled and understood. The fundamental problem when analysing cities is the sheer complexity of the involved phenomena and processes and how to untangle the spatial relationships for insights from the data collected (Longley and Batty, 1996). As the digital age sees great progression in the amount, availability and operability of data, streamlining analytical processes to be feasible, operational and understandable becomes more challenging. Moreover, a systematic approach that can catch any suspected and unforeseen relations between the various data has its limits.

Here, this dissertation examines the methods and tools from geocomputation. Geocomputation is defined as "...a family of recently devised tools that make use of computational power to address problems in spatial analysis that resist attack by alternative means" (de Smith *et al.*, 2007, p. 383). Most geocomputation platforms offer VPLs for handling data (see for an overview: Dobesova, 2014). This enables domain-specific users that lack textual programming skills such as urban designers and planners to utilise software for their intended purposes. Moreover, VPLs allow them to design their own software through intuitive, (relatively) easy-to-use interfaces. The greatest benefit here is that domain experts are given access to the knowledge and expertise normally reserved to experts in the computer domain (Dobesova, 2014).

Through a deductive approach, this dissertation seeks to:

i) identify, evaluate and understand spatial relationships through a systematic approach that is comparable across different contexts; and
ii) apply software tools for geocomputation to improve spatial analysis for understanding spatial relationships.

1.3. The knowledge gaps

At present, there is little explicit understanding of the spatial relationships influenced by spatial configuration such as the connection with crime (van Nes and López, 2010), congestion, traffic accidents (Fwa, 2006, p. 4-6), the distribution of real estate prices (Law *et al.*, 2022; Law *et al.*, 2013; Law *et al.*, 2017; Ota *et al.*, 2021), allocation of development investments and the concentration of planning efforts to name a few. This is a result of a mismatch between sectors and disciplines (i.e. urban design and planning, traffic and transport engineering) (Marshall, 2005; van Nes, 2021; Neuman and Smith, 2010; Silva *et al.*, 2017, p. 348). Moreover, the available software tools to help make sense of the vast amount of data on this issue are not easily understood by a non-expert group of stakeholders (Dobesova, 2011; Mikalef and Krogstie, 2019; Russo *et al.*, 2018; Wästberg *et al.*, 2020).

An in-depth study of the state-of-the-art literature on the spatial properties of urban environments and its effects on densification patterns and energy usage for transport reveals that a sizable body of knowledge exists (see for example: De Pascali and Bagaini, 2019; Lefèvre, 2009; Næss, 1996; Nichols and Kockelman, 2015; Papa *et al.*, 2014; Silva *et al.*, 2017; Steemers, 2003). However, some writings lack a clear and unambiguous description of the interrelations between built environments, densification patterns and transport energy usage (Hillier, 1996, p. 2; Silva *et al.*, 2017). Næss' (1996) study on transport energy usage and urban form shows how studying urban form falls short in explaining socio-spatial urban phenomena. Although relationships are found between transport energy usage and selected 'urban form variables', the author is unable to conclude that "...the geometric shape of the towns has much influence on per capita energy usage" (Næss, 1996, p. 252). Most research confirm the classic Newman and Kenworthy study (1989) on how high-density environments, as found in many European and Asian cities, have lower fuel consumption per capita for transport than low-density environments, as commonly found in North American and Australian cities (Nichols and Kockelman, 2015; Papa *et al.*, 2014; Steemers, 2003). However, these studies do not make it clear why some spatial features of the built environment promote the use of one type of transport more than others. Likewise, there is a lack of understanding about which spatial features encourage the use of sustainable mobility means such as walking, cycling and public transport (Luta *et al.*, 2017). Thus, the spatial configurative aspects of the built environment are missing in the debate on energy usage for transport. There is therefore a need to understand how different spatial configurations affect densification patterns and transport energy usage as assessed through multiple scales, from the city and the region (henceforth, the macroscale) to the individual buildings, streets and neighbourhoods (henceforth, the microscale) (Nichols and Kockelman, 2015).

Understanding how spatial configurations affect densification and mobility patterns is key in designing urban environments that are more sustainable and liveable. Potential outcomes could include urban areas that are more compact than at present to sustain socio-economic activities by facilitating walking and cycling as natural choices of travel supported by an efficient public transport system. This would reduce the average space and energy consumption per capita as well as emissions for travel whilst ensuring safe access for all (United Nations, 2017).

There are different approaches to analysing urban areas ranging from qualitative observations, systematic classifications, to quantified statistical analysis depending on the scope of the study (Creswell, 2009). The above approaches have evolved through computer-aided spatial analysis. However, spatial analysis requires a high level of expertise, access to data and software, and the ability to interpret and translate the outputs (Longley and Batty, 1996; de Smith *et al.*, 2007; Ye and van Nes, 2014). Here, there is a need to understand which opportunities current geocomputational tools offer regarding spatial analysis as well as the limitations of the technology for wider usage within the field and by non-expert stakeholders. The classical problem of 'black boxes' in computational analytical models, where stakeholders – be they policymakers or citizens – have difficulties understanding the outputs of simulations and computational models of their reality, should be avoided (O'Sullivan and Unwin, 2003). After all, involving stakeholders early in the process and communicating the results of complex spatial data research in an understandable way is vital to the successful implementation of research in planning and development (Ataman and Tuncer, 2022). The challenge is to create more comprehensible visualisations of large amounts of complex data. However, as Wästberg *et al.* (2020) point out, there is a risk of focusing more on the tools and the technical improvements itself and the question of how to present spatial parameters in a visually comprehensible way, rather than solving the problem at hand. This is a common critique on Planning Support Systems (PSS), an umbrella term for a variety of computer-based modelling approaches to support land use and transport planning. Despite the possibilities on offer, there seems to be an implementation gap (Geertman, 2017). This gap is caused by a poor fit to the tasks and users, low usability, 'learnability' and visualisation capabilities (Russo *et al.*, 2018). Whilst the presence of models is pervasive both in public and commercial domains of urban design and planning, most either take on a normative approach without a knowledge-based foundation in theories of how cities function or tend to have a limited focus on a specific sub-domain (Batty, 2007; te Brömmelstroet, 2017; Pelzer *et al.*, 2015). Thereby, these models either fail to predict the outcome of plans, policies and designs, or ignore or neglect other important aspects.

1.4. Research questions

The above knowledge gaps hampering sustainable development can be mitigated by gaining knowledge on the role of spatial relationships in urban areas. Departing from the fields of urban design and planning to focus on applying software tools for spatial analysis, this dissertation seeks to answer how spatial relationships in cities can be identified with software tools and geocomputation through the following main research question (MRQ) and subsequent research questions:

Which spatial relationships, as expressed through densification patterns and transport energy networks, are identified through analysis of spatial configurations with software tools for geocomputation?

The question seeks to find operational links between spatial relationships as phenomena (for example: the clustering of shops, the relation between location and housing prices, or the occurrence of traffic congestion) through analysing spatial configuration and can be split into three subsequent research questions. The first step towards answering the main research question is to identify and capture the relevant metrics that determine spatial configuration. To find out what these are, an inquiry is done into the established theories on spatial analysis (see Chapter 2). The dissertation then proposes a combined approach for identifying spatial relationships (de Koning *et al.*, 2017; de Koning *et al.*, 2020a; de Koning *et al.*, 2020b). To ensure external validity, the same inquiry is replicated across two expressions – densification and transport energy use – of spatial configurations (de Koning and van Nes, 2019; de Koning *et al.*, 2017; de Koning *et al.*, 2020a; de Koning *et al.*, 2020b) and two cases in North-West Europe. The evidence from these cases are expected to provide insights into the question:

How does spatial configuration affect densification patterns? SRQ1

This dissertation proposes to identify spatial relations in densification patterns by studying:

i) **urban structure**, through calculating spatial configuration (street network) metrics expressed as axial integration, angular choice and angular segment integration (these metrics are described in Section 3.3.1);
ii) **urban form**, represented as polygons, for quantifying the ratio of floor space used for certain land uses; and
iii) **building density**, by quantifying building density metrics, expressed as building intensity and plot coverage (these metrics are described in Section 3.3.2); and
iv) **land use mix**, expressed as the type of activity (amenities, workplaces and housing) and the degree to which land uses are mixed and distributed (this is explained in Section 3.3.2)

The metrics axial integration, angular choice and angular segment integration under (i) represent spatial configuration best. The metrics for densification patterns – building intensity, plot coverage and land use mix – are derived from (ii), (iii) and (iv). The data will be aligned spatially and the values will be compared. All other things being equal, the expectation is that a positive relationship exists between spatial configurational values and densification metrics: higher spatial configurational values are associated with better connected or spatially integrated areas, and are expected to correspond with higher average building densities than less well-connected or spatially segregated areas. Similarly, a higher mix of land uses is expected in spatially well-integrated areas in comparison to spatially segregated areas.

To identify these relationships, research will be conducted on the city of Bergen, Norway to seek out densification potentials. First, the spatial structure of the city will be registered, and the metrics (i-iv) described above will be gathered, mapped and prepared for analysis. Next, twelve areas that were selected by the local authorities will be analysed for their densification potential (ii, iii and iv) based on the spatial configuration values (i). The aim here is to be able to provide informed recommendations on where to focus policymaking and investments for densification strategies, specifically: where to densify and how, i.e. how much building density and land use mix can be supported based on the level of spatial integration of the street network. State-of-the-art theories on spatial analysis reveal how and which spatial configurations need to be examined and which relevant operable categories are observed (Hillier, 1996; Hillier *et al.*, 1998; Hillier *et al.*, 2007) (see Section 2.3.1).

Given that transportation is a crucial factor in determining how infrastructure in cities are planned and laid out, the next focus of the research will be on the transport mode that is widely used and its energy usage. Car-dominated spatial configurations are considered to detract from all meaningful forms of sustainable mobility (Banister, 2007; Buchanan, 1963; Gehl, 2011; Salingaros, 2005b). The nature of transportation and mobility will necessitate an exploration at both the citywide and local scale in the following sub-question:

How does spatial configuration affect transport energy usage? SRQ2

To investigate how transport energy usage relates to spatial configurations in urban areas, the city of Bergen, Norway and Zürich, Switzerland are researched. Traffic data for both cities sourced from local authorities and the road administration provide the relevant metrics for calculating transport energy usage for each street segment:

i) **urban structure**, through calculating spatial configuration (street network) metrics expressed as axial integration, angular choice and angular segment integration;
ii) **urban form,** containing the dimensions and spatial locations of the network of roads, streets, paths and alleyways; and
v) **transport energy usage**, the amounts of traffic and maximum speeds on the roads and streets to calculate transport energy usage (see Section 3.3.3).

The transport energy values are compared to the spatial configurational values (i) through a bivariate correlation. The expectation is to see an effect from spatial configurations at different levels of scale on transport energy usage: a positive correlation is expected between spatial configuration values on the citywide scale and energy usage by cars. Conversely, high spatial configuration values on the local scale are expected to have a negative correlative relationship with transport energy usage.

To investigate the subjects addressed by the main research question and the related subsequent research questions above, several analysis methods are employed which all rely on geocomputational software to collect, prepare and compare data. Data operability is paramount therein, and this depends starkly on the capabilities of the modelling software used. In that respect, the third question relates the domain-specific question to computing science:

How can analyses of spatial relationships be conducted and improved using geocomputational software? **SRQ3**

The proposed method for demonstrating how geocomputation can be applied consists of the construction of a prescriptive, executable software model using a VPL that aids in automating a portion of the workflow in GIS. The expectation is that the model can contribute to standardise spatial analysis into configurational properties of settlement structures and densification patterns, and aid in overcoming issues related to data heterogeneity, compatibility and comparability of results. Moreover, the model is designed to streamline the workflow by automating some of the time-consuming and repetitive steps of collecting, preparing and comparing spatial data in GIS.

1.5. Scientific contribution

This dissertation addresses the knowledge gap by advancing theories on space and form with the application of geocomputational software tools. Combining theories on spatial structures and urban morphology, the dissertation proposes to create an approach to identify spatial configurations that influence densification patterns and transport energy usage. Using two medium-sized cities in North-West Europe as cases, this dissertation aims to contribute new data and evidence of spatial relationships. These cases are examined on both the level of the macroscale and the microscale. Spatial data will be combined and compared with building density data, land use data and transport energy data using the software tools DepthmapX (Varoudis, 2012) for Space Syntax calculations and ESRI® ArcMap as the GIS platform for facilitating spatial analysis. To optimise the processing of large datasets for spatial analysis across platforms and tools, a VPL model builder in GIS will be used to create an executable model that can be used by other researchers without programming expertise (ESRI, 2021d).

Spatial configuration and its elements are studied in various disciplines (see Sections 2.1 and 2.2 for a detailed explanation). However, a systematic and comprehensive way of identifying spatial relationships is lacking. Knowledge sharing across the discipline via usable, accessible, compatible and comprehensible software tools and methods could narrow the gap. This dissertation proposes a conceptual approach to study spatial relationships through its spatial configuration, socio-economic functions and human activities systematically. A matrix is proposed for identifying potential densification strategies based on spatial configuration to help focus policies and prioritise investments. In addition, a typology is proposed for identifying land uses and transport patterns to aid in achieving more sustainable energy usage patterns.

Studying spatial relationships requires the processing of comparable and compatible spatial datasets, from axial maps of street networks to land use functions and transport energy outputs as georeferenced data. This is a multiscale and multistep process that can be difficult to streamline and optimise for use. In the search for sustainable forms of development in increasingly complex urban environments, spatial analytics in urban design and planning rely increasingly on GIS platforms for the management of progressively complex data (Longley and Batty, 1996; O'Sullivan and Unwin, 2003; de Smith *et al.*, 2007). This brings into consideration the challenges of cross-platform translation of data and data transferability. Moreover, the various users (authorities, consultancy firms, researchers etc.) in different countries and cities utilise diverse methods to store and represent data. The Spacescape® (2013) method used in this dissertation (see Section A in Chapter 4) is but one example of how spatial relationships can be studied. Whilst a common overarching platform in the form of GIS is beneficial for exchanging data, the differences in approach when it comes to handling data are great and many. These differences range from the type and version of GIS platforms used, file types, projection systems and units of measure to the way data is generalised, classified, aggregated and interpreted.

This dissertation will pilot a workflow and refine it through the study of densification patterns and transport energy usage in relation to spatial configuration across cases in different contexts. The executable model to be built will expand on the theory of natural movement (Hillier, 1996; Hillier and Hanson, 1984; Hillier *et al.*, 1993) and the theory of the natural urban transformation process (van Nes *et al.*, 2012; van Nes and Yamu, 2021b; Ye and van Nes, 2013, 2014).

Many different disciplines are concerned with the organisation of urban environments via data analysis. This is reflected in the number of emerging technologies used in the field today for collecting and analysing data, ranging from Artificial Intelligence (AI) and Machine Learning (ML) algorithms to the use of wireless (mobile) data, (remote) sensors, laser scanning, data capture via Light Detection and Ranging (LiDAR) and satellite imagery for creating 'digital twins', which are dynamic digital counterparts of a real-life object or situation (Armstrong, 2020; Yamu *et al.*, 2023). It is not logical to expect that all stakeholders and end-users are well-versed in the software tools available or have the relevant programming skills to handle the underlying scripts and code. This dissertation demonstrates the value of VPLs for conducting replicable spatial analysis research by domain-specific users through making an executable model for streamlining the workflow. This model, which is presented in (de Koning *et al.*, 2022), automates several of the steps in the workflow that are commonly required when analysing spatial data. First, this is important for researchers to gain knowledge on possible relationships between spatial configuration and spatial relationships in urban areas without the need for extensive programming knowledge and skills. Second, better insights into spatial relationships and what is necessary to analyse them will help to improve the model for more targeted use by domain experts (Yap *et al.*, 2022). Finally, the gained knowledge can support informed decision-making for developing cities in a sustainable matter (Bibri, 2021).

1.6. Societal relevance

Society is constantly addressing the issue of the functioning of cities coupled with sustainability. This originates from a paradigm shift that took place in the earlier 20th century regarding how cities should be organised for health, safety, employment and access to nature. The wave of industrialisation brought material wealth and new inventions. The most pervasive and iconic is arguably the automobile, which had a tremendous impact on how cities developed and functioned from the first half of the 20th century (Hidayati *et al.*, 2019; Kenworthy and Laube, 1996; Neuman and Smith, 2010; Salingaros, 2005b). Modernist urban planning welcomed the car as the transport mode of the future and developed spatial planning strategies to facilitate car use. This streamlined the rapid reconstruction of infrastructures that was necessary after two world wars that left many cities in shatters, with a focus on transport efficiency (Banister, 2007).

Ultimately, the adverse effects of industrialised consumerism and motorisation began to show up as the impacts of this paradigm shift. The industrial complex that was created and manifested in the spatial layout of urban environments led to an uptake in failed harvests, natural disasters, dwindling resources, health impacts, and competition for space, resources, labour and currency (Hall, 2014) rather than cooperation. The ensuing shift from incrementally evolved, compact cities to planned sprawl changed the relationship between spatial configuration and the use of cities (Neuman, 2005). This industrial complex and its subsequent spatial manifestation in cities cannot sustain humanity for much longer (Jensen *et al.*, 2021; Meadows *et al.*, 1972). Cities in developed industrial countries such as the Northwest-European cities under investigation in this dissertation need to transition into more sustainable forms. There is a window of opportunity to not repeat the mistakes from before. To that end, new insights are needed into the spatial relationships that influence densification patterns. This dissertation examines which spatial properties of the street and road network promote densification potentials and lessen transport energy use in cities. Insights are expected to provide evidence on what type of densification is suitable or desirable, and what typologies of land use and transport patterns are more efficient than others. The use of open-source data and intuitive software tools can also democratise the process of spatial analysis for a wider audience. By making spatial analysis possible through software tools that are efficient and user-friendly, users from various communities and with diverging technical expertise can gain knowledge of how to plan more sustainable cities. Being able to direct resources and investments of public goods and funds to achieve maximum benefit from densification is crucial for an efficient and fair planning process. In addition, knowing the differences in land use and transport typologies (i.e. types of streets for specific land use functions) can aid urban designers in creating and upgrading sustainable areas in their cities. More importantly, a democratised planning information and visualisation system (such as via GIS platforms) can increase citizen participation and commitment to achieving more inclusive sustainable urban forms (Yap *et al.*, 2022).

One of the key contributions the field of urban design and planning can make for our societal grand challenges (see for example: United Nations, 1992, Chapter 7: Promoting sustainable human settlement development) is to provide insights into how to organise our living environments better than at present to combat environmental impacts and stimulate cooperation rather than competition. To situate the contributions of this dissertation, the current policy context for urban design and planning will be discussed in the next section.

1.7. Policy context

In the aftermath of the first global oil crises in the 1970s, a long-awaited paradigm shift of awareness occurred. Urban designers and planners realised that the planning traditions and technologies of that time had a negative impact on the global environment, and that action would be needed to mitigate this (Holden *et al.*, 2017; Meadows *et al.*, 1972). One of the main messages of the Brundtland Commission was that global climate change is caused by human activity, notably the emission of greenhouse gases (CO_2, NO_x, CFKs etc.) (World Commission on Environment and Development, 1987). The number of environmental disasters such as floods, storms and wildfires have increased disproportionately and in extremes over the last years (Peduzzi, 2019). This can be expected to occur more frequently unless human consumption patterns and how cities are organised changes radically and rapidly. This will require a radical shift in how our cities are used, designed and planned (Jensen *et al.*, 2021). More research insights are needed into the effects of global human activity on the global climate. Actionable insights into how spatial configurations can achieve more sustainable outcomes are therefore needed now to counteract the possible and likely negative effects of human activities.

The sustainable agenda

Sustainable development is defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.” (World Commission on Environment and Development, 1987). Within urban design and planning, it is an inescapable term. However, a clear definition of the adjective ‘sustainable’ was never given. Neither was it defined what ‘the needs of the present’ are, let alone the needs of ‘future generations’. Although views on the matter differ, it can at least be said that for humans to sustain themselves (to survive), they need food, water, clothing, shelter and human contact. In Norway, free access to nature is also enshrined in the constitution (Lovdata, 2021). Secondary conditions imply safety needs: health, personal and financial security; social needs: to love, be loved and have a sense of belonging; esteem needs: respect, self-respect, esteem and self-esteem; and finally the need of self-realisation and self-actualisation (Maslow, 2012). These secondary needs are essential for people not just to survive, but to thrive. Sustainable development, then, should be approached holistically, beyond the scope of environmental sustainability alone and including social sustainability and equity (Holden *et al.*, 2017) when considering how cities should be organised and function.

At the Earth Summit in Rio de Janeiro in 1992, this approach was politically vocalised by identifying three P’s: ‘People, Planet and Profit’ (‘Profit’ was later augmented to ‘Prosperity’) to describe the social, ecological and economic components of sustainable development (United Nations, 1992). This trinity of social, ecological and economic sustainability was adopted by the ensuing conferences on climate change and reflected in 17 SDGs agreed upon during the 2015 Climate Change conference in Paris (United Nations, 2017).

A general problem with the SDGs as well as the 169 subsequent ‘targets’ is that they are a blend of goals and means. Moreover, some of the SDGs are formulated in a vague manner or have interpretable and ill-defined terms in them, such as the terms inclusive, safe and resilient in SDG 11. Though the targets reveal a little more detail, they too remain vague (Tan, 2019). A crucial factor that is overlooked, for example, is the social aspect of accessibility. Although Target 11.1 and 11.2 mention that housing and transport ought to be affordable, it is common that those in a weaker economic position have little choice on the housing market. Housing that can be afforded is often found in the most peripheral or spatially segregated areas. Combined with economic restraints to own a car and a limited offer of public transport options in peripheral areas, the ability to access the job market and basic services is impacted considerably as a result. Inclusiveness implies equal access for all to basic services (commerce, institutions for education, leisure and recreation), job opportunities, green areas and public spaces without owning a car or depending exclusively on public transport (Holden *et al.*, 2020). Unavoidably, most of these services would simply have to be within walking distance, but that is not how most cities are organised spatially. Improving densification pattern identification and implementation strategies (this dissertation) can contribute to understanding this spatially driven socio-economic inequality better and make cities more inclusive.

The link between safety and natural surveillance is recognised as a paramount aspect of sustainable urban design. Whereas one school of thought, embodied in Newman's work Defensible Spaces (1972), sees the 'stranger' as a threat that one needs to be protected from, the positive aspects of natural surveillance and life on the streets were studied and popularised by Jacobs (1961) and Gehl (2011; Gehl *et al.*, 2006). In a nutshell, human activity stirs curiosity and thus invites more human activity, whilst the absence of it repels human activity and stirs a sense of insecurity. Understanding desirable spatial relationships from human activity (e.g. a vibrant shopping street) and their appropriate spatial configuration (this dissertation) can provide design guidelines for creating safer environments.

The term resilience in SDG 11 is defined as resistance against 'disturbances' which cause (major) changes in the physical environment or how the environment is used (e.g. extreme climatic conditions, changes in population, economic or cultural crises, introduction of new technologies) and is an implicit quality of sustainable cities. A built environment that can absorb societal, economic, and environmental changes in its existing spatial configuration with ease is more resilient than a rigid built environment that requires great physical, political and economic efforts and costs to facilitate changes (Ribeiro and Gonçalves, 2019). Therefore, urban design and planning have a vital role to play in finding suitable spatial configurations that have these properties (this dissertation) that can contribute to more resilient, and thus more sustainable built environments (Hillier, 2009).

1.8. Limitations

This dissertation recognises theoretical limitations, limitations in the analysis methods, and challenges in assessing the adequacy of the software model. Additionally, as an interdisciplinary research, epistemological challenges were encountered in defining the object of study, representing it through maps and models, and interpreting the results. Experiencing phenomena in the physical world versus observing selected phenomena through abstract virtual models produce differences in the manner in which the object of study is perceived and hence how knowledge is gained. This is a challenge that is acknowledged in this dissertation.

Theoretical limitations are:

- Human activity and behaviour are complex and not always predictable; therefore, measurable urban form is not always an absolute nor complete representation of human activities in society;
- The density paradox, whereby the trade-offs between density and sustainability are not fully captured by how density is measured; and
- Context dependency, whereby in each situation, socio-cultural peculiarities sometimes defy how objective urban form and spatial configurations can be perceived and measured.

These limitations are further explored in Section 2.4.
Limitations in analysis methods are:

- The accuracy of hand-drawn axial maps and computer-generated maps depends on the researcher, the available data or the available software;
- Although there is a systematic approach to measuring density, the choice of the area of aggregation affects the outcomes;
- Determining the type(s) of land use relies at times on ambiguous categorisations of type of functions that can differ across cases; and
- Transport energy in this dissertation is calculated using the average energy consumption of vehicles which does not account for other modes.

These methodical limitations are discussed further in Section 3.7.2. Lastly, limitations pertaining to the assessment of the practical adequacy of the software model are discussed in Section 3.7.3.

1.9. Structure of the dissertation

This dissertation consists of two parts:

Part I consists of six chapters. Chapter 1 (this chapter) introduced the dissertation and its scope of research, knowledge gaps, research questions, and contributions to science and society. Chapter 2 addresses the theoretical basis of existing paradigms in urban studies. In Chapter 3, the methodical approach for conducting the research will be presented. The way these are applied is explained, and the strengths and limitations are addressed.

Chapter 4 summarises the results from three peer-reviewed journal articles and one conference article published during the dissertation and is divided into three expressions. The first expression (A) summarises the highlights of one article that examines the densification patterns of Bergen, Norway:

Paper A1:

de Koning, R. E., Roald, H. J. & van Nes, A. (2020a): A Scientific Approach to the Densification Debate in Bergen Centre in Norway. Sustainability, Vol. 12:21, 9178. Available at: https://doi.org/10.3390/su12219178

In the second expression (B), the highlights of two articles are summarised that discuss the relation between transport energy usage and spatial configuration:

Paper B1:

de Koning, R. E., Tan, W. G. Z. & van Nes, A. (2020b): Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities. Sustainability, Vol. 12:19, 8146. Available at: https://doi.org/10.3390/su12198146

Paper B2:

de Koning, R. E., van Nes, A., Roald, H. J. & Ye, Y. (2017): Strategies for integrated densification with urban qualities. Combining Space Syntax with building density, land use, public transport and property rights in Bergen city. *In:* HEITOR, T., SERRA, M., SILVA, J. P., BACHAREL, M. & CANNAS DA SILVA, L., eds. Proceedings of the 11th International Space Syntax Symposium, 3rd – 7th July, Lisbon, Portugal: Instituto Superior Técnico, Departamento de Engenharia Civil, Arquitetura e Georrecursos, #56, 863-879. Available at: http://www.11ssslisbon.pt/docs/proceedings/papers/56.pdf

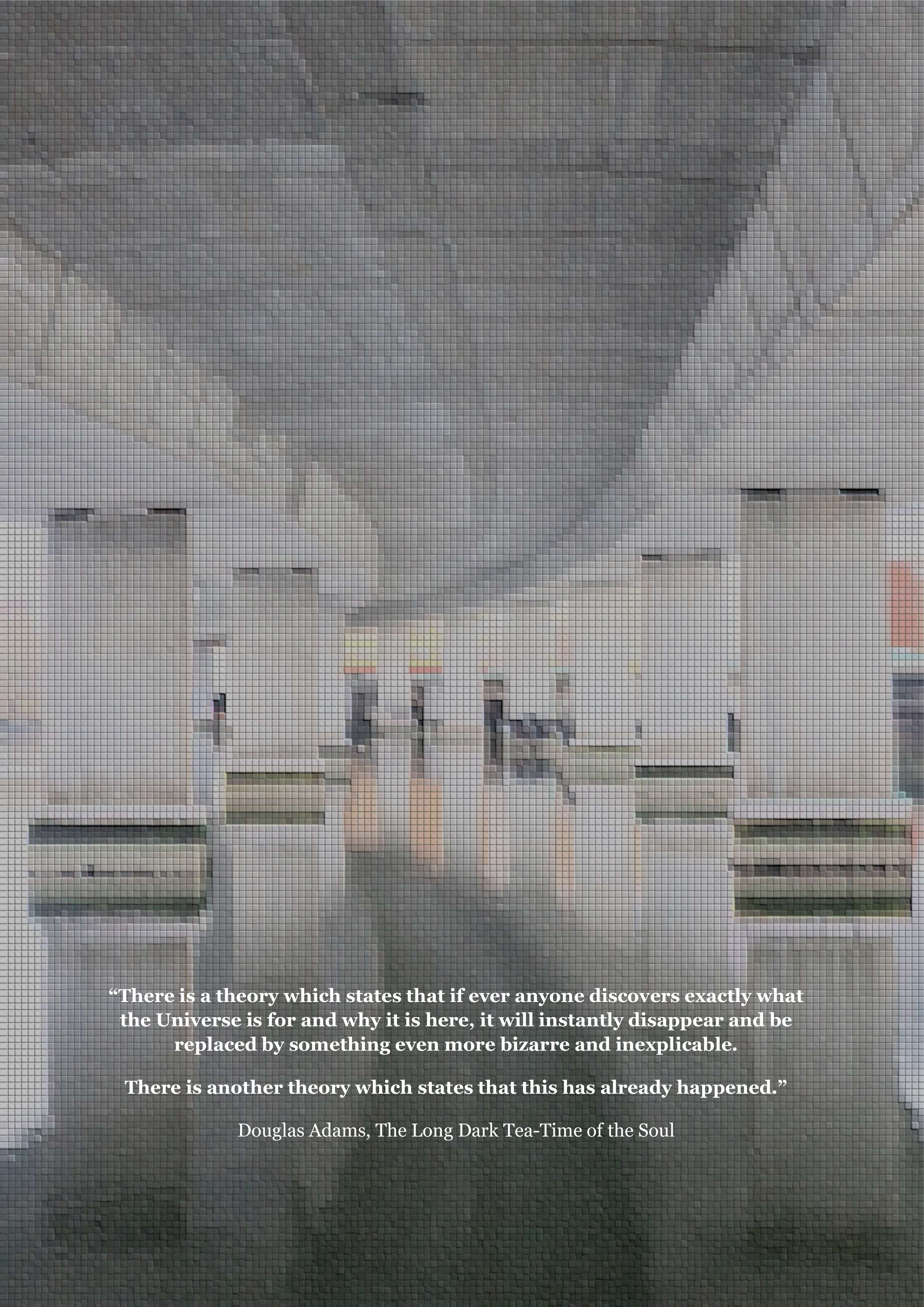
In the third expression, the highlights are presented of one article discussing the data used for researching spatial relationships and describes the entire scientific workflow:

Paper C1:

de Koning, R. E., Heldal, R. & Tan, W. G. Z. (2022): Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: the cases of Bergen, Norway, and Zürich, Switzerland. Data in Brief, Vol. 42:108290. Available at: https://doi.org/10.1016/j.dib.2022.108290

Chapter 5 presents the findings from published research and analyses the findings regarding the role of spatial relationships, identification approaches, the spatial analysis process, typologies of transport networks, and the role of software tools and geocomputation. Chapter 6 summarises the findings and discusses the contributions and limitations of this dissertation. The chapter closes with a discussion, based on the findings in this dissertation, on how we can understand cities better than we presently do with a view to understand how they could be better organised spatially to become safer, more inclusive and more resilient environments for all.

Part II consists of the three peer-reviewed journal articles and the conference article published during the dissertation.



“There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.

There is another theory which states that this has already happened.”

Douglas Adams, The Long Dark Tea-Time of the Soul

2. Theoretical framework

This dissertation will explore how spatial relationships influence the distribution of density of the built mass and land use mix patterns, and how it affects the way people use these areas for their mobility and activities. Various approaches exist in the fields of urban design, urban planning, urban geography, environmental psychology, and social physics that study urban form and its related urban processes. Two of these are relevant for this dissertation: urban morphology and the urban network approach:

- **Urban Morphology**: the study of patterns and order of urban forms over time (Moudon, 1997) is the object of research in this dissertation.
- **Urban Network** (Space Syntax): "a theory and method for describing and quantifying the configurative spatial relationships in the built environment that shape socio-economic activities" (van Nes and Yamu, 2021b, p. 20). It provides operationalisation to identify, analyse and evaluate the studied spatial configurations of urban structures.

Urban morphology focuses on the changes in physical characteristics, spatial patterns and order of the built environment over time. The urban network approach has its roots in morphological studies and focuses on the extrinsic properties of the built environment (van Nes and Yamu, 2021a, p. 21, 30). Together, these two different approaches provide a complementary lens to understand spatial configuration through urban structures and form. The disciplines, their interrelationships and theoretical underpinnings are introduced next.

2.1. Urban Morphology

Urban morphology is concerned with the study of the physical and spatial form of "...the city as human habitat" (Conzen, 1960; Krier, 1979; Moudon, 1997, p. 3; Muratori, 1960; Panerai et al., 2004) based on three principles of form, resolution and time (Carmona, 2021; Moudon, 1997, p. 7):

- Urban form is defined by three fundamental physical elements or forms that are the buildings and their related open spaces, plots, and streets.

- Urban form can be studied at four resolution levels also known as levels of scale of the building, the building block, the city, and the region.
- Since the physical elements continuously change over time, urban form can only be understood historically and through a temporal lens.

The field of urban morphology is generally recognised to consist of three distinct schools: the Italian (Caniggia, 1976; Caniggia and Maffei, 2001; Muratori, 1960), the French (Panerai *et al.*, 2004) and the English (Conzen, 1960; Whitehand, 1981). The Italian, or: Muratorian School, spearheaded by Muratori and Caniggia, promoted a process-typological approach to "...establish a universal classification of man-made structures" (de Oliveira, 2016, p. 167). The fundamental concepts of this approach pertain to the classification of building types and urban tissues (Caniggia, 1976; Muratori, 1960; Rossi, 1984). The French School analyses patterns of land division and cadastres (Panerai *et al.*, 2004). The English, or: Conzenian School embodies the historico-geographical approach for classifying the physical form of cities based on a tripartite division into town plan, building fabric and land use (Conzen, 1960; Moudon, 1997; de Oliveira, 2016; Whitehand, 1981).

These approaches to studying the morphological elements has yielded a wide range of typological qualifications of various aspects of urban form, such as: buildings (Muratori, 1960; Rossi, 1984), plots and lots (Panerai *et al.*, 2004), urban blocks (Whitehand, 1981), property patterns (Conzen, 1960; Whitehand, 1981), squares (Krier, 1979), and streets (Marshall, 2005). These qualifications are related but different in terms of level of scale (i.e. from the level of scale of the building to the region) and local context (e.g. culture, society and economy). In general, the city was regarded as a collection of artefacts (van Nes and Yamu, 2021b, p. 7). According to Rossi and Poëte, some artefacts constitute the shape or pattern of the city through its continuous transformation process (Periton, 2018; Rossi, 1984). These kinds of artefacts are named 'primary elements' and have an influence on the further transformation of urban areas. Examples are important or unique public buildings such as railway stations or theatres, infrastructure such as canals or city walls, or historic events such as city fires, natural disasters, urban expansion plans etc. Scholars from the Italian school and the Versailles school developed a conceptual framework for describing and classifying the typo-morphology of buildings in relation to the urban block and the plot (Caniggia, 1976; Caniggia and Maffei, 2001; Panerai et al., 2004). Cullen (1961) described the relationships between the various ingredients of the townscape based on the fundamental concepts of serial vision of how one moves through space, the experience of place in the physical environment, and the content of urban fabrics, showing "…evidence of different periods in its architectural styles and the various patterns of the layout (Cullen, 1961; de Oliveira, 2016, p. 148).

Most urban-morphological research wielded qualitative approaches to understand the forms and patterns of urban artefacts based on social, technological and political changes over time. In recent years, quantitative urban-morphological research methods have been developed, which rely heavily on calculus. These methods have been continuously improved and refined over the past six decades, aided by advancements in computing capabilities. Examples are Steadman's use of graph theory for analysing urban fabrics and buildings (1983), Rådberg's correlations of building intensity, plot coverage and open space (1988, 1996), Batty and Longley's fractal analysis (1994), Porta's Multiple Centrality Assessment (2006b) and Intersection Continuity Negotiation (2006a), Marshall's classification of street pattern types (2005) and the Mixed-Use Index (MXI) method (Dovey and Pafka, 2017; van den Hoek, 2009) for quantifying the ratio of monofunctional versus multi-functionality of urban blocks. All methods are descriptive, objective and complementary, and can be applied on all types of built environments. The two morphological methods developed by Rådberg and van den Hoek are applied in this dissertation for analysing building densities and land use mix (see Section 2.3.3 and 2.3.4).

2.2. Urban Network

The urban network approach focuses on the extrinsic properties of space in terms of analysing the spatial relationships of urban structures. The Space Syntax method (Hillier, 1996; Hillier and Hanson, 1984; Hillier and Iida, 2005; Hillier *et al.*, 1993) defines spatial elements with high precision and objectivity. This means that the texture, shapes, function and form of urban networks as structures are not relevant. The method has been refined for more than four decades and is a considerable departure from the urban-morphological schools' analysis of urban fabrics (Erin *et* *al.*, 2017, p. 1393). With current technology, software development and computer capacities, it has in recent years become possible to apply this analytical method on large metropolises and even entire countries (Law *et al.*, 2022; Serra and Hillier, 2017, 2019; Space Syntax Limited, 2021). The method is utilised by an international community across multiple disciplines. This has yielded a substantial database of research that provides external validity to the Space Syntax method and its findings (Hillier *et al.*, 2007). From this, a number of interrelated theories on space, spatial relationships and flow of movement, and economic activity have developed. The theories that describe (explain) and predict effects of spatial configuration are:

1. **the theory of spatial combinatorics** (Hillier, 1996, p. 216-261); describes the basic spatial elements and their fundamental interrelations. It explains the spatial laws that govern how objects placed in space contribute to integrate or to segregate urban spaces. An example is how local design decisions such as a new road connection or placement of buildings have an effect on the global (i.e., citywide) configuration of spaces. Spatial combinatorics is used in this dissertation to understand how the primary spatial elements affect spatial relationships in cities (see Section 2.3.6);
2. **the theory of natural movement** (Hillier et al., 1993); explains the relation between spatial configurations, human movement patterns and the location of attractors. This theory can explain and predict "…the proportion of urban pedestrian movement determined by the grid configuration itself" (Hillier *et al.*, 1993, p. 32) as well as vehicular movement when including geometrical and metrical distances (Hillier and Iida, 2005; Penn *et al.*, 1998; Serra and Hillier, 2017, 2019). Hence, it is used in this dissertation to compare spatial configurations with transport energy usage.
3. **the theory of the natural urban transformation process** (van Nes *et al.*, 2012; van Nes and Yamu, 2020; Ye and van Nes, 2014) relates the distribution of building densities and land uses to spatial configuration. It builds on the above theories and links spatial configuration to both the distribution of building densities and non-residential commercial and non-commercial land uses in cities. This theory is pertinent to understanding urban densification patterns, which this dissertation seeks to achieve.

Space Syntax and its related methods have been consistently developed since the 1970s (Hillier, 1996; Hillier and Hanson, 1984; van Nes and Yamu, 2021b). Hillier and Hanson (1984) performed ground-breaking work developing theories of space as a creator of interactions between people. Rather than studying the form of physical objects, the importance of the spatial relationships between the objects is emphasised with spatial configuration as an abstract product of the concrete (i.e. the form of built objects) that defines the structure of space (Hillier, 1996, p. 65-69). In turn, space creates regularities in spatio-temporal processes such as social behaviour, cultural events and practices (Hillier, 2014; Hillier and Hanson, 1984). In cities that developed incrementally from small settlements, new streets and road connections were consolidated by formalising already present movement routes between places of importance through surveying, mapping, paving and being constituted by built objects. Before becoming part of the formalised street network in a formalised built environment, these routes had come about under the influence of topologically defined spaces between destinations (Hillier *et al.*, 2007). This bilateral influence of space and movement patterns is a good example of a spatial relationship wherein the need for movement creates spaces in which movement takes place, and in turn the built objects conform to these spaces by constituting them. Moreover, it reflects the notion that cities are "human products" (Hillier, 2014, p. 45).

The approaches discussed above are complementary. Urban morphology focuses on the intrinsic properties of urban space (van Nes and Yamu, 2021a, p. 21-25), seeking to understand the meaning of various urban form factors. The urban network approach is subdivided into the study of spatial patterns and the study of spatial structure (van Nes and Yamu, 2021b, p. 15). All approaches discuss and define the configuration of space and its effects on various socio-economic processes, but only the study of the structure of space considers its extrinsic relational properties. Hence, it is important to study urban form through urban structures. The details of how these approaches are combined and used are discussed next.

2.3. Building blocks for understanding spatial relationships

Following the approaches described above, the following building blocks of urban space are used in this dissertation to explore and identify spatial relationships. These building blocks are:

- **urban structure**: spatial configurations, i.e. the structure of arrangement of one space to all other spaces within a given area that can be measured in an objective fashion (Hanson, 1989a; Hillier, 1996; Hillier and Hanson, 1984; van Nes and Yamu, 2021b);
- **urban form**: the physical characteristics of a given built environment and how these are experienced (Alexander, 1964; Conzen, 1960; Moudon, 1997; Panerai *et al.*, 2004; Rossi, 1984);
- **building density**: the amount of built-up floor space in a certain urban area (i.e. a plot, an urban block, a district etc.) (Rådberg, 1988, 1996);
- **land use mix**: the functional use within the buildings based on the type of activities performed there (Dovey and Pafka, 2017; van den Hoek, 2009);
- **transport energy usage**: the amount of energy consumed daily by cars calculated for each street segment (MacKay, 2009).

2.3.1 Urban structure

In urban planning, design and their related fields, the term space can refer to unused, disused or unbuilt land, or unexploited building space. Simultaneously, the term space can refer to the volumes that are encapsulated by buildings and around the them, and as a concept (Salingaros, 2005a). The definitions of space and distance are important for measuring and analysing spatial relationships. Space, as referred to in this dissertation, is understood through its structural patterns or its configuration (Hillier, 1996; Hillier and Hanson, 1984; Marshall, 2005; van Nes and Yamu, 2021b). Configuration is defined here as "…simultaneously existing relations … of each space to all others" (see Hillier, 2014, p. 20). Studies of urban spatial patterns (see for example: Alexander, 1977; Marshall, 2005) reveal that cities often display a combination of regular and irregular spatial patterns and, by extension, varying degrees of *order*. Yet the study of urban structure aims to identify spatial relationships between spatial *structures* on different levels of scale. An orderly plan may not necessarily be well-structured, such as the modernist layout of Slettebakken in Figure 2 (right). Conversely, a seemingly disorderly plan may be very well-structured, such as the historic centre of Bergen depicted in Figure 2 (left) (Karimi, 2012, p. 39).

This way of analysing urban space allows for a measurement and comparison of urban form which this dissertation employs. In addition, the reduction of space into patterns and hierarchies allows for the assigning of values for the connectivity and integration of a given space following the logics of urban network theory (Hillier and Hanson, 1984). This is a departure from traditional urban morphology approaches where only forms and patterns were studied. **This explains the focus of this dissertation on urban structures as spatial configuration.**

The contribution of the methodology is the representation of spaces based on visibility since orientation and wayfinding are primarily informed visually (Hillier, 2003). Space Syntax identifies three ways of representing space. In addition, it can measure and express distance in three different ways.

Three ways of representing space

The three types of representation used in Space Syntax are i) isovist, ii) convex space, and iii) the axial line (Batty and Rana, 2004) and the derived segment line. Isovists and convex spaces are useful representations to analyse (inter)visibility, orientation and interaction of architectural space (see for example: Turner *et al.*, 2001). The axial line is a linear sightline in urban space that indicates a movement path (Yamu *et al.*, 2021, p. 5). Axial lines (Figure 1, left) represent the interrelation of spaces by demarcating the longest lines of sight, using the fewest lines possible to cover and connect all convex spaces in the system in between the physical objects whilst making all direct line-to-line connections (Hillier and Hanson, 1984, p. 17, 99; Hillier and Penn, 2004; Hillier and Stonor, 2010; van Nes and Yamu, 2020). In the example of Figure 1, three axial lines are needed to cover and connect all convex spaces in the system between the physical objects, and intersecting lines (indicating convex spaces that are spatially connected) are directly connected to each other.

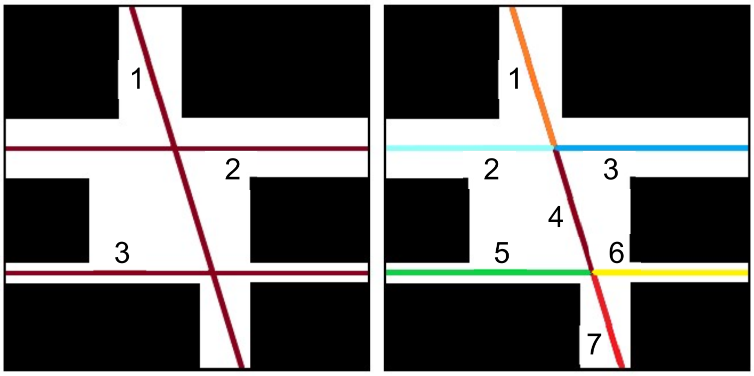


Figure 1 Illustration of axial lines (left) and segment lines (right). Source: author.

This dissertation uses segment line maps, a derivative representation from the axial line map. Increasing computer capabilities and software development, motivated by several critiques on axial map analysis that it does not deal with metric distance (Hillier and Penn, 2004; Ratti, 2004a, 2004b), led to the axial line-based analysis being replaced with segment analysis (Dalton, 2001; Hillier and Iida, 2005; Hillier *et al.*, 2007; Turner, 2001). Segment lines are obtained by breaking up each axial line where it overlaps and intersects another axial line (Hillier *et al.*, 2007). In the example of Figure 1, axial line 1 is broken up where it intersects axial line 2 and 3, resulting in three segment lines 1, 4, and 7. Line 2 and 3 are broken up where these intersect axial line 1, resulting in segment lines 2, 3, 5, and 6 (see Figure 1 right). Segment-to-segment calculations allow the metric length of each segment to be included as well as the angle between segments (Hillier and Iida, 2005; Turner, 2000, 2001). The measures of distance and the possibilities for segment analysis are explained next.

Three ways of measuring distance

Distance is most commonly described as Euclidean *metric* distance. Whether it is distance travelled on a path or absolute distance (as the crow flies), it is expressed in metric units of meters and kilometres. The nature of Space Syntax focusing on relational properties of spaces has been criticised for not taking metric distances into account (Ratti, 2004b). With segment analysis, it has become possible to consider metric distances by including the segment length in the calculations. A second way of expressing distances is topological, i.e. the number of direction changes within all routes. Topological distance embraces the behavioural aspect that governs human movements from origin to destination whereby individuals tend to prefer routes with the fewest amounts of turns (Hillier and Iida, 2005; Hillier *et al.*, 2007; van Nes and Yamu, 2021b; Turner, 2001). Classic axial line integration analysis uses topological distance (Hillier and Iida, 2005; van Nes and Yamu, 2021b). Another aspect of human movement is captured by the third way of measuring distance, i.e. via geometry. Geometric distance measures the degree of total angular deviation on a route between an origin and a destination (Turner, 2000). The British Library example (Conroy-Dalton, 2003) best explains this effect of how humans cognitively tend to choose the path with the lowest angular deviation towards their destination.

By segmenting axial lines, both metric and geometric distance measurements are now included in the Space Syntax method. The various aspects of natural movement and wayfinding are therefore better captured than with the original axial line analysis. The two metrics that include all three distance measurements for measuring spatial relations are 'betweenness', or: angular choice, and 'closeness', or: angular segment integration. Betweenness reflects the degree to which segments fall on the shortest routes between two pairs of segments within a given metric distance (termed 'radius'). It indicates potential through-movement. Closeness shows how geometrically close (i.e. with the least angular deviation) each segment is to all others within a given metric radius. It indicates potential to-movement, or: the likeliness of a street to be a destination (Hillier and Iida, 2005; van Nes and Yamu, 2021b) (see also Section 3.3.1). These two measures are especially useful when studying urban areas with a complex structure. There is strong empirical support for the 'least angular deviation' or angular method being more accurate in predicting flows of movement in relation to spatial configuration than the axial-topological 'fewest turns' method and the 'shortest path' or metric method (Hillier and Iida, 2005; Hillier and Stonor, 2010). Moreover, it solves the issue of including metrical distances (Hillier and Penn, 2004; Ratti, 2004a, 2004b). The above measures aid in understanding spatial relationships in urban areas and are used in this dissertation for analysing these relationships.

2.3.2 Urban form

Urban form is a container term for the physical characteristics of urban areas, such as the size, shape, materialisation, type, typology and pattern of the built artefacts. Examples considered are:

- building typo-morphological classifications relating to building height and plot coverage (Panerai *et al.*, 2004; Rådberg, 1988, 1996; Salingaros, 2005a);
- networks, which can be understood as tree- or network structures (Alexander, 1965; Marshall, 2005); and
- street typologies describing the type of street (motorway, avenue, neighbourhood street, access road) (van Eldijk *et al.*, 2014).

This dissertation focus on urban form via the degree of density in the urban block. Most urban morphology research emphasise the largest changes on the relationship between buildings and urban blocks is the change that took place with the modern movement (Panerai *et al.*, 2004; Salingaros, 2005b). As a result, two contrasting types of urban form are distinguished: self-organised urban form and planned urban form (Berghauser Pont and Marcus, 2015; Hillier, 2009; Porta *et al.*, 2006a; Ratti, 2004b). Self-organised urban areas are "…moulded directly by social and economic processes without the imprint of conscious design" (Hanson, 1989b, p. 22). Within self-organised urban form, spaces are the voids defined by physical elements that develop incrementally over long periods of time. Though such urban forms are, strictly speaking, never entirely unplanned, the patterns of growth could be described as 'organic', and this process follows certain spatial laws (see for an explanation: Hillier, 2014). In contrast, urban areas that were planned according to certain design principles commonly seek to order urban space (i.e. street patterns and blocks) through geometric forms (Hanson, 1989a; Hillier and Hanson, 1984, p. 4; Karimi, 2012). This goes for pre-modernist plans such as Hausmann's Paris or Cerda's Barcelona, but 20th century modernism is also strongly associated with the latter view. However, within modernist urban form, space is undefined apart from the topography of the landscape. Buildings are positioned in open space as individual or groups of objects (Carmona, 2021, p. 216). Because of the contrasting spatial properties from self-organised urban form or pre-modernist planned urban form, it is argued that for modernist planned urban forms, these properties cannot be captured through conventional morphological approaches or configurational analysis alone (Berghauser Pont and Marcus, 2015). Therefore, a combination of methods is required when analysing such areas.

This contrast is shown in Figure 2 through two figure-ground maps of two distinct different areas in Bergen. The image on the left shows how in the historic centre, the buildings define the urban blocks, streets and squares. The zoning plan's grid structure was proposed in 1855 (Roald, 2010, p. 49-53). The image on the right shows Slettebakken, an example of a modernistic zoning plan on previously undeveloped land approved in 1950 (Roald, 2010, p. 153). Here, the buildings are free-standing in open space surrounded by local roads. Rather than being defined by the built mass, the roads follow their own logic and the cell-size of the road system is coarser than that in the centre.

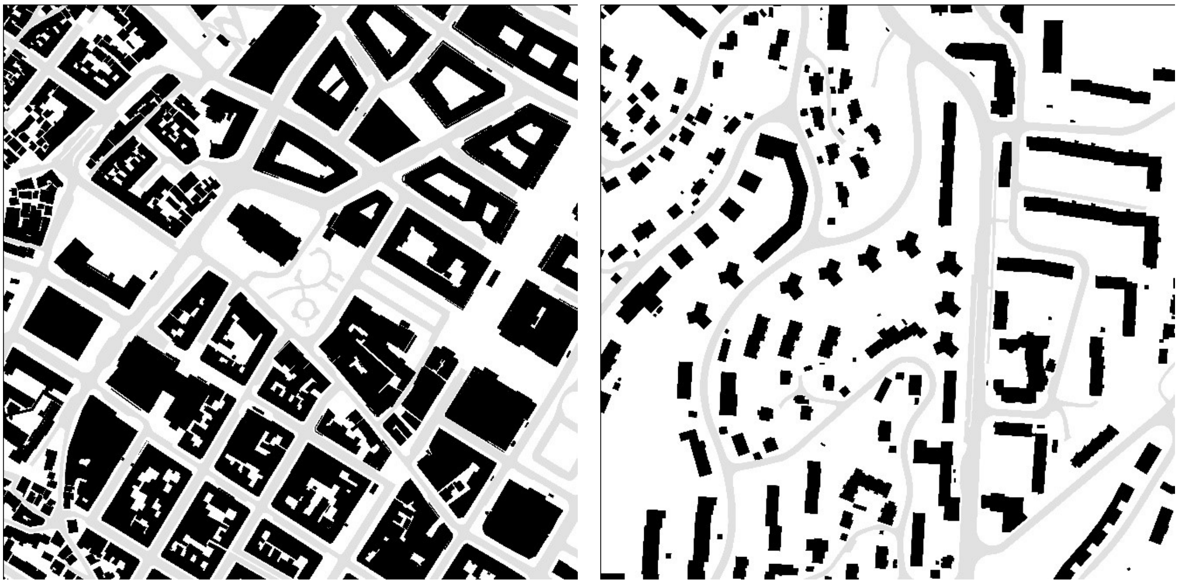


Figure 2 500x500 m figure-ground map of Bergen centre (left) and Slettebakken (right)

The method for classifying building density, shape and form, originally developed by Rådberg (1988, 1996), made it possible to make a conceptual framework for a quantitative typo-morphology of buildings. Considering the degree of plot coverage (point, strip, and block) and building heights (low-, medium- and high-rise), nine typo-morphologies of buildings in relation to the urban block are identified (see Figure 6a in: de Koning *et al.*, 2020a, p. 8). The city centre of Bergen can be classified as mid-rise block, whereas the Slettebakken area can be described as mid-rise and high-rise strip with some single-family houses defined as low-rise point.

2.3.3 Building density

Density is concerned with the degree of urbanity (i.e. built mass, land use mix and urban activities in and between these) within a given finite urban area. Discussions on urban form usually lead to density debates (see for example: Berghauser Pont and Haupt, 2009; van Nes *et al.*, 2012; Rådberg, 1988, 1996; Siksna, 1997; Ye and van Nes, 2013). In fact, the level of urbanity is often dictated by the density of inhabitants, workplaces or housing units. Through density, urban form has a direct impact on energy consumption for heating, cooling and powering buildings and for transport. These factors are directly affected by urban planning policies (Lefèvre, 2009, p. 3), which in turn are shaped by the transport technologies that were dominant at different stages of cities' development (Jabareen, 2016). This mutual relationship has been widely researched since the late 1980s (Crane, 2016; Jabareen, 2016; Lefèvre, 2009; Nichols and Kockelman, 2015; Papa *et al.*, 2014). The implementation gap lies in the coupling of this spatial relationship at both the citywide scale and the local scale (Crane, 2016) (see Figure 1 in: de Koning *et al.*, 2020b, p. 3). Moreover, density as an expression of space helps to put into perspective the use of space in relation to the land uses and activities performed there. For this, we turn to Rådberg's quantitative method to measure building density and related properties of built form (1988). By expressing building density in terms of space, investigations can be made into the spatial distribution of building densities. Subsequently, these measurements can be compared with measurements of spatial configuration to understand densification patterns better, which is the aim of this dissertation.

2.3.4 Land use mix

Whereas Newman and Kenworthy's (1989) research focused on the comparison of urban population density and motorised travel (i.e. car use), it is the spatial distribution of the different land uses that triggers the generation of transport needs (Marshall, 2000). The more concentrated the land uses, the lower the total travel demand between these is to be expected. Cervero and Kockelman (1997) discovered that the amount of distance travelled by car versus non-motorised modes of transport (walking, cycling) was reduced not only in areas with significantly higher land use mixes, but also in residential neighbourhoods with local amenities (shops, schools etc.). These findings seem to confirm the idea that compact urban form with a certain degree of land use mix contributes to more sustainable mobility patterns through a reduction in the need for motorised transport. Ye and van Nes (2014) demonstrated how both the spatial distribution of land uses and building densities in cities react to variations in the spatial configuration of its public spaces. Considering that this dissertation seeks to provide insights into spatial relations through densification patterns by gathering descriptive evidence, this warrants a quantitative assessment of land use distributions for comparison with spatial configurations. To that end, the MXI method (Dovey and Pafka, 2017; van den Hoek, 2009) is applied to describe the degree of land use diversity in terms of space as the ratio of space used for different types of urban activities.

2.3.5 Transport energy usage

In the previous two sections, it was explained how the distribution of land uses generates transport needs between these. The more concentrated these land uses are through the density of the built environment, the lower transport needs are to be expected. Travelled distances are shorter, thereby both reducing the amount of energy required for travel and making walking (and cycling) more feasible transport modes. Combining multiple trips into one is also more feasible in areas with higher land use mix. For motorised traffic, then, urban areas with higher densities and higher land use diversity would consume a lower total amount of energy for transport than areas with low building densities, a low degree of land use mix and larger distances between the land uses. Since building density and land use mix react to spatial configurations of the form and structure of cities (Ye and van Nes, 2014), it is expected that spatial configuration and transport energy usage also are related. This effect of the structure on transport is investigated in this dissertation.

In the following three sections, the theories on spatial relationships used in this dissertation are explained.

2.3.6 The theory of spatial combinatorics

This theory describes how objects placed in space contribute to the integration or the segregation of spaces (Hillier, 1996, p. 216-261). The theory was developed in the search of an architectural theory for buildings, but it also applies to the macrolevel of scale. It emphasises how local interventions, which can be translated as design choices, affect the generic function of a space and eventually its spatial configuration. Within the larger complex system of networks, the theory extrapolates how local interventions to the network may affect the global spatial system.

The theory of spatial combinatorics helps understand how, when a system of interconnected (convex) spaces is partitioned by placing objects (e.g. buildings) in it, one or more shortest routes between two or more subspaces will no longer be available, and a detour must be made. It follows that, in total, more topological steps (i.e. directional changes from one subspace to another) are required to reach from all spaces to all other spaces. The partitioning of spaces in different configurations yields four principles to describe spatial relationships (Hillier, 1996, p. 226-234):

- **Centrality**, where the more central a fixed object is placed on a line or in a system or sequence of spaces, the more the total topological depth of the entire system increases (Hillier, 1996, p. 226-228);
- **Extension**, whereby longer partitions dividing up convex spaces create more depth gain than shorter lines (Hillier, 1996, p. 228-230). This is intuitive since longer lines (i.e. street segments) tend to be part of more shortest routes in a system than short lines. If that long line is broken up, more routes will be affected, which adds to the total topological depth gain of the whole system. This can be generalised by considering the partitioning in relation to the whole: the larger the system that the partition is a part of, the lower the total depth gain (Hillier, 1996, p. 226-234);
- **Contiguity** relates to the scale or size and the shape or geometry of the partitioning object. The principle demonstrates that large contiguous objects require longer detours than small separate objects, thus total topological depth increases more (Hillier, 1996, p. 230-232); and the principle of
- **Linearity**, which states that linearly shaped contiguous objects increase topological depth more than contiguous objects that are coiled or block-shaped (Hillier, 1996, p. 232-234).

This theory is helpful for understanding the basic spatial elements and their fundamental spatial interrelations: since connecting spaces (e.g. making new street connections) in a system is essentially the inverse of partitioning spaces, the four principles of spatial combinatorics that describe *gain* of topological depth gain also govern the *loss* of topological depth. Thus, the more central, extended, contiguous or linear a larger space (or: a new connection) is positioned in relation to the whole system of spaces, the higher the loss of topological depth – and therefore the increase of integration – in the entirety of the system (Hillier, 1996, p. 236-239). A well-integrated city with efficient connections in its network should reflect low topological values. The use of spatial combinatorics to define structures as a system of spaces partitioned by various objects placed in them allows this dissertation to examine spatial configurations systematically.

2.3.7 The theory of natural movement

"Urban grids … evolve and grow in such a way as to ensure that natural movement is linearly predictable from spatial pattern, because the structuring – and therefore the predictability – of movement is the fundamental purpose of the grid."

(Hillier et al., 1993, p. 64)

The theory of natural movement links spatial configuration with human activities through movement as opposed to the theory of spatial combinatorics that governs how objects configure space. Natural movement states that unambiguous human movement flows in built environments when all other elements are equal (van Nes and Yamu, 2020) are generated by and depend on the degree of spatial integration of the street network (Hillier and Hanson, 1984). Natural movement in a network is defined as "…the proportion of urban pedestrian movement determined by the grid configuration itself" (Hillier *et al.*, 1993, p. 32). The theory also applies to vehicular movement (Penn *et al.*, 1998; Serra and Hillier, 2017, 2019). The higher the spatial integration on various levels of scale, the higher the flow of natural human movement (Hillier *et al.*, 1998). Spatial integration has an exponential effect on movement. This relationship is not linear, but logarithmic as "…movement is usually post-dicted best by integration against logged movement rates" (Hillier *et al.*, 1993, p. 44). The spatial configuration of the street network influences not only the flow of human movement but also the location pattern of shops (Hillier and Iida, 2005; Hillier et al., 1998; van Nes and Yamu, 2020). Here, spatial configuration is observed to influence movements and attractors in urban space (see Figure 3). This observation is based on the rationality that businesses strive unambiguously to maximise profit and do so by seeking to attract as many potential customers as possible. Hence, the proximity of the location to potential customers is essential to economic success. This is evidenced in most retail streets having high amounts of pedestrian movements, also known as footfall.

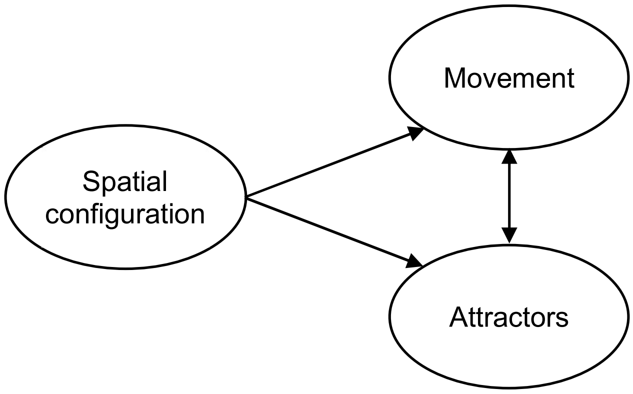


Figure 3 Diagrammatic representation of the relationship between configuration, movement and attraction (Figure 3 in Hillier et al., 1993, p. 31)

2.3.8 The theory of the natural urban transformation process

To discover the spatial relationships between building densities, land use mixes and movement, a sister theory is required which is derived from the theory of natural movement, namely the theory of the natural urban transformation process. The theory states that the spatial configuration of the street network is the "...spatial framework of the socio-economic component of the built environment" (van Nes and Yamu, 2020, p. 7). It argues that higher spatial integration on various levels of scale leads to higher building densities, whereby more functions and potentially more types of functions can occur to allow for land use diversity in urban areas (van Nes and Stolk, 2012; Ye and van Nes, 2014) (see Figure 4).

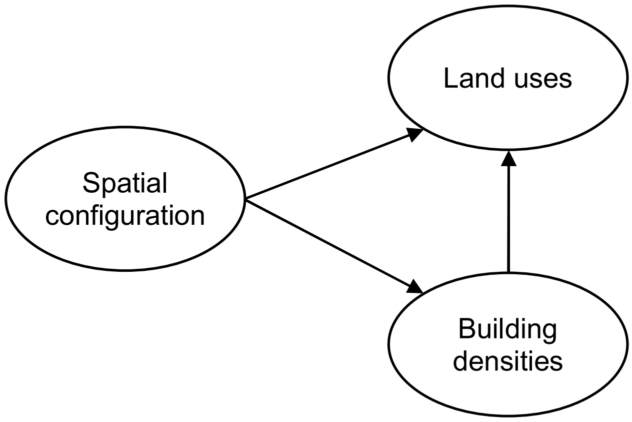


Figure 4 Diagrammatic representation of the natural urban transformation process. Adapted by the author from: (Ye and van Nes, 2013, p. 34, Figure 15).

These proposed relationships above are corroborated by studies conducted on most cities worldwide over the last decades[1]. The applicability of this theory to cities of different sizes and cultural contexts testifies to the external validity of the resulting method. This interrelationship between movement, land use and building densities (Figure 4) regarding spatial configuration are the fundament of conceptualising spatial relationships in cities, which is the aim of this dissertation.

2.4. Theoretical limitations for understanding spatial relationships

The above building blocks (concepts and theories) allow for a systematic understanding of spatial relationships, within the following limitations:

- Human activity and behaviour are complex and not always predictable, whereby measurable urban form is not always an absolute nor complete reflection of society via its use of urban form;
- The occurrence of the density paradox, whereby the trade-offs between density and sustainability are not fully captured by how density is measured; and
- Context dependency, whereby socio-cultural peculiarities in each situation sometimes defy how objective urban form and spatial configurations can be perceived and measured.

2.4.1 Human activity and behaviour

Through the urban-morphological approach, real patterns and regularities of different phenomena in urban areas are found. However, the approaches strive for objectivity by assuming homogenous perception and habits, which is difficult to align with how people perceive and use the urban areas that they inhabit or visit as every individual will differ in how they utilise urban space. Furthermore, the definitions of the elements that pertain to urban structures and forms are often imprecise or subjective. The theory of natural movement and derivative theories are amongst the most convincing theories available explaining the relation between spatial

[1] For an overview, see the Journal of Space Syntax (http://joss.bartlett.ucl.ac.uk/journal/index.php/joss), the special issue of Sustainability (https://www.mdpi.com/journal/sustainability/special_issues/space_sus_city) and the proceedings of the biennial International Space Syntax Symposia (https://www.spacesyntax.net/symposia/).

configurations of urban structures and human activity and behaviour. However, this is only the case when the generic understanding of space or the assumed homogeneity of individuals are not open to interpretation. Here, the urban network approach falls short as well. The likelihood of a route chosen as expressed through mathematical principles presupposes that there are no irrational intentions or reasons to deviate from the simplest route from origin to destination. Other factors such as the presence of specific places of interest, personal habits, a hilly landscape, slopes and elevation differences play a role in pedestrian route choice. In warm climates, shading is a factor that heavily influences walking route choices (see for example: Luta *et al.*, 2017), whilst sun exposure and protection from rain and wind might be of influence in colder and wetter climes. To conclude, the chief value of the theories and approaches used in this dissertation is that they allow an objective description of spatial relationships. The unpredictability of human behaviour means that these objective descriptions are at best an intelligent approximation of what most behaviour would adhere to. Of course, more complex methods exist to understand human behaviour and movement. However, as with most measures, a balance needs to be sought between variations and generalisability of findings.

2.4.2 The density paradox

The implications of various densification patterns on human movement and further spatial development are a key feature of this dissertation. An argument in favour of higher densification patterns locally (i.e. the concept of the 'compact city') is the assumption that these support more economic activity in walkable ranges, making effective use of space, resources and infrastructure shared by more persons. There are multiple claims that compact cities are by default more sustainable (Jabareen, 2016). That density equals to sustainability can also lead to extreme situations where social and ecological sustainability are ignored. Consider for example the densely built residential towers in low-income settlements in Hong Kong. Those are compact and dense, but not necessarily sustainable. Conversely, a 'green city' that is more dispersed and able to facilitate recreation, biodiversity, food production, water runoff management and urban cooling might be more sustainable and desirable in comparison. There is therefore a threshold of density between efficiency and social and ecological desirability (Neuman, 2005; Rådberg, 1988, 1996). Current approaches for studying spatial configuration are still limited. The density calculations commonly employed only produce a range on densities but not normative judgement on which is more desirable or an assessment of which is more sustainable. This dissertation acknowledges this limitation and uses density in relation to mix of functions to approximate sustainable development. Future research should seek nuance and become less ambiguous through the refinement of the theory of urban typo-morphology. This refinement must include more studies of as many varied examples as possible to distil universal and generalisable values and caution applied to blanket assumptions that dense means sustainable.

2.4.3 Context dependency

The biggest advantage of the urban network approach is the fact that spatial configuration can be assessed objectively. Texture, shape, form, or any subjective associations with the built environment are eliminated as variables. What is left is the organisation of the spaces in relation to each other. This relational value makes the method robust, internally valid and suitable for the comparison of spatial configurations across vastly different contexts. For example, researchers have used this method to compare spatial configuration with real estate prices (Law *et al.*, 2022; Law *et al.*, 2013; Law *et al.*, 2017), crime rates (van Nes and López, 2010) and mortality rates by natural disasters (Fakhrurrazi and van Nes, 2012) to name a few. However, it is evident that not all urban phenomena are linked to spatial configuration alone. They are co-dependent, and other urban form factors play a role such as street profiles, size, shape, texture and form of buildings, the quality of the design of the public domain, the presence of (un)pleasant sensory experiences and more. Although the method allows for an objective assessment of the influence – "all other things being equal" (Hillier, 1996; Serra and Hillier, 2017, p. 1) – of the spatial configuration of urban structures on these phenomena, some knowledge of the local context will always have to be taken into consideration. This dissertation acknowledges this theoretical limitation and has employed validation of the findings with local experts when possible (de Koning *et al.*, 2020a).

2.5. A theoretical framework for spatial configurations

This chapter has presented the building blocks of spatial configurations and how they are represented and measured considering the underlying theories. This becomes the theoretical framework for understanding spatial relationships in urban areas through their urban structures, densification patterns and human activity and behaviour regarding mobility. Two key theoretical approaches were used: i) the urban-morphological approach and ii) the urban network approach. Whereas the urban-morphological approach studies urban form and establishes patterns and typologies based on shape, form, texture, materials etc., the urban network approach studies urban areas as a continuous sequence of interconnected spaces.

Using these approaches, this chapter present five building blocks for understanding spatial relationships. These are i) urban structure as spatial configuration, ii) urban form, iii) building density, iv) land use mix, and v) transport energy usage. These building blocks can be understood through three theories: i) the theory of spatial combinatorics, explaining how the spatial relations between the various subspaces contribute to integrate or segregate spaces in relation to all others; ii) the theory of natural movement linking movement to spatial configuration; and iii) the theory of natural urban transformation, describing the interrelationships between spatial configurations, building densities and land use mixes. These theories link spatial configuration to densification patterns, understood through building density and land use mix, and movement patterns, understood through transport energy usage (see Figure 5). These building blocks and theories can explain the differences between various urban forms. Self-organised urban form, which evolves incrementally over a long period of time, features naturally mixed land uses and efficiently structured movement. Modernist urban form, which stems from ideals for liveable cities, erases the human scale and natural mechanisms that are indispensable for economic and social interaction in cities.

However, this framework for understanding spatial relationships in cities has three limitations. Firstly, human activity and behaviour are not always unambiguous, and subjective aspects also affect how individuals use urban areas. Secondly, the density paradox describes how the two diverging concepts of the ‘compact city’ and the ‘green city' each focus on diverging aspects of sustainability, instead of being considered simultaneously. Lastly, while analysing urban structures through the urban network approach has the merit of being objective, one always relies on some knowledge of the area of study that depends on the context.

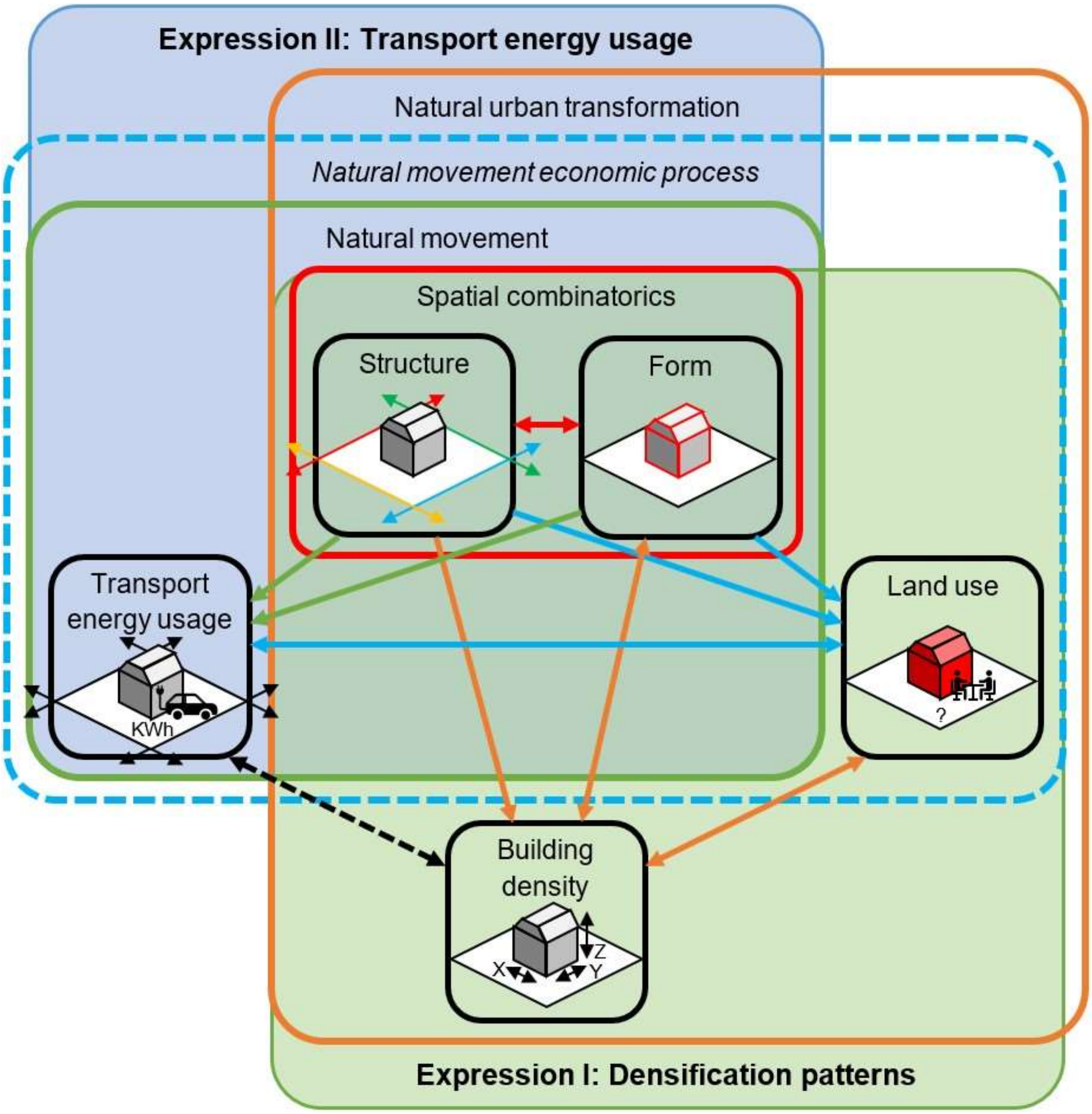
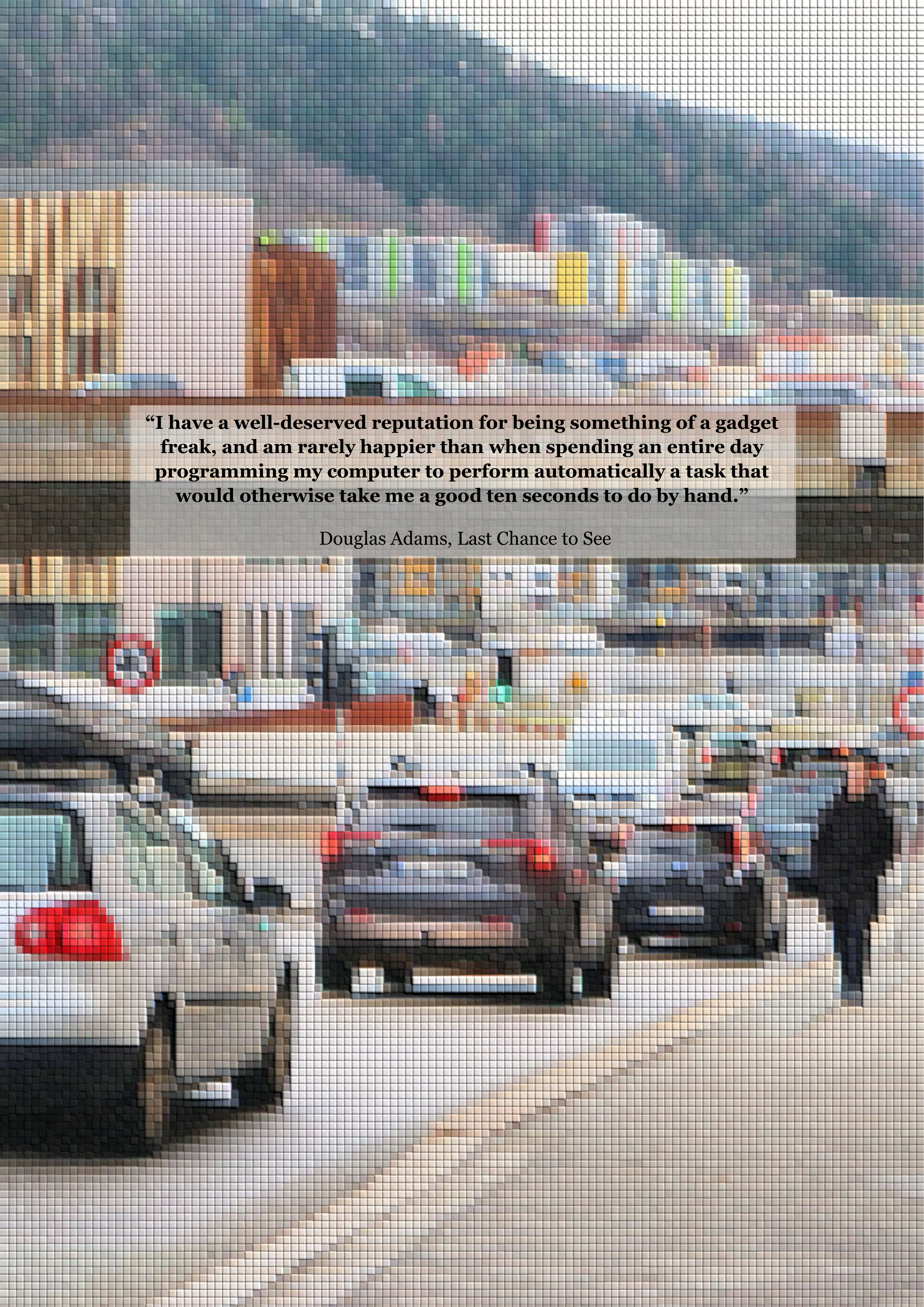


Figure 5 Building blocks linked to their affiliated theories and expressions. Source: author.

The theoretical building blocks for understanding spatial relationships will be tested through a combination of methods for operationalisation. These methods are presented in the next chapter.



“I have a well-deserved reputation for being something of a gadget freak, and am rarely happier than when spending an entire day programming my computer to perform automatically a task that would otherwise take me a good ten seconds to do by hand.”

Douglas Adams, Last Chance to See

3. Methodology

This chapter describes the methodological approach used to conduct the research and a description and evaluation of the various analysis methods that are applied. Section 1 elaborates on the research design approach used for this study. The second section presents the case studies that were selected for the research. Section 3 describes the building blocks for operationalising the research and its associated analytical methods. In the fourth section, the data sources and collection process are explained, as well as the (limitations to) data availability. The fifth section explains the steps in the scientific workflow of aggregating, coding and analysing the data, including the automated steps in the workflow. Section 6 describes the software tools used to conduct the research. The final section reflects on the limitations of the methods used and explains how validity and reliability are achieved.

3.1. Research design

Aiming to understand the structures and forms of cities and the spatial relationships therein expressed as densification patterns and transport networks, this dissertation performs an exploratory, quantitative cross-case comparison whereby spatial relations are the unit of analysis. Although it is possible to use qualitative methods, this dissertation chooses to employ quantitative methods based on the theoretical pillars described in the previous section to deduce a descriptive understanding of the studied phenomena. Studying spatial relationships and interrelated phenomena through the structure of space minimises the use of linguistic significations, allowing objective research free of subjective values.

This dissertation employs a design science research (DSR) approach. The approach relies fundamentally on the exertion that gaining knowledge and understanding about an unsolved design problem and its solution is done by building and applying an artefact. The choice of a DSR is justified because the aim of this dissertation is to solve an explicit practical problem (i.e. designing cities to become more sustainable than at present) whilst lending from the theoretical knowledge base (i.e. the theories of spatial combinatorics and natural movement) aiming to make a theoretical contribution (i.e. a better understanding of spatial relationships) regarding how the problem can be solved in principle through the construction of an artefact (i.e. a partially automated workflow for analysing spatial data) (see Figure 6). For the research to obtain relevance, there needs to be a clear practical application in a real-world environment, i.e. people or organisations that can apply the research artefact using available technologies. By grounding the research in foundations (e.g. theories and methods) and methodologies in the knowledge base, the research gains rigour. Lastly, the research must contribute to the knowledge base by answering a heretofore unanswered question in a novel way. The relevance, rigour, practical application and theoretical contribution are discussed below.

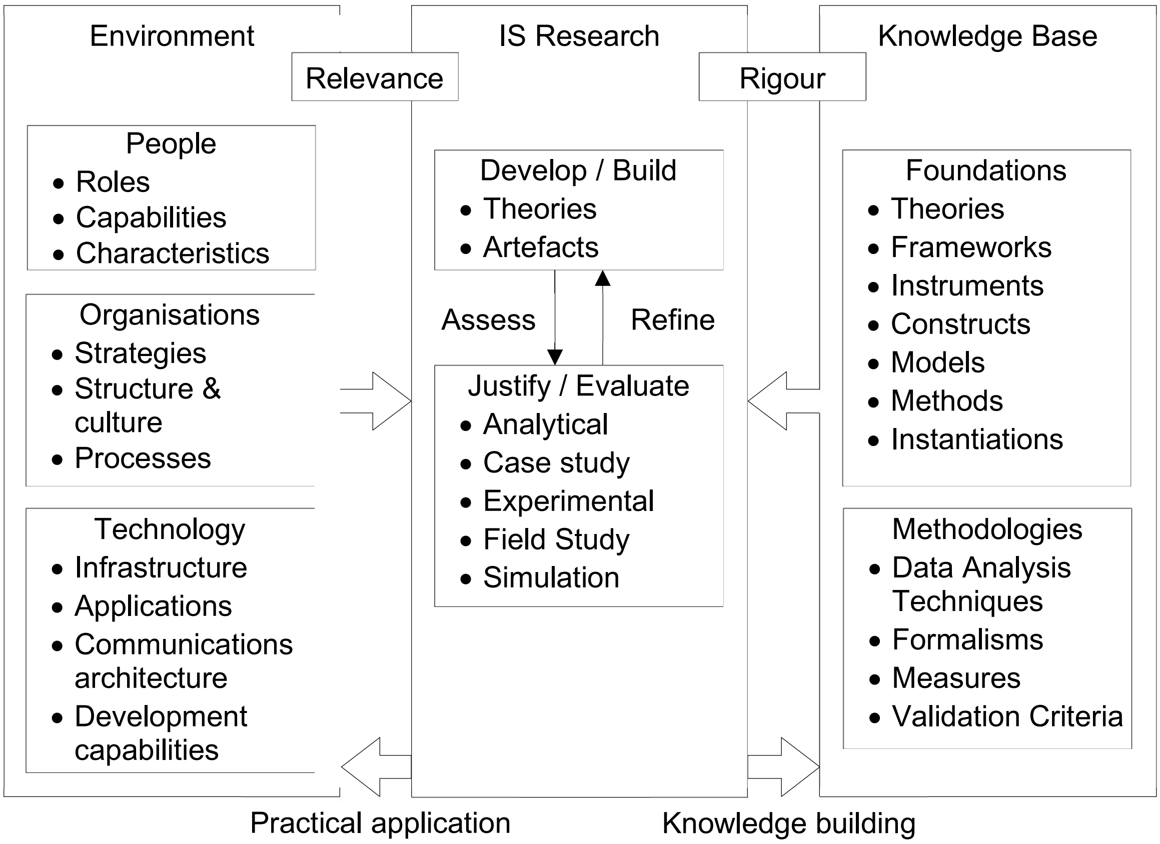


Figure 6 Information Systems Research Framework.
Source: (Hevner et al., 2004, p. 80, Figure 2).

3.1.1 Relevance: practical application in the environment

The research is practically relevant to academics, practitioners and policymakers, each with their specific tasks and capabilities, who work with Geographical information Systems (GIS) and other geocomputational software programs to achieve the various goals (such as the Sustainable Development Goals (SDG)) through practical spatial planning efforts, or to gain knowledge about how to meet these goals in principle. During previous cooperation with the planning department of the City of

Bergen and a consulting partner, it became apparent that limitations were experienced in i) technical (computing) skills of some of the involved stakeholders, ii) combining and interpreting the various spatial data, and iii) the magnitude of the workload associated with the steps in the geocomputational workflow. This dissertation argues that these limitations can be mitigated by creating a practical workflow for analysing urban structure and form using geocomputational software tools for understanding spatial relationships better (see Figure 7). Applications commonly available to the relevant users (i.e. GIS) are utilised to build the artefact. This software is used by professionals in a wide array of domains concerned with geocomputation, and the software is well-established through a long process of refinement and testing. Hence, the artefact can be applied practically, as well as be modified to custom needs or further developed by users with basic geocomputing skills.

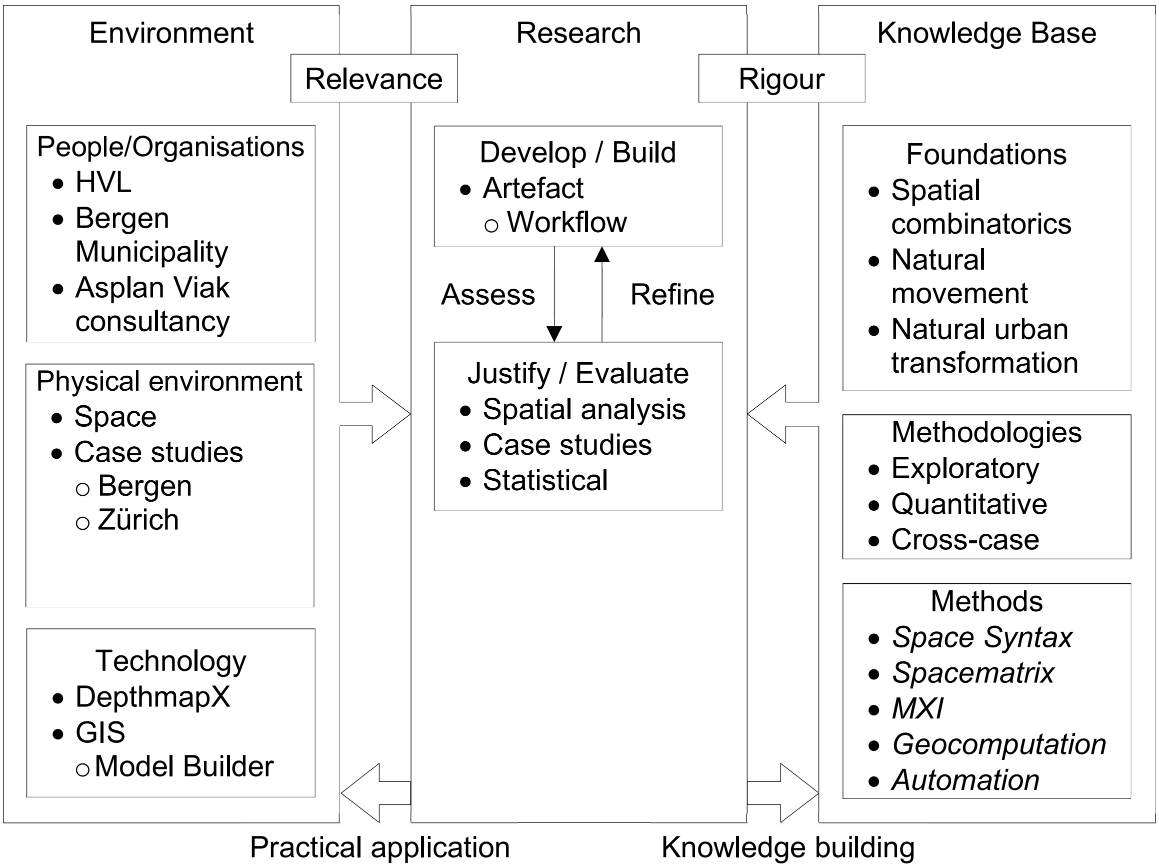


Figure 7 Design science research diagram.
Adapted by the author from: (Hevner et al., 2004, p. 80, Figure 2)

3.1.2 Rigour: theoretical contribution to the knowledge base

Achieving rigour is done by "appropriately applying existing foundations and methodologies" (Hevner *et al.*, 2004, p. 80). The existing theoretical foundations this research is based on are the theories of spatial combinatorics, natural movement and the associated theory of natural urban transformation, as described in Chapter 2. These theories explain how movement, building density, and land use mix are associated with urban structure and urban form, and which measures and affiliated methods need to be considered. Therefore, these theories are guiding in the design of the artefact, which operationalises the building blocks and affiliated analytical methods addressed by these theories.

The methods used in the analytical workflow and the workflow itself are used in a consistent and objective way. Subjective interpretations are eliminated, yet these are explained in a transparent manner where they do occur (see for example the critique on hand drawing axial lines and classifying land uses in Section 3.7.2).

Crucial for DSR is to offer an innovative way of solving a relevant problem. This dissertation proposes to answer the main research question (MRQ) through application of an artefact (i.e. a workflow which is partially automated via an executable model). This artefact addresses the knowledge gaps identified in Section 1.3. It is intended for academics and practitioners (such as city planners in the public sector and spatial analysis consultants in the private sector) who study urban structure and form using commonly used GIS software and encounter problems relating to the necessary level of expertise, access to data and software, the pros and cons of current software and the ability to visualise, interpret and translate the outputs.

3.2. Case selection

The analytical part consists of a study of the topic as it takes place in real life situations. Two mature European cities in two different countries are studied: Bergen, Norway and Zürich, Switzerland. Whilst there are obvious differences between these cities, they also have some similarities (see Table 1):

Table 1 Properties of the case study areas

	Mid-sized European cities
Spatial configuration	Dense urban spatial configurations ranging from suburban to highly urban
Densification patterns	Wide variation in densification patterns (building density and land use mix) from highly dense to low-density (suburban)
Transport network	Identifiable transport networks (streets and transit)
Planning	Self-organised cities by origin; subjected to various planning traditions
Socio-economic activity	Regional capitals with over 250 000 inhabitants

Based on these similarities, it is anticipated the two European cities display some similarities in densification patterns (see Figure 8 and 9) and comparable spatial configurations. Simultaneously, both cities have distinctive metric and angular properties of the urban structure and unique topographical conditions. Based on these and other factors not considered, both cities display unique variations in densification patterns and movement patterns (i.e. transport usage). This makes it possible to verify whether the various datasets nevertheless 'tell the same story'.

Figure 8 shows how the cases and related publications were used to study densification patterns and transport energy usage. Densification patterns (SRQ1) were studied through the cases of the city of Bergen. Transport energy usage (SRQ2) is studied through the cases of Bergen and Zürich. The following sections provide an overview of the characteristics of the two European cities and a description of the relevant urban form factors they have in common, and what sets them apart.

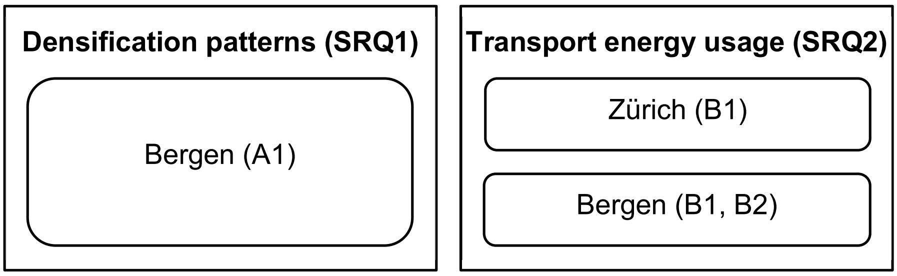


Figure 8 Case studies and related publications (A1, B1 and B2) linked to the research topics. Drawn by author.

3.2.1 Bergen

The city of Bergen, located in western Norway, is the second largest city in Norway. It was officially founded in the year 1070 CE under the rule of King Olav Kyrre as a trade post between the northern trade route and merchants from the south. The exchange of maritime products, mainly cod, from the north and grain and other goods from the south that were unavailable in the northern landscape made the ice-free natural harbour of Bergen the most important trade hub in Scandinavia. The city would become the capital of Norway for the next two centuries to come, in which the Hanseatic League played an important role in fuelling its economic development.

Bergen city is renowned for its topographical situation. The buildings crawl up to the steep mountain slopes on either side as the city extends south through the 2,5 km wide Bergensdalen valley. These mountains present a natural border for how far the city can expand. The steep terrain causes streets and roads to follow a swinging pattern up rather than a straight line to maintain an acceptable gradient. The streets tend to follow the topology, leading to a pattern of streets that run predominantly parallel to the valley in areas with considerable differences in height (see Figure 9).

In 2020, The municipality of Bergen has a population of 285 070 (Statistisk sentralbyrå (SSB), 2021b). 16 per cent of the total area of 465 km2 is built-up land, and an additional 13 per cent is occupied by road infrastructure (Statistisk sentralbyrå (SSB), 2021a). The most important industrial economic drivers are the off-shore industry related to the extraction of crude oil products, fishing and fish-farming. In addition, Bergen has several institutes for higher education, with in total 38 130 enrolled students in 2020 (Statistisk sentralbyrå (SSB), 2021d).

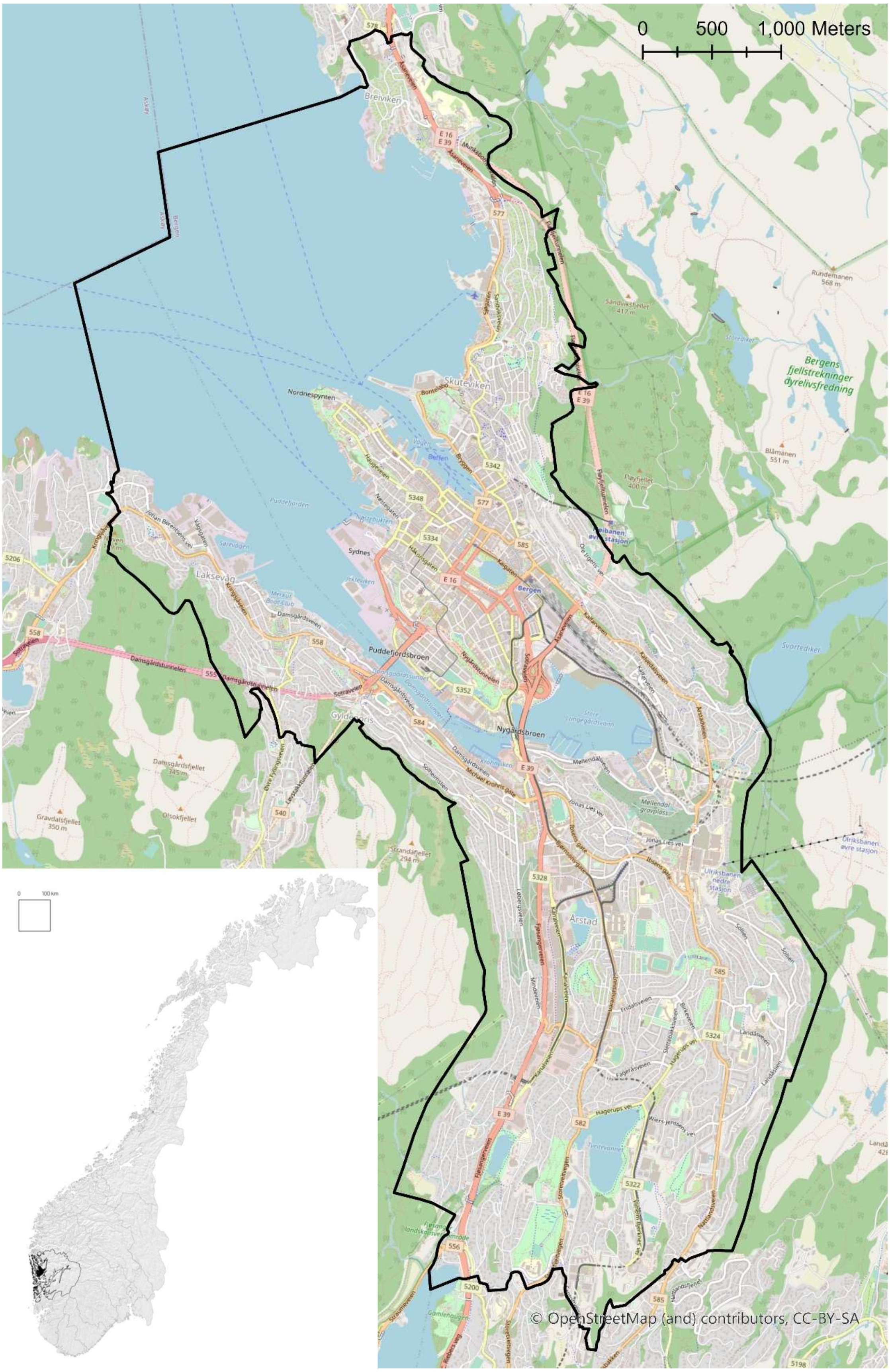


Figure 9 Topological map of the city of Bergen. The study area is outlined in black. Source: OSM (www.openstreetmap.org)

3.2.2 Zürich

Zürich is the capital of Kanton Zürich in northern Switzerland (see Figure 10). It is strategically located on both sides of the river Limmat at its origin at Lake Zürich. It was founded as a tax collection point for goods travelling up and down the river. Zürich is a hub for road, rail and air traffic. The main economic drivers are banking, finances and international business. The municipality of Zürich had a population of 415 367 in 2019 (Bundesamt für Statistik (BFS), 2020).

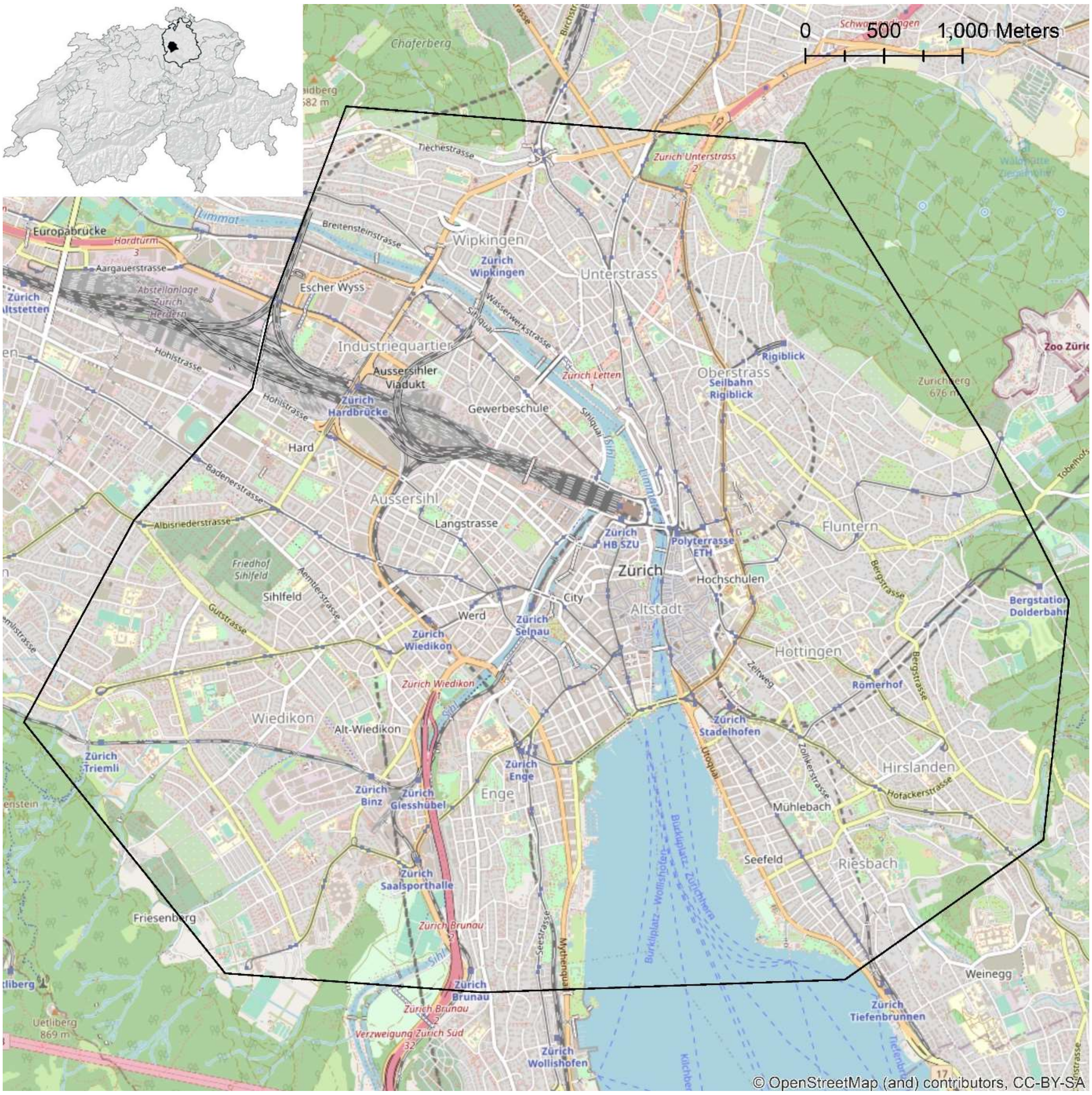


Figure 10 Topological map of the city of Zürich. The study area is outlined in black. Source: OSM (www.openstreetmap.org)

Topographically, the landscape on which Zürich is built is less challenging than that of Bergen: the valley in which the city is situated is much wider and less sloped than is the case in Bergen. On the west bank, where the terrain is relatively flat, the resulting street pattern exists predominantly of grid structures. On the north and east side, where the terrain is more sloped, the street pattern tends to run more parallel to the lake, the river and the sloping terrain, with regular cross connections.

3.3. Building blocks for understanding spatial relationships

The building blocks that were identified in Section 2.3 for understanding spatial relationships in cities (i.e. i) urban structure, ii) urban form, iii) building density, iv) land use mix, and v) transport energy usage) can be understood through the theories of i) spatial combinatorics, ii) natural movement and iii) natural urban transformation. The measures under investigation in this dissertation apply to urban areas in the north-western European context (Karimi, 1998, p. 269) for self-organised and planned urban areas with no excessive car-dependence (as is the case in many North-American cities) and where a stranger is not de facto perceived as a dangerous intruder (as is the case in many South-American and African cities) (see for example: Monteiro and Cavalcanti, 2015). The methods for operationalising these building blocks and theories are described in the following three subsections.

3.3.1 Urban structure: Space Syntax

In Section 2.3.1, it was asserted how segment analysis in Space Syntax best captures through-movement (betweenness) and to-movement (closeness) potentials. These metrics consider all three ways in which distance is measured in Space Syntax: metrically, topologically and geometrically. Through the theory of spatial combinatorics, it was explained how the relational properties (i.e. the three distance measures) between spaces affect the spatial configurational values. The theory of natural movement and associated theories explain how the distribution of these values in turn affect the distribution of building densities and land uses, which are the two building blocks for understanding densification patterns (SRQ1). In addition, it was described how understanding integration, betweenness and closeness on different levels of scale could contribute to explain variations in transport energy usage (SRQ2).

Level of scale

To understand the effect of urban spatial configurations on different levels of scale, both the macroscale (i.e. the city and the region) and the microscale (i.e. the buildings and streets or neighbourhood) are studied simultaneously. The choice of scale is based on the fact that car trips generally are longer than walking and cycling trips, "…and motorists therefore read the matrix of possible routes according to a larger-scale logic than pedestrians" (Hillier, 1996, p. 120).

For the macroscale, a radius (R) of 5 000 m is used. This concerns car-based distances or city scale accessibility, i.e. driving for 5 – 6 minutes at an average speed of 50 km / h. There seems to be a lack of knowledge about how spatial configurations affect energy usage for transport on this level of scale (SRQ2).

On the microscale, there is a need to understand whether and how local spatial configurations influence pedestrian route choice. A radius (R) of 500 m is taken for the local or microscale level. This radius concerns walkable distances or local accessibility, which corresponds to walking for 5 – 6 minutes at an average speed of around 5 km / h. These distances are pertinent to how easy or difficult it is to get to a given location and how likely one is to pass through certain urban spaces (Hillier and Iida, 2005) within certain metric radii. In addition to that, the measures for calculating betweenness and closeness as proxies for accessibility take the angular deviation of each topological step into account.

Axial and segment line map

This section describes the process of creating axial line maps and deriving the segment line maps. As was discussed in Section 2.3.1, axial and segment lines represent traversable lines of sight, i.e., covering areas that are both visible and accessible. Hence, mapping spatial structures in this way captures the visual-cognitive aspect of orientation and wayfinding as well as the relational aspects of interconnected spaces.

Various spatial software tools can be used to draw axial and segment line maps, including DepthmapX, various CAD-software and GIS. For this dissertation, GIS is used to align with other urban form data and for georeferencing. First, the longest lines of sight are drawn by identifying the longest physically traversable convex spaces in the urban system and mouse-clicking at either end of these spaces to mark the beginning and end of each line. Next, all lines that intersect these longest lines of sight are drawn, and so on, until all convex spaces in the system of spaces are covered and connected. A set of simple rules of thumb is applied to check the correctness of the axial map (Hillier and Penn, 2004, p. 507):

- Can a line be extended to make further connections?
- Can two lines be simplified into one?
- Are all pairs of lines which have a direct connection connected by a line?
- Are all parts of space covered?
- Are all 'rings' around built forms represented?

When the above conditions are satisfied, the axial lines that cross, but are not linked, such as bridges, viaducts, underpasses or tunnels, need to be identified. In a separate file, each 'unlink' is marked with a point on the intersecting lines. This file is imported into DepthmapX to inform the software which intersecting lines on the axial line map are not connected. The last step is to split all axial lines where they intersect to obtain the segment line map, which is a required step for performing the analyses below.

Angular Choice

Angular choice, or 'betweenness', represents how likely a segment is part of a route, or: how likely one is to pass *through* a segment when moving from any origin to any destination in a built environment. It measures the number of times each street segment falls on the shortest path between all pairs of segments within a selected metric distance (termed 'radius'). The 'shortest path' refers to the path of least angular deviation (*geometrical* distance), in other words the straightest route through the system (Rashid, 2017, p. 475). Angular choice is used for relating spatial configuration of complex built environments to transport energy usage (SRQ2) since it correlates better with vehicular flow than axial analysis (Hillier and Iida, 2005). This is especially the case on the citywide level of scale (R = 5 000).

Angular Segment Integration

Segment integration, or 'closeness', shows how easy it is to get *to* a street segment from all other segments within a selected metric distance. It measures how close each street segment is to all others in terms of the sum of angular changes that are made on each route (Rashid, 2017, p. 475-490). If the value is high, the street segment (a segment of a street between two junctions) that the segment line represents is more likely to be a destination than if the value is low. In other words, streets with high values have a higher expected footfall. The theory of natural movement and affiliated theories explain that non-residential land uses (e.g. shops) rely on footfall for the best efficiency or productivity (e.g. profit). Therefore, angular segment integration as a measure of the spatial configuration of the urban structure is pertinent in investigating the relation with densification patterns, which is the aim of this dissertation (SRQ1) (de Koning *et al.*, 2017; de Koning *et al.*, 2020a).

Aggregated Angular Choice

Showing angular choice for high and low radius simultaneously helps to find out which areas are well-integrated into the local street network and enjoy good accessibility on the citywide scale. The method of representing local and global scale together was developed recently (de Koning and van Nes, 2017, 2019; de Koning *et al.*, 2017; Maiullari *et al.*, 2019).

First, the values that were generated and normalised for angular choice for the low radius (R = 500 m) and the high radius (R = 5 000 m) are categorised for each segment into low (L), medium (M) or high (H) values according to the natural break method (ESRI, 2021b; Longley and Batty, 1996). Then, the values are aggregated, allowing for a combination of nine aggregated choice categories that might be associated with possible street typologies (see Table 3 in de Koning *et al.*, 2020b, p. 9). For example, segments with low local betweenness values and high citywide values are expected to exhibit higher energy usage by cars than segments with high local betweenness values and low citywide values. This simultaneous assessment of potential through-movement on two levels of scale is important for gaining insights into route choice and mobility choices (MRQ, SRQ2) (de Koning *et al.*, 2017; de Koning *et al.*, 2020b).

3.3.2 Urban form: densification patterns

The methods described in this section relate to properties of buildings, notably the typo-morphological classification (i.e. building density and form on plot level) and its functional capacity (i.e. what the buildings are used for). These two measures are examined to understand the distribution of building densities and land uses in relation to spatial configuration (SRQ1). Although each individual building is catalogued, the analysis focuses on the aggregated results on macroscale level to identify patterns, similarities and discrepancies between different areas in the case studies (de Koning *et al.*, 2020a).

Building density

Density can be calculated in two principally different ways. On the one hand, density expressions can be derived from population, such as population density, housing density and workplace density. Values are commonly expressed as a factor of space, for example: inhabitants per hectare. These are good indicators for comparing the potential amount of social life and economic activity between areas. However, they are unable to express the spatial conditions to which these activity patterns pertain.

To put population density and workplace density in a spatial perspective, an expression of the density of the built mass in spatial terms is needed. Rådberg developed a method to express building density in relation to the amount of floor space area per land use and the total plot size of the land use (Rådberg, 1988, p. 7-9). The method has become most known as Spacematrix, with the variables Floor Space Index, Ground Space Index and Open Space Ratio (see Figure 11):

a) **Floor Space Index (FSI)** indicates the building intensity. It reflects the ratio of total floor space inside the building to the land use plot area;
b) **Ground Space Index (GSI)** indicates plot coverage, i.e. the percentage of the land use plot that the building covers with its footprint; and
c) **Open Space Ratio (OSR)** reflects the degree of 'spaciousness'. This measures the amount of available open space in relation to the amount of floor space inside the building.

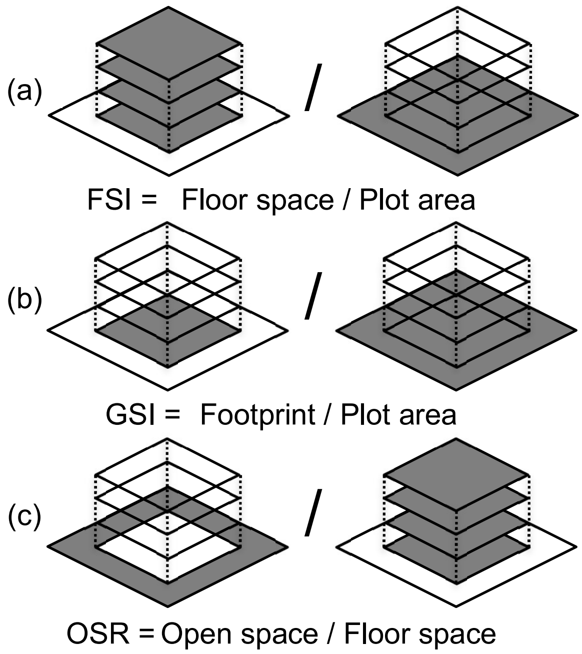


Figure 11 (a) FSI, (b) GSI and (c) OSR. Source: author.

By categorising FSI and GSI into low, medium and high values for each building, 9 typologies of their morphology can be identified. For example, high-rise buildings tend to have a high FSI (a high amount of floor space) and a low GSI (i.e. a small footprint) in relation to the land use plot. Conversely, industrial buildings (e.g. factories, warehouses) often have a low FSI and a high GSI in relation to the land use plot. Analysing building densities through these metrics is pertinent for understanding spatial relations of densification patterns (SRQ1).

Land use mix

Measuring and indexing the degree of functional mix is necessary for understanding densification patterns as expressed through the land uses. This degree of functional diversity is represented quantitatively as a ratio of specific types of activities. Three types are distinguished: amenities (for commercial, social, cultural and institutional land uses), offices (and factories, for workplaces) and housing (for all residential land uses) (van den Hoek, 2009). Dovey and Pafka (2017) use the same categorisation, yet call the categories 'visit', 'work' and 'live' respectively. Calculating the resulting ratio of the mix of the three types of activities (in ratio of floor space for each) is referred to as the Mixed-Use Index method.

An urban block consisting of a group of buildings with functions from each category is classified as multi-functional. Conversely, a purely residential urban block or neighbourhood is categorised as mono-functional. Likewise, individual buildings can contain one or more functions (this is sometimes called vertical mixing). In this case, the ratio can be calculated by considering the ratio of floor space allocated to each function. As an example, a four-storey apartment building with a shop on the ground floor is categorised as bi-functional with a ratio amenities / office / housing of 1 / 0 / 3, or a percentage of 25% / 0% / 75%.

3.3.3 Variables for transport energy usage

Energy consumption was calculated for each street segment for a twenty-four-hour interval. The calculation consists of four variables:

1. speed (maximum allowed traffic speed);
2. distance (length of the street segment);
3. volume (Annual Average Daily Traffic (AADT)); and
4. average energy consumption per vehicle (MacKay, 2009).

One car is assumed equal to one passenger trip. Maximum speeds, distance and AADT were sourced through publicly available road data, specifically from OpenStreetMap (OSM) and from the Norwegian Public Road Administration's (Statens Vegvesen, SVV). For the Zürich analysis, traffic data was generated through The Agent-based Transport Simulation program called MATSim (Horni *et al.*, 2016). By combining the average energy consumption for one vehicle travelling the distance of a given street segment with the maximum speed for that segment and multiplying by the total number of cars passing that segment each day, the total average daily energy consumption is calculated for each segment. A detailed description of the method for calculating energy usage from the four variables can be found in (Section 3.5 in de Koning *et al.*, 2020b, p. 8-10).

3.4. Data sources and collection

To answer the research questions put forward in the introduction, a range of data are required that can be categorised according to the building blocks they represent. This data is also used to test the executable model. The inputs for the spatial analyses are georeferenced digital maps in the ESRI® shapefile format (.SHP). These contain the data pertaining to the building blocks defined in this dissertation:

- **Urban structure**, represented as line segments. In a new file spatially matching the urban form data, axial line maps are hand-drawn in GIS such that the lines cover all the spaces in the system and describe all the connections in the network between the spaces. From these maps, axial integration, betweenness and closeness values are generated in DepthmapX as attribute data;
- **Urban form**, represented as polygons, contains the dimensions and spatial locations of the buildings with a high level of accuracy. The attribute data include land use, number of floors and number of housing units. For the spatial location of the roads and streets, Road Center Line (RCL) data is sourced from OSM;
- **Building density**, this data is calculated from the dimensions of the polygons in the building shapefile and the land use plots shapefile (when available);
- **Land use mix**, or functional use, is stored as attribute data in the building shapefile and is supplemented manually where unavailable;
- **Transport energy usage**, stored in proprietary shapefiles as measured and simulated attribute data, where the maximum driving speeds and average daily traffic volume are the relevant attributes. Its spatial geometry matches that of the OSM RCL data.

3.4.1 Data availability

The overall aim of the dissertation and limitations on the availability of data led to the choice to focus only on comparing energy data from private car use with spatial configuration. Energy usage by cars is the one mode that is most practical for comparing transport energy usage with spatial configuration. Furthermore, car energy usage is most representative for transport energy consumption by citizens in Western-European cities as a derivative of spatial configuration. There are several reasons for this. For the first, only accurate car traffic data could be obtained for Bergen. For Zürich, calibrated, simulated traffic was used. Secondly, energy consumption from travelling by public transport was not considered, since public transport lines are subject to non-rational planning choices and do not always follow the most integrated, fastest or shortest routes whereas private car drivers do, provided that road policies allow it (some streets are one-way, car-free or for public transport only). Similarly, goods transport is bound to specific locations that often are situated in more peripheral areas (distribution centres, transhipment facilities etc.). Furthermore, the current data availability for both cities makes it difficult to determine the itinerary of public transport passengers, and therefore it is impossible to accurately predict how many trips a bus line represents. For cars, on the contrary, each trip is assumed equal to one passenger.

Agent-based simulations provided by the MATSim model can generate trips for different transport modes, including transfers to different lines and modes underway. However, the agents' route considerations are determined according to a travel cost algorithm. The most cost-effective route, then, is not necessarily always the 'simplest' route (i.e. the route with the fewest turns and the least angular deviation, see Section 3.1). The measured traffic data for Bergen is therefore expected to reflect actual traffic more accurately. Lastly, energy consumption from walking and cycling were not modelled since pedestrians and cyclists move around using energy which they 'produce themselves'. Moreover, registrations of pedestrian movement patterns in the case study areas could not be made for both cities due to worldwide restrictions on free trade, free travel and freedom of movement imposed by the national governments of Norway and Switzerland from March 2020.

3.4.2 Data description

Table 2 below lists the input data necessary for analysing spatial relationships (this dissertation). Spatial configuration values are derived from the hand-drawn axial maps and obtained through calculations in DepthmapX. These are stored as secondary data representing betweenness (choice) and closeness (segment integration) on the two levels of scale described in Section 3.3.1. The values for aggregated angular choice combining both radii are calculated from these inputs.

Table 2 List of variables used in the scientific workflow

Variable	Description
Spatial configuration (Urban structure)	
Global Integration (R = n)	Integration at the citywide scale
Local Integration (R = 3)	Integration at the local scale
Normalised Angular choice (R = 500) (NACH500)	Through-movement potential (betweenness) with 500 m metric radius
Normalised Angular choice (R = 5 000) (NACH5000)	Through-movement potential (betweenness) with 5 000 m metric radius
Normalised Angular segment integration (R = 500) (NAIN500)	To-movement potential (closeness) with 500 m metric radius
Normalised Angular segment integration (R = 5000) (NAIN5000)	To-movement potential (closeness) with 5 000 m metric radius
Aggregated angular choice (CAGGR)	Combination of high radius and low radius through-movement potential (NACH500 × NACH5000)
Densification patterns (Urban form, building density and land use mix)	
Floor Space Index (FSI)	Building intensity
Ground Space Index (GSI)	Plot coverage
Plot size	Area of the land use plot
Amenities	Percentage of land use for amenities
Offices	Percentage of land use for offices
Housing	Percentage of land use for housing
Mixed-Use Index (MXI)	Functional mix / land use mix (Ratio % Amenities / % Offices / % Housing)
Transport networks (Transport energy usage)	
Maximum speed	Maximum speed in km / h
Annual Average Daily Traffic (AADT)	Average traffic volume in cars / day
Energy Consumed without Stops	Total car energy usage per street segment per day (kWh / day)

Of the six variables concerning building data, the first two, building intensity and plot coverage, are derived from the primary building data and plot data, i.e. the spatial dimensions of the entities. The land use (through 'Amenities', 'Offices', 'Housing' and the aggregate of these, 'MXI') is obtained from attribute data for the case of Bergen. This data was partly lacking for Zürich and was therefore supplemented manually. In the traffic data files, the two attributes for maximum speed and average traffic volume are needed to calculate total car energy usage per street segment per day. The individual data files are described in detail in (de Koning *et al.*, 2022).

3.5. Data aggregation, coding and analysis

3.5.1 Data aggregation

To prepare the data for statistical correlation using the methods above, the different spatial layers need to be coupled on a GIS platform. This coupling is performed according to certain spatial parameters. ESRI® ArcMap offers a range of tools that combine data based on spatial match options. Spatial Join, for example, is a common function in ArcGIS software for aligning various data according to certain spatial parameters such as the closest object, an object within an object, an object within a certain distance, joining an object to one or many, etc. (see: ESRI, 2021c; de Koning *et al.*, 2022).

3.5.2 Workflow

This section describes the 19 steps taken in the scientific analysis process regarding the data and associated methods described in the previous sections. The process can be divided into three stages: i) data collection, ii) data preparation and iii) data comparison. The tasks are listed in Table 3 below. A schematic diagram of the workflow is shown in (Figure 2 in de Koning *et al.*, 2022, p. 8).

Table 3 The 19 steps in the workflow of data collection, preparation and comparison

Step	*Action*	*Application*	*Tool*	*Manual/ Automated*
		Data collection		
		Spatial configuration (Urban structure)		
1	Draw axial line map	ArcMap	Map Editor	Manual
		Densification patterns (Urban form, building density and land use mix)		
2	Obtain building data	ArcMap	Attribute editor	Manual
		Transport networks (Transport energy usage)		
3	Obtain traffic data	ArcMap/MATSim	Attribute editor	Manual
		Data preparation		
		Spatial configuration (Urban structure)		
4	Run axial analyses	DepthmapX	Graph analysis	Manual
5	Convert to segment map	DepthmapX	Convert map	Manual
6	Run segment analyses	DepthmapX	Angular Segment Analysis	Manual
7	Normalise values	DepthmapX	Update column	Manual
8	Categorise segments	Arcmap	Field Calculator	Manual
9	Aggregate analyses	Arcmap	Field Calculator	Manual
11	Create buffer lines	Arcmap	Buffer tool	Manual
11	Assign Symbology	Arcmap	Attribute editor	Manual
		Densification patterns (Urban form, building density and land use mix)		
12	Calculate FSI	Arcmap	Field Calculator	Manual
13	Calculate GSI	Arcmap	Field Calculator	Manual
14	Calculate Spacematrix	Arcmap	Field Calculator	Manual
15	Classify Building function	Arcmap	Field Calculator	Automated
16	Calculate MXI	Arcmap	MXI Calculator	Automated
		Transport networks (Transport energy usage)		
17	Calculate car energy usage per segment	Arcmap	Field Calculator	Manual
18	Join Space Syntax and energy usage	Arcmap	OSM Aggregator Tool	Automated
		Data comparison		
19	Correlate Space Syntax and energy usage	SPSS		Manual

The first step of data collection is to draw the axial maps as was described in Section 3.3.1. This is done in a new shapefile, which is laid over basic map data that visualises the topography of the study areas' spatial structure: the buildings, roads, streets, water etc. This allows the accurate drawing of axial lines with the correct geospatial location. After obtaining building data and traffic data from open and proprietary sources, the data can be prepared.

The axial analyses are run and the map is converted to a segment line map. Next, the calculations are made to obtain betweenness and closeness values for each segment line. The last task in DepthmapX is to normalise these values using the formulae provided in (Section 2.2 Data preparation in de Koning et al., 2022, p. 8-15). The files are finally exported for use in GIS (i.e. Arcmap). Here, the values are prepared further by categorising them as low, medium or high and applying a buffer polygon around the segment lines.

Building data is prepared by calculating FSI and GSI using the building dimensions and the dimensions of the land use plots to obtain the building density. Land use mix through the Mixed-Use Index is obtained from attribute data for Bergen and is supplemented manually for Zürich where this data is missing or unavailable. Transport energy usage is calculated from the attributes in the traffic data file that contain the values for maximum speed and traffic volume. Finally, the data are linked to the street network (RCL) for spatial comparison with betweenness and closeness.

3.5.3 Data-driven workflow automation

Geoprocessing

The fundamental purpose of geocomputation, or: geoprocessing, as it is called in GIS, is to automate tasks relating to spatial analysis, modelling and visualisation (O'Sullivan and Unwin, 2003) such as the steps described in Table 3. Almost all uses of GIS involve a combination of different tasks as well as the repetition of tasks, as is the case with the workflow in this dissertation. Both the repetitiveness of geoprocessing and the need for standardisation in urban analysis necessitate methods to automate workflows.

Geoprocessing is based on a framework of data transformation. A typical geoprocessing tool performs a computational task on a dataset (such as creating a feature class, raster, or manipulating a table) and produces a new dataset as the result of the computation. Each geoprocessing tool performs a small yet essential operation on spatial data (e.g. projecting a dataset from one map projection to another, adding a field to a table, merging features, creating a buffer polygon around features etc.). ESRI® ArcGIS includes hundreds of such geoprocessing tools (ESRI, 2010). Even a simple analysis may require several geoprocessing tasks to obtain a result.

Graphical software models are commonly visualised as graphs. Nodes represent the computational tasks to be performed. Arrows connect the nodes and represent the dependencies between them. The third component of the graph is the input (data) in (Figure 6-7 in de Koning *et al.*, 2022, p. 16). Each node can be edited through a Graphical User Interface (GUI) which conceals the underlying code, allowing users without programming skills to use them (Figure 5 in de Koning *et al.*, 2022, p. 16). Moreover, the visual representation of the steps shows precisely how the data was processed to obtain the output.

Directed graphs in GIS

The ongoing increase in availability of steadily more detailed and complex (spatial) data seems to run in parallel with technological advances in computing capabilities and software applications. Whilst the new opportunities this poses seem promising and endless, there lies a risk in the fact that more specialised professionals are becoming necessary in the process. From software engineers and IT specialists to researchers and decision-makers, more expertise is needed (e.g. knowledge of programming, complex mathematical operations), potentially making the process slow, bulky, non-transparent and incomprehensible.

To mitigate this problem, many software solutions exist that allow non-expert researchers to perform the complicated work with data without the need for extensive computing skills. This solution is offered in a variety of licensed and non-licensed software designed to make Human-Computer Interaction (HCI) simpler and more intuitive. All these solutions utilise some type of GUI.

This dissertation chooses to utilise a VPL-based model builder included in licensed GIS software to answer SRQ3: how analyses of spatial relationships can be conducted and improved using geocomputational software (DepthmapX and GIS). The model builder provides researchers that use spatial data the opportunity to create software through directed graphs for simplification and replication of their workflow without the need for textual programming (Dobesova, 2011). Building both simple and complex models is (relatively) intuitive and user-friendly. ESRI® ArcGIS ModelBuilder™ (ESRI, 2021d) is such a built-in graphical model builder. It is used in this dissertation to combine and automate geoprocessing tasks. This partial workflow automation through the Model Builder is presented in (de Koning *et al.*, 2022).

3.6. Description of the software tools

The previous sections described how the data were collected, prepared and processed through DepthmapX and ESRI® Arcmap. This section explains these tools and their applications.

DepthmapX

The DepthmapX (Varoudis, 2012) application was originally designed as a simple isovist processing program in 1998 (Turner, 2004) and has a domain-specific purpose of creating and calculating spatial configurations. It uses two distinct types of layers: Visibility Graph Analysis (VGA) layers made up of closed polygons for isovist, convex and agent-based analysis, and line layers for axial and segment analysis (see Figure 1). Layers are imported from a drawing file or drawn directly in the application's Map view. It also offers a function to automatically generate a line layer from a VGA layer by first using the 'All-line map' function, and then reduce to a fewest-line map via a 'greedy' algorithm (Turner, 2004). All other analytical functions are operated through simple GUIs. This allows the user to select the desired settings without entering scripts or code.

ESRI® ArcMap

ESRI® ArcMap is a digital environment for handling quantitative geographical models and techniques and allows for the combination of spatial data with other georeferenced data types for further analysis. This and other available GIS applications are designed for more widespread and generic use: the applications are meant to ease the work of professionals chiefly in the fields of geography, geology, road and transport planning, land registration, and urban design and planning. Longley and Batty (1996, p.1) explain how GIS enables "…the development of rigorous models of spatial distributions, the analysis of locational patterns and problems, and the investigation and forecasting of space-time dynamics", with a focus on human and social systems with reference to physical systems. To link models to physical systems on the surface of the earth, georeferencing occurs via coordinate systems. GIS specifically provides the possibility to model and represent these systems graphically, and interpret spatial relationships through an array of geoprocessing tools that aid in data alignment and transformation. Data is stored in geodatabases or feature classes and can be categorised as raster or grid-based or vector-based (O'Sullivan and Unwin, 2003, p. 4-5; de Smith *et al.*, 2007). Raster-based data models represent features using discrete cells arranged as a contiguous two-dimensional grid, and each cell can have one or more attribute values stored associated with them (de Smith *et al.*, 2007, p. 18). Vector data models consist of lines or arcs with beginning and end points. These are called features, and can represent objects as points, lines or polygons. Like cells in raster data, each feature can have many attribute values in the form of numerical values or text that describe some property of the object (de Smith *et al.*, 2007, p. 20).

3.7. Threats to validity

This chapter presented the scientific methods used in this dissertation that are pertinent to understanding spatial relationships in urban areas. These are known methods which are commonly used for analysing spatial relationships. It was explained that spatial configurations can be understood through the quantitative metrics representing betweenness and closeness calculated from hand-drawn axial maps. Densification patterns are expressed through building intensity (FSI), plot coverage (GSI) and functional mix (MXI). Energy usage from transportation networks was shown to depend on the availability of measured or simulated traffic data reflecting traffic volume and traffic speed. The methods and data presented were shown to best capture the urban elements under investigation in this dissertation for the selected cases in the north-western European context. Therefore, it is expected that these methods are also applicable to other urban areas within the same context.

However, some limitations need to be pointed out in the form of potential inaccuracies or weaknesses.

3.7.1 Validity and reliability

This dissertation aims to achieve internal validity through the creation of unique, hand-drawn axial maps by attentively and consistently applying the set of rules described in Section 3.3.1. This way, it can be assured that all topological relational values in the maps are accurate. Any variations in angular deviation (i.e. geometrical values) are considered negligible or to cancel each other out, thereby not influencing the overall results. Metric distance is not impacted by any geometrical variations in the map. Maps generated with experimental software can yield equally valid results, yet checking the correctness is still a manual task. Hence, the chances of overlooking any mistakes made by the software (the aforementioned black box effect) are much higher than with hand-drawn maps where each line is drawn intently.

By performing the various steps for collecting, preparing and comparing data consistently as explained above, subjectivity is avoided as much as possible, assuring the internal reliability of the methodology. External validity is sought by triangulating the data on two different expressions and two different case studies. These case studies differ from each other in terms of spatial context (e.g. two Mid-size European cities with unique topographical conditions and street network structures).

Inaccuracies in the data will most likely be caused either by errors in the (unavailability of) source data or by problems during the various data operations (e.g. data aggregation, where building data will be coupled erroneously to the wrong street segment's data), rather than mistakes made manually (e.g. whilst drawing the axial maps or classifying building functions). Moreover, with cities being dynamic entities undergoing constant change, each piece of data presents only a temporal 'snapshot' of the actual real-life situation. Hence, external reliability of the methodology is offered by explaining the methods as they were applied and being transparent regarding the potential shortcomings, weaknesses and inaccuracies that need to be considered.

3.7.2 Limitations to the analysis methods

Urban structure

Regarding the Space Syntax method for calculating spatial configurations, one criticism is that hand-drawing the axial maps can be considered (too) subjective (Batty and Rana, 2004). The act of creating a single line on a digital map involves two mouse clicks at some geospatial location to mark the beginning and end of each line. Although a set of rules exist for drawing these lines to ensure the correctness of axial maps (see Section 3.3.1), the fact that it is a manual process means that different individuals drawing maps of the same urban area will produce slightly different results even if they all follow these rules. Moreover, there exist no objective methods for checking whether an axial map is correct. This too, is a manual task. It is argued that for axial maps, where only topological relationships are examined, slight variations in the spatial placement of each line will produce the same result of topological interrelations (i.e. direction changes). Additional pitfalls when analysing linear urban space are discussed by van Nes and Yamu (2021b, p. 83, Section 2.8).

Density

Whilst the method for quantifying building density is objective, there lies a potential weakness in the calculation in that it depends on the chosen area of aggregation. This is referred to as the Modifiable Areal Unit Problem (MAUP) (Longley and Batty, 1996; Openshaw, 1984, 1996). As the base unit of measure, the area of aggregation, defined as the geographical area on which density calculations are made, differs depending on the level of scale used. The land use plot is the area of aggregation used in this dissertation. However, the urban block, the neighbourhood or the entire city can be used as area of aggregation. The higher the level of scale, the more area is taken into account that serves as infrastructure (which adds up to almost a fifth of all land use in Norway (Statistisk sentralbyrå (SSB), 2021c)), parks, water etc. Thus, the higher the level of scale, the more the base unit of measure increases disproportionately to the built mass. This potential weakness is mitigated by using the land use plots (coupled to legal ownership and land use) as the base unit for aggregation (for an example on land use plots, see Figure 1c in de Koning *et al.*, 2022, p. 5).

Land use mix

Regarding the Mixed-Use Index for calculating land use mix, there are two weaknesses. Firstly, the division into categories is not unambiguous. After all, whilst a shop is a visiting location for its customers, the employees consider it a workplace. Conversely, offices may receive visitors regularly to exchange services. Likewise, elderly living in a retirement home consider it their home, whilst the nursing staff sees it as their workplace. The second weakness of the MXI method is that no distinction is made between types of visiting locations. A dentist, a corner shop and a theatre are all mapped as amenities. Hence, both commercial (e.g. a bookstore) and non-commercial (e.g. a library) public buildings fall in the same category. These ambiguities may be difficult to overcome, yet this dissertation attempted to avoid gross inaccuracies by assigning activity types based on the dominant activity and the expected footfall. For example, whilst some offices may receive some customers (say 15 per day), this number may not exceed the number of workplaces (say 50). Likewise, an institution marked as an amenity may have many workplaces (say 50), but on average more visitors (say 200 per day). Although this does not eliminate the inaccuracy, it was attempted to prioritise the dominant activity performed.

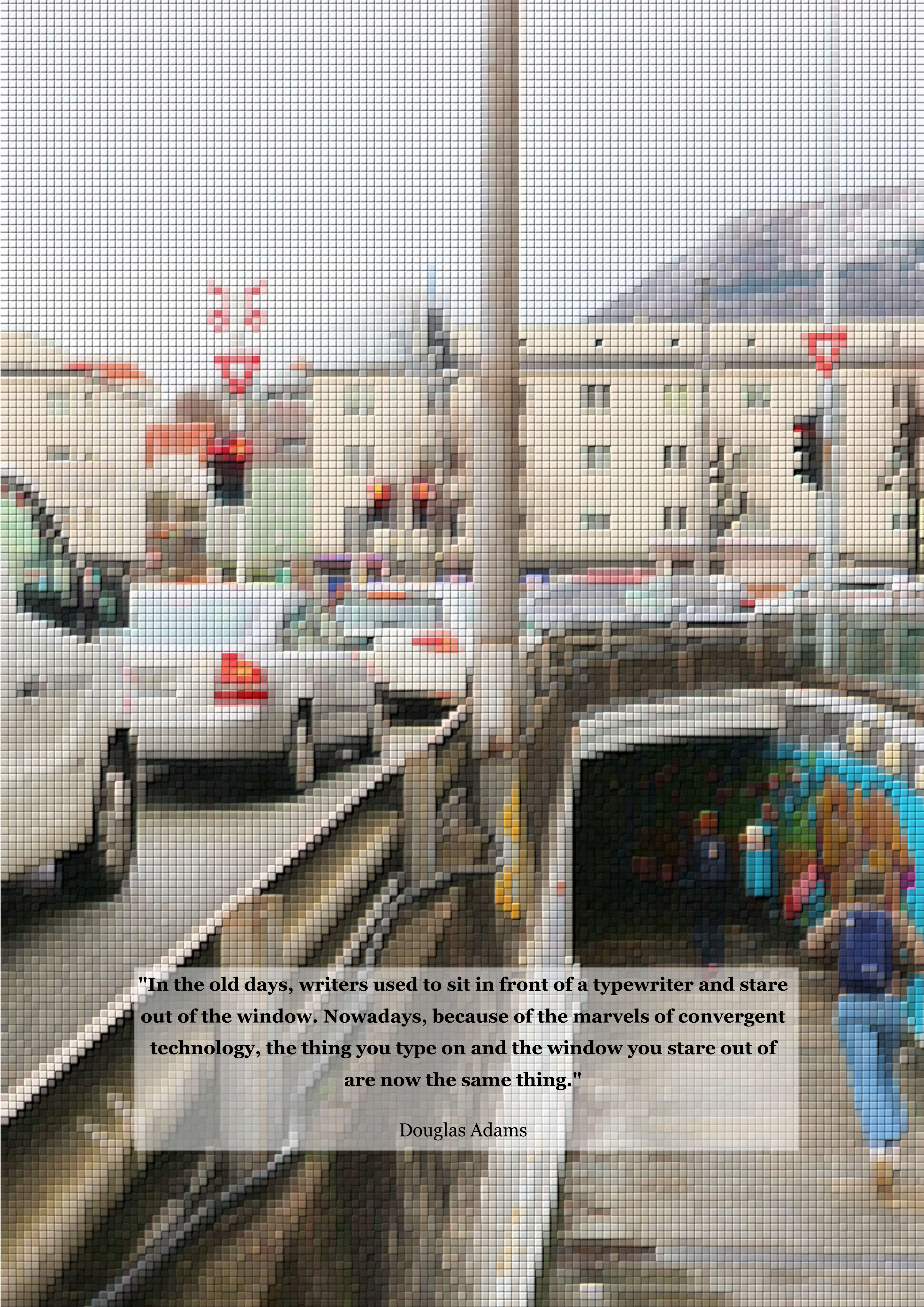
Transport energy

The calculation of transport energy is an approximation with a few inaccuracies. First, the actual energy consumption for each vehicle is based on average values for wind resistance (i.e. the vehicle profile) and combustion engine heat loss (i.e. the energy conversion efficiency of the vehicle). Second, environmental factors affecting energy consumption such as slopes, turns, and stops (e.g. at a traffic light), are not considered. Although eliminating these variables in the calculations may influence the accuracy of the results, the applicability on and comparability of the case studies in this dissertation as well as future studies can be assured.

3.7.3 Limitations of the artefact

Whilst the artefact created through a DSR has a clear practical relevance, with a clear foundation in and contribution to the theoretical knowledge base, it is acknowledged that assessing the practical adequacy of the artefact is difficult to do before actual implementation (Kasanen *et al.*, 1993). This may pose a possible validity threat regarding making statements about its applicability. This can be demonstrated better if the artefact is tested by relevant stakeholders such as public and private sector practitioners or fellow academics who study spatial relationships of urban structures and forms. To mitigate this potential weakness, internal and external validity and reliability are sought through securing the accuracy of the data on different case studies, using established theoretical knowledge and their methods, and relaying the steps in the workflow comprehensively and transparently.

Scientifically, the main aim of the artefact presented in this dissertation is to answer the question how analyses of spatial relationships can be conducted and improved using geocomputational software (SRQ3). This is achieved by demonstrating how the workflow of comprehensive spatial analysis on a GIS platform can be automated in principle for a selected number of representative steps. However, more steps could be automated. For example, calculating density would require a model similar to that for the calculation of land use mix. The main differences are the input parameters and the way attribute fields are calculated. Although further automation would increase the chances of practical implementation of the workflow, demonstrating how the problem can be solved in principle is in focus here considering the overall aim of this dissertation, which is to answer the question: which spatial relationships are identified through spatial configuration analyses with software tools for geocomputation (MRQ).



"In the old days, writers used to sit in front of a typewriter and stare out of the window. Nowadays, because of the marvels of convergent technology, the thing you type on and the window you stare out of are now the same thing."

Douglas Adams

4. Highlights of the results

Section A: Densification patterns

Paper A1:

de Koning, R. E., Roald, H. J. & van Nes, A. (2020a): A Scientific Approach to the Densification Debate in Bergen Centre in Norway. Sustainability, Vol. 12:21, 9178. Available at: https://doi.org/10.3390/su12219178

Section B: Transport and energy networks

Paper B1:

de Koning, R. E., Tan, W. G. Z. & van Nes, A. (2020b): Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities. Sustainability, Vol. 12:19, 8146. Available at: https://doi.org/10.3390/su12198146

Paper B2:

de Koning, R. E., van Nes, A., Roald, H. J. & Ye, Y. (2017): Strategies for integrated densification with urban qualities. Combining Space Syntax with building density, land use, public transport and property rights in Bergen city. *In:* HEITOR, T., SERRA, M., SILVA, J. P., BACHAREL, M. & CANNAS DA SILVA, L., eds. Proceedings of the 11th International Space Syntax Symposium– 3-d - 7th July, Lisbon, Portugal: Instituto Superior Técnico, Departamento de Engenharia Civil, Arquitetura e Georrecursos, #56, 863-879. Available at: http://www.11ssslisbon.pt/docs/proceedings/papers/56.pdf

Section C: Workflow automation

Paper C1:

de Koning, R. E., Heldal, R. & Tan, W. G. Z. (2022): Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: the cases of Bergen, Norway, and Zürich, Switzerland. Data in Brief, Vol. 42:108290. Available at: https://doi.org/10.1016/j.dib.2022.108290

Section A: Densification patterns

de Koning, R. E. & Roald, H. J. (2020): A Scientific Approach to the Densification Debate in Bergen Centre in Norway. Sustainability, Vol. 12:21, 9178. Available at: https://doi.org/10.3390/su12219178

A1 Title: A Scientific Approach to the Densification Debate in Bergen Centre in Norway

Abstract: The municipality of Bergen in Norway aims to densify fifty per cent of new housing within the city's central parts. The Ministry of Local Government and Modernisation ordered and financed an investigation to be carried out by the Western Norway University of Applied Sciences and the consulting firm Asplan Viak to give research-based input to the densification strategy debate in Bergen. This article demonstrates how the Space Syntax method can be applied to urban densification strategies in urban planning and policymaking. The Geographical Information System (GIS) is used to obtain, select, and aggregate operational information. First, the spatial attributes that constitute an area's attractiveness were registered. Then, this analysis was modelled after the Spacescape® method. Next, the Space Syntax methodology was applied to predict to-movement and through-movement flow potentials. Finally, through weighting the relevant parameters, including impediments such as land ownership, twelve areas were identified as having major potential for transformation based on their overall score. As it turns out, the spatial structure of the street and road network is the underlying driver for how and where to densify. Now, the challenge is how to apply this knowledge into current planning practice.

Keywords: densification, urban transformation, Space Syntax, planning strategies

Highlights of Section A

The papers in section A explores city (densification) patterns and functions. The most important findings are:

- To understand the densification patterns in Bergen, Norway, eight spatial variables were mapped, and analysed using the Space Syntax and the Spacescape methods to produce frameworks for evaluating potential locations for densification of future developments (see A1). A total of 12 locations were identified that can streamline future development investment priorities.
- Analysing the spatial integration of current densification patterns in Bergen (street networks) shows that well-integrated areas (urban core, local centres and adjacent neighbourhoods) support higher building density and economic activities, whereas more segregated areas (suburbs and urban fringes) have high potential for densifying with residential functions and improving local street

network connections (see A1). This complies with the theory of natural urban transformation.

- The analysis of densification patterns in Bergen through its spatial configuration (street networks) leads to a spatial densification matrix. With this matrix, with the axes global and local integration, policy makers can identify locations for potential densification. For example, areas with High global integration but Low local integration (HGI+LLI) and those with Low global integration but High local integration (LGI+HLI) are more promising than areas with low values on both axes (see A1).
- The spatial analysis requires the combination of spatial configuration, land use and building density data into a singular, comparable platform. This is made possible by using GIS as a visualisation and mapping tool for a multitude of complex data (see A1).

Section B: Transport and Energy Networks

de Koning, R. E., Tan, W. G. Z. & van Nes, A. (2020): Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities. Sustainability, Vol. 12:19, 8146. Available at: https://doi.org/10.3390/su12198146

B1 Title: Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities

Abstract: Energy usage in cities is intertwined with its spatial configuration—the denser and more compact the city, the more concentrated and efficient the energy usage is to be expected. To achieve sustainable communities, cities (and their inhabitants) must reconsider its spatial configurations in the context of rapid urbanisation and growth in light of limited resources and conflicting spatial claims. This article seeks to understand how spatial configurations affect transport energy usage in cities and propose an integrated assessment approach factoring spatial configurational analysis in relation to transport energy usage at the micro- and macroscale. Comparing Bergen, Norway, and Zürich, Switzerland, findings showed that spatial configurations were positively correlated to transport energy usage. Street structures suitable for walking and less suitable for car traffic tended to exhibit lower amounts of energy usage. Following this, nine typologies of transport and land use patterns are described to support planning for more sustainable means of transport.

Keywords: transport energy usage; sustainable mobility; space syntax; natural movement; natural urban transformation.

de Koning, R. E., van Nes, A., Roald, H. J. & Ye, Y. (2017): Strategies for integrated densification with urban qualities. Combining Space Syntax with building density, land use, public transport and property rights in Bergen city. *In:* HEITOR, T., SERRA, M., SILVA, J. P., BACHAREL, M. & CANNAS DA SILVA, L., eds. Proceedings of the 11th International Space Syntax Symposium– 3^{-d} - 7th July, Lisbon, Portugal: Instituto Superior Técnico, Departamento de Engenharia Civil, Arquitetura e Georrecursos, #56, 863-879. Available at: http://www.11ssslisbon.pt/docs/proceedings/papers/56.pdf

B2 Title: Strategies for integrated densification with urban qualities. Combining Space Syntax with building density, land use, public transport and property rights in Bergen city

Abstract: Bergen city in Norway is presently undergoing an enormous population growth. In this respect, Bergen municipality wanted to identify all the possibilities for densification in the current situation. Therefore, the following issues were evaluated: street network and public transport accessibility, building density, degree of functional diversity, restrictions on (private) properties and current land use plans.

Our approach is to analyse the central areas in Bergen in the current situation to discover how the urban transformation takes place in a natural way. Firstly, we studied the relationship between street network accessibility (with the Space Syntax method), degrees of FSI and GSI on building density (with the Spacematrix method) and degrees of function mix (with the MXI method). Secondly, we wanted to reveal the legal issues that arise from the strong Norwegian property rights. Thirdly, we added the accessibility of public transport lines through the angular step depth in the Space Syntax analysis. We combined all these issues by using GIS. Unlike in earlier research (Ye and van Nes, 2013, 2014), the buffer line function in GIS was used to correlate building density, function mix and degree of spatial integration.

It turns out that the degree of street network integration affects the location of commercial activities and the degree of building density and function mix. When the street network accessibility increases on a local and global level, property owners start to submit plans that exploit their properties to the utmost. The same occurs around public transport stops with frequently running light rail trams. As follows from the theory of the natural urban transformation process, densification can thus be steered

by improving the street network accessibility on multiple scale levels, combined with high public transport accessibility.

Keywords: building density, land use mix, property rights, public transport, natural urban transformation

Highlights of Section B

- Energy usage in cities correlates with its spatial configuration – the denser and more compact the city, the more concentrated and efficient the expected energy usage (see B1, B2). Compact cities, where local centres with high building and function densities are connected by highly integrated transportation networks, are more energy efficient and hence, more sustainable.
- Street structures with high local integration (more suitable for walking and less suitable for car traffic) tend to exhibit lower amounts of energy usage than areas with high values at a citywide scale (more car-oriented) (see B1). This contributes to a refinement of the theory of natural movement.
- Nine typologies of transport and land use patterns are identified to support planning decisions and strategies for more sustainable means of transport (B1).
- Spatial analysis (with Space Syntax) shows that the local integration analytic value seems to impact transport energy usage more than global (citywide) integration values (see B1). In Bergen and Zürich, high local integration corresponds with a reduction in energy usage, whereas low local integration presents as high in energy usage.
- Spatial configurations of urban structures determine transport energy usage through mobility choices (see B1). Spatial configuration of urban structures influences building densities and the distribution of land uses (attractors) which generates movement. The collective movements reflect individuals' mobility choices. Therefore, route choice and mode choice (mobility choices) are influenced by spatial configurations.
- The degree of transport network (street) integration affects the location of commercial activities and the degree of building density and function mix (see B2). When the street network integration increases on a local and global level, property owners start to capitalise on expected increased footfall.

- Spatial configuration of urban structures can be analysed through three separate methods: i) the Space Syntax method (connectivity of spatial structures as axial lines and public transport with angular step depth), the Spacematrix method (degrees of FSI and GSI on building density) and the MXI method (degrees of functional mix). GIS is an effective platform in which to combine these methods successfully to examine spatial relationships (see B2). This is a pilot for the methods of spatial analysis aided by applied computing science as used in this dissertation.
- To understand spatial configuration of urban structures better, this dissertation proposes the application of a buffer line model (see B2). The model aids in combining categorised Space Syntax values within proximity of a particular street segment. This creates (aggregated) areas of integration values corresponding to the integration values of the street segments that should be considered for spatial analysis.
- In analysing spatial configuration of urban structures, three types of models (representation of spatial data) exist. The raster model is useful for overall strategic planning and visualisation. The polygon model is useful for urban designers and architects who work on the plot level and with spatial objects, while the buffer line model is useful to represent the spatial potentials of transport networks for traffic and transport engineers (see B2). The process of creating the buffer line model is a contribution to the spatial analysis approaches made possible by the aid of applied computing science.

Section C: Workflow automation

de Koning, R. E., Heldal, R. & Tan, W. G. Z. (2022): Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: the cases of Bergen, Norway, and Zürich, Switzerland. Data in Brief, Vol. 42:108290. Available at: https://doi.org/10.1016/j.dib.2022.108290

C1 Title: Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: the cases of Bergen, Norway, and Zürich, Switzerland

Abstract: A better understanding of how the spatial configuration of cities, understood as urban structure and forms, can achieve sustainable development is

needed. This paper presents spatial data and an automated workflow for studying the urban structures (i.e., road and transportation networks) and forms (i.e., building size, position, function and density) of two medium-sized European c–ti–s - Bergen, Norway and Zürich, Switzerland. Focusing on the densification patterns and transport energy usage of these cities, the data provides insights on how to achieve an efficient spatial distribution of building densities and land uses in relation to their transport accessibility.

Spatial and tabular datasets for i) urban structures, ii) urban forms, iii) building density, iv) road centre lines and v) transport energy usage are obtained as georeferenced files from OpenStreetMap (OSM) and upon request from collaborating local and national authorities. Transport energy data is derived from traffic data collected from the Norwegian Public Road Authorities or simulated via a traffic model. Open-source data is used wherever possible. Data gaps within proprietary data are supplemented with proxies or open-source data.

Hand-drawn axial maps drawn by the authors using the Space Syntax methods and analysed via DepthmapX software are a crucial dataset presented here. All analysed data are then returned to a Geographical Information System (GIS) platform and processed via an automated workflow of 19 steps built via the ModelBuilder™ tool in ESRI® ArcGIS. The automated workflow allows for repetitive cross-city comparison and the compilation of diverse spatial data sources for analysis.

The data provided are used for finding the correlation between densification patterns and transport energy use in the related research paper (de Koning *et al.*, 2020). Data show that well-integrated urban areas accessible at both the neighbourhood and citywide levels with sufficient building density and diversity of land use mix will favour walking and cycling as the main mobility choice instead of the car. These tend to have more sustainable transport energy usage. In combination with the novel workflow, the dataset can be used for future comparative studies in spatial planning, transport planning and management of energy systems to facilitate informed decision-making towards more sustainable developments.

Highlights of Section C

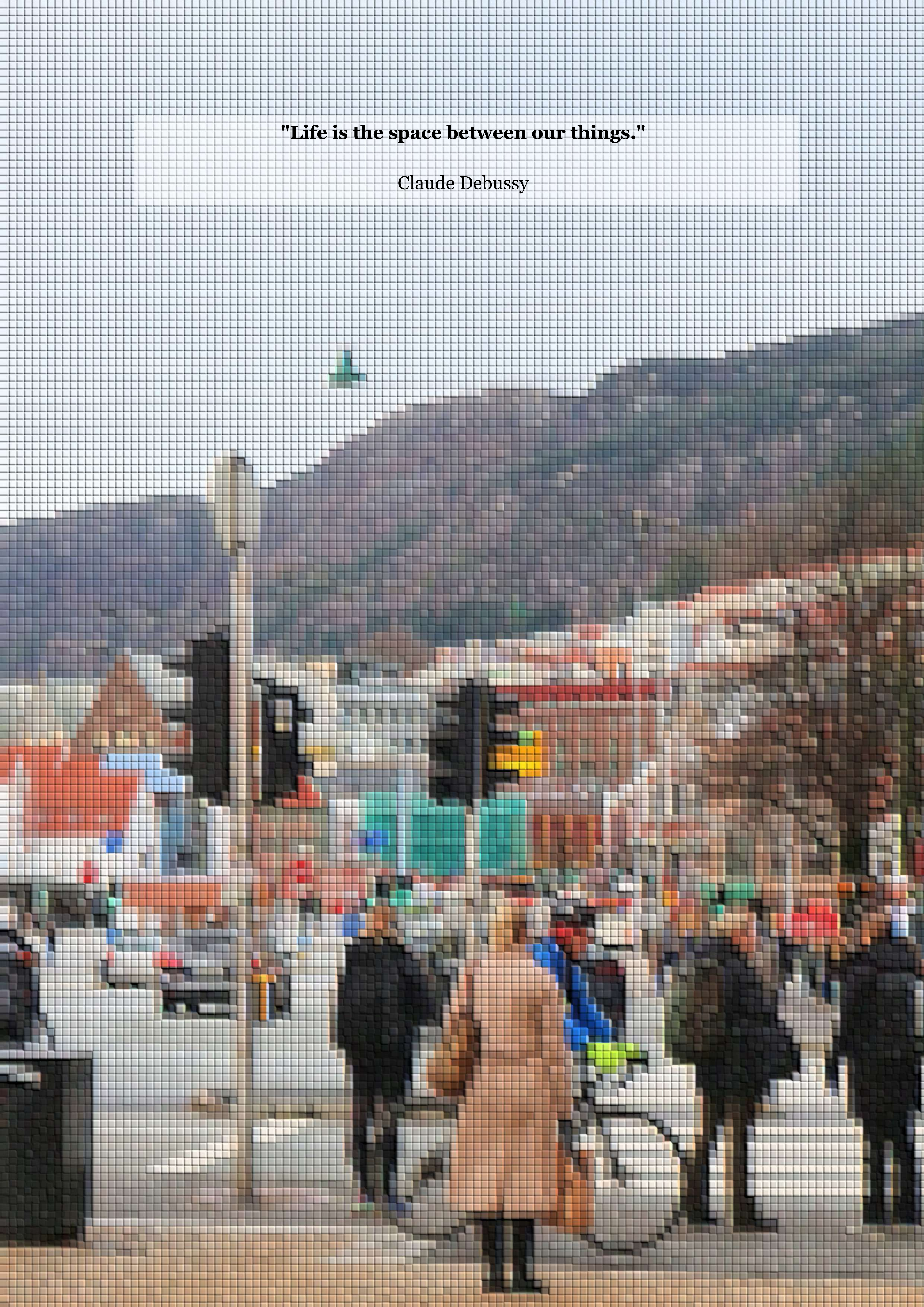
- The spatial configuration of urban structures and forms in relation to densification patterns and transport energy usage can be studied through software tools for geocomputation commonly known as Geographical Information Systems (GIS). This can be used to gain insights in how these phenomena are related to each other (C1).
- Comparable data on densification patterns and transport energy from cities in different countries are however not readily available. Data on urban form, building density and road centre lines are found at varying units and levels of scales (i.e., neighbourhood and citywide). The data described and shared (C1) are available as georeferenced shapefiles that are usable across multiple GIS platforms and allow other researchers to compare with their own cities.
- The dataset produced and published (C1) contains spatial data such as building, plots and street networks attached with non-spatial data of building functions and simulated transport energy usage. The data is analysed in a novel way by i) aggregating values from different scale levels, ii) applying a buffer model to improve comparison of spatial configurations and building data; and iii) comparing spatial configuration with energy usage by cars. The comparison is essential for drawing insights on spatial relationships to achieve sustainable development.
- The primary data of hand-drawn axial maps of Bergen and Zürich are georeferenced and validated. Furthermore, this unique data is confirmed with local authorities and experts involved in the research project available to other researchers.
- The data for urban structure carries the metri‘s ‘f 'betwe’nness‘ a‘d 'clo’en’ss' calculated based on Space Syntax theories and methods (Hillier, 1996; Hillier and Hanson, 1984) via DepthmapX. These metrics improve current geographical and transport planning approaches of proximity or access through speed and distance to improve planning decisions for sustainable mobility.
- The data for urban form (dimensions, age and functions) and building density (function, floor space and plot sizes) are calculated with the Mixed-Use Index (MXI) calculator designed for this workflow. Decision-makers can use this to

consider how space is distributed, if the distribution is efficient, and if the content of the distribution can facilitate liveability and sustainability.

- Limitations were posed by i) the availability of data, ii) compatibility of various software, and iii) verifiability of the output results. Some of the data used in this paper are proprietary. Therefore, this data is not available to everyone. Data is prepared with DepthmapX and GIS. Whilst the data can be interchanged between both software programs by exporting to compatible file types, it prevented automating some parts of the scientific workflow. The workflow proposed is experimental in nature and although alternatives and proxies are used to substitute incomplete or proprietary data, there is a possibility inaccuracies and errors.
- The workflow concerned with collecting, preparing and comparing complex spatial data can be partially automated (C1). Specifically, this can be done through a model builder on a GIS platform by pre-programming various geocomputational tasks via a Visual Programming Language (VPL). This unique workflow automation allows for repetition of data input by other users using other cities while allowing for generalisability across different cases. The automated workflow (C1) improves the reproducibility of the work, and make it feasible for a wide range of users. The user interacts with the models through a Graphical User Interface (GUI), which is an intuitive and user-friendly way of selecting data and variables for analysis. The knowledge and insights can be helpful for strategic planners, policymakers and road engineers to make well-informed decisions on how to develop urban areas more sustainably and offer methods for analysing cities.

"Life is the space between our things."

Claude Debussy



5. Findings and analysis

This chapter describes the overall findings from the research as presented via the publications in part II on spatial relationships in cities relating to i) densification patterns, ii) transport energy networks, and iii) how software tools for geocomputation aided in acquiring these findings. The findings from identifying and analysing the aforementioned spatial relationships are described in Section 1, after which Section 2 provides the findings from the identification approaches used. Section 3 provides details about the spatial analysis process. Next, Section 4 describes transport network typologies that were identified. The final section elaborates on the role that software tools and geocomputation have played in the research process.

5.1. Identifying and analysing spatial relationships

The spatial relationships investigated in this dissertation can be identified by analysing their spatial configuration (street and transport networks) in relation to land use, building density and energy usage for transport. The more essential a function is, the more likely it is to be in higher densities along spatial configurations with high values. Moreover, configurations with higher local integration values demonstrate lower energy usage.

The analysis of urban densification patterns (de Koning *et al.*, 2020a) provides support for the theory of the natural urban transformation process (van Nes *et al.*, 2012; Ye and van Nes, 2013, 2014), as understood through the correlation of spatial configuration with land use and building density. In Bergen, the highest densities and most varied land use mix are found along the most integrated streets. These streets have the highest choice (betweenness) and segment integration (closeness) values. Urban cores, local centres and their adjacent neighbourhoods usually have an elevated level of density.

Transport energy usage in cities correlates with its spatial configuration - the denser and more compact the city, the more concentrated and efficient the expected energy usage (de Koning *et al.*, 2017; de Koning *et al.*, 2020b). Street structures with high local integration (more suitable for walking and less suitable for car traffic) tend to exhibit lower amounts of energy usage than areas with high values at a citywide scale (more car-oriented) (de Koning *et al.*, 2020b). In compact built environments, where highly integrated transportation networks connect local centres with high building and functional densities, transport is more energy-efficient.

When seeking to understand spatial relationships in cities, it is imperative not to neglect the historical aspect of how it has evolved over time and to be cognisant of the inter-relationship between spatial configurations (street networks), land use mix and building density (de Koning *et al.*, 2020a: p. 6, see Figure 4b). Cities that have grown incrementally tend to have naturally evolved structures and spatial configurations, meaning that the networks of streets have developed with no other rationale than to facilitate movement between origins and destinations as efficiently as possible to places of meaning:

> *"the spatial form of the self-organized city … is already a reflection of the relations between environmental, economic and socio-cultural forces, that is between the three domains of sustainability."*
>
> *(Hillier, 2009, p. K01:01)*

Through Hillier's (2009) work on spatial structures, several vital spatial relationships are uncovered. The most fundamental is that spatial relations show a path dependency on the movement that the inhabitants carve out in the city's spatial structures and configurations while also being influenced by existing (historical) spatial relationships for commerce, culture, and community. In Bergen, the parts of the city that had more historical structures were utilised more intensively (i.e. higher building density) than newer developed areas and had a higher diversity of land use functions (de Koning *et al.*, 2020a).

In contrast, urban areas planned during the brief period of modernism in the 20th century display mutated spatial relationships between its spatial configurations, densification patterns and transport energy usage. This is shown in this dissertation by the spatial analyses of Bergen and Zürich which revealed that, in peripheral parts of cities developed in the modernist era of planning, global high integration values and low local integration values were found to correspond with higher transport energy use. Conversely, more highly integrated local spatial configurations in the historical cores exhibited lower transport energy use.

Newman & Kenworthy (1989) classically provided evidence that the level of efficiency regarding energy usage for transport relates to the level of density of inhabitants. In turn, this dissertation shows that building density correlates with the spatial configuration of the street network. Jabareen (2016) contributed to the understanding of sustainable urban forms by praising the compact city – where density features strongly – as the most sustainable form. Holden *et al.* (2020, p. 6) pointed out that due to the shorter distances to (private and) public services in areas of a certain density, good alternatives to the car are feasible and available. This enables local residents to make their daily trips by more sustainable means (i.e. walking, cycling or public transport) on average and with fewer, shorter trips made. Such micro Daily Urban Systems (DUS) (de Graaf, 2017) are representational of the spatial relationships that this dissertation studies. For example, the positive correlation of lower energy usage with higher density areas can be found in the study of the cities of Bergen and Zürich (de Koning *et al.*, 2017; de Koning *et al.*, 2020b).

However, it is evident that density is not the only factor that can reduce the need for transport. Other things being equal, an increase in the built mass would soon lead to increased traffic, congestion and pollution (Jenks *et al.*, 1996). Neither do compactness and high density correlate with social equity and cohesion (Neuman, 2005). Instead, a right mix of public and commercial functions supported by a clustered customer base in proximity is also required. The spatial analyses in this dissertation confirm that higher degrees of land use mix are present in areas with locally highly integrated spatial configurations in Bergen and Zürich (de Koning *et al.*, 2020b). Therefore, the dissertation proposes that to understand the complex socio-spatial relationships in urban areas, novel approaches for identification are necessary.

5.2. Identification approaches

The identification of spatial relationships within cities requires spatial analysis combining:

i) spatial configuration as street networks, building density and land use data to understand densification patterns (de Koning *et al.*, 2019; de Koning *et al.*, 2020a), and

ii) spatial configuration as transport networks correlated to energy usage (de Koning *et al.*, 2020b).

Spatial configurations can be identified and analysed through Space Syntax and its methods. This was combined with established methods for analysing building density and land use mix. These methods require the study of complex and complicated amounts of data, especially when studying larger urban areas and regions. Hence, the use of Geographical Information Systems (GIS) becomes indispensable for combining these methods efficiently and successfully (Hillier, 2019; de Koning *et al.*, 2017). The proposed combination of methods is a pilot for improving spatial analysis aided by software tools, specifically with the use of Visual Programming Languages (VPL) in GIS to build executable models to align data inputs and analytical processes for gaining insights into spatial relationships.

These methods importantly prioritise the spatial component – the study of space – rather than the study of form as in the urban-morphological approaches. With the urban-morphological approach, studies of its elements are possible, but the relationships of usage of these elements are less present (Hillier and Hanson, 1984). Space Syntax allows for the study of urban structures (both streets and buildings) and how they are linked through a value-free description of the interrelationship of spatial elements. It includes the human cognitive aspects involved in wayfinding and orientation as well as socio-economic rationality taking place within and between these elements. The analysed spatial elements are unambiguously defined with minimal intervention of normative linguistic concepts (Hillier, 2009, p. K01:01). This makes the identification approach suitable for building towards more descriptive understanding of spatial relationships in cities.

5.3. Spatial analysis process

To understand spatial relationships in urban areas and how to better identify them, two expressions – the densification patterns and transport energy usage in cities – were considered for analysis. Each expression utilised a variation of the combination of methods. The choice for analysis techniques and representation depends on the scale, scope and focus of the object of study.

With the study of densification patterns in Bergen, Norway, eight spatial variables were mapped and analysed using the Space Syntax and the Spacescape® (2013) methods to evaluate potential locations for densification of future developments (de Koning *et al.*, 2020a). The analysis of densification patterns in Bergen through its spatial configuration (street networks) leads to a spatial densification matrix (see Figure 15 and 16 in de Koning *et al.*, 2020a, p. 18-19). In this matrix, with the axes global and local integration, policy makers can identify locations for potential densification. Hereby, a denser street network and higher concentration of various land uses would be advisable to encourage more sustainable mobility choices (i.e. walking instead of driving) (de Koning *et al.*, 2017; de Koning *et al.*, 2020a). In addition, nine typologies of transport and land use patterns were identified to support planning decisions and strategies for more sustainable transport (see Section 4.2 in de Koning *et al.*, 2020b, p. 16-17).

In analysing spatial configuration of urban structures, three types of models (as representation of spatial data) exist. The raster model is useful for overall strategic planning and visualisation. The polygon model is useful for urban designers and architects who work on the plot level and with spatial objects, while the buffer line model is useful to represent the spatial potentials of transport networks for traffic and transport engineers. The three types of models were compared in (de Koning *et al.*, 2017, p. 56:4, Figure 1).

Building upon the evaluation of urban areas via the strategic densification matrix described above, this dissertation proposed the application of a buffer line method (see Figure 1 and 4 in de Koning *et al.*, 2017, p. 56.54, 56.57) to understand spatial configuration of urban structures better. This method aids in combining categorised Space Syntax values within proximity of a particular street segment to a polygon. This creates (aggregated) areas of integration values corresponding to the integration values of the street segments. The buffer line method expands the potential of analysing objects beyond a line or point towards a polygon unit of analysis without loss of value, in relation to other area-based data sources.

For correlating spatial configurations and its values to transport energy usage by cars, street segments were linked to Road Centre Line (RCL) features (de Koning *et al.*, 2020b) to perform a statistical comparison of the data via SPSS with bivariate correlation. Both the street segments and RCL features are polyline features and are thus easily combined. For comparing street segments (polylines) with densities and land use mix (polygons), the buffer line model was required and applied. For calculating overall attractiveness in Bergen (de Koning *et al.*, 2020a), street segments (polylines) were coupled with the remaining attractiveness variables (de Koning *et al.*, 2020a, p. 12, Table 2).

The above variations in methods demonstrate the diverse ways in which spatial structures and spatial relations in cities can be identified and analysed using the urban network approach through Space Syntax. This dissertation showcased the various possibilities that are available for combining various spatial data in GIS.

5.4. Role of software tools and geocomputation

This dissertation explored how the analysis of spatial relationships can be aided by appropriate application of geocomputational software tools. For this purpose, two specific tools are used which were described in Section 3.6. The strengths and weaknesses and their respective roles in the research are discussed here.

DepthmapX was built for the specific purpose of executing countless complex mathematical operations specified by the user to calculate the various degrees of spatial integration of convex, axial and segment line maps. Although it may not be the most (visually) intuitive of programs, the biggest strengths are that the number of available functions is limited and learning how to use them is relatively easy (van Nes *et al.*, 2021). Moreover, no programming or scripting is required to perform any of the required and available tasks, although it is possible for more advanced users to edit the software (Turner, 2004, p. 4, 41-42). The most complicated task is to enter the formulae for normalising the analysis values (see Hillier *et al.*, 2012; de Koning *et al.*, 2022, p. 9). The biggest weakness that limited the research is that DepthmapX is a stand-alone application, which made integrating the tasks into workflows that include other applications a time-consuming manual task since this was not programmable through the available VPL.

The generic character of GIS applications has the advantage that these are broadly applicable in a wide array of spatial research domains. The possibilities are seemingly infinite, and operating the basic functions can be done in GIS with relatively little training. However, even simple tasks might require a substantial number of steps. Fortunately, many of these steps can be automated via the model builder described in Section 3.5.3 and in de Koning *et al.* (2022).

Despite the variety of applications in various professional fields, there are critiques to the GIS platforms used in this dissertation. It is argued that they are needlessly complicated, thus requiring a certain level of specialised expertise and experience from the user, and are resource-hungry (de Smith *et al.*, 2007, p. 7). For more domain-specific queries involving specific complex data operations (e.g. those which require a script), some extra translation and adaptation needs to occur.

The possibilities particularly in mathematical applications have pushed the development of fields of research that did not exist before the widespread availability of personal computers. Simultaneously, post-graduate learning, continued skills training and professional development during the lifespan of one's career becomes more essential with leaps in technological advances.

This dissertation encountered limitations in terms of automating tasks within the workflow. Some tasks had to be done manually, while others required programming skills. These same limitations may apply to end users as well. Although repetitive tasks can be automated, knowledge on how a tool operates and which steps are best combined based on the query to the data is required. Moreover, pre-processing the data as required in this dissertation (de Koning *et al.*, 2022) is largely a manual task that each user has to perform before being able to use the toolkit. A weakness of GIS software, particularly ESRI® ArcMap, is that it has a steep learning curve requiring a certain level of pre-existing knowledge and skills to use it efficiently for advanced spatial analysis. There are numerous tutorials and guides available but they are not always customisable for the questions raised.

Being a commercial product, the source code for ESRI® ArcMap is not disclosed. This limits transparency and thereby further development. Python scripting language is supported in ArcGIS, but learning even the basics of scripting requires a certain amount of training and experience through online courses or substantial textbooks (for example: Tateosian, 2015). For that reason, various free, open-source GIS software are available that allow for further experimentation and development such as QGIS, GRASS, ILWIS, SAGA (see for an overview of free to access software: GISGeography, 2021). Due to its open-source nature, there are many user-created plugins in QGIS that simplifies tasks that take more time and effort in ArcMap. However, the challenges of performing more complex operations and repeating tasks remain.

The more complex the question asked of the data, the more likely there is no readily available automated software for the task and increasingly extensive computer skills and knowledge of tools are needed. This highlights a trade-off between domain-specific knowledge of the subject (i.e. spatial relationships in cities and interpreting the outcomes of analyses meaningfully) and domain-specific skills to operationalise the investigation (i.e. using geocomputational tools, models and scripts). This can be considered an impairment on the researcher's capacities. The question is to what extent the limitations to the usability of software tools could be further mitigated. Notwithstanding the potential pitfalls of black box effects and relying on AI for generating insights (i.e. knowledge of the subject), the development of low-code-no-code (LCNC) tools for automatically generating code (see for example: Cabot, 2020; Sufi, 2023) seems to be a good way forward. However, close cooperation between software developers and specific domains that desire improved usability of (generic or domain-specific) software applications will be required, since software developers are not commonly trained in spatial analysis (Longley and Batty, 1996, p. 3). With the development of the various software tools for analysing spatial configurations (DepthmapX amongst others), this has indeed been the case.

The domain-specific application this dissertation employed can provide insights to geocomputation via refinement of software tools and workflows that are better attuned to user needs, experience, and requirements for co-production of the next generation of applications or plugins. The development of software tools by tailoring to the needs of various domain-specific end users such as mentioned above has been the case with most (licensed) software available at present. This is likely to be accelerated with the current surge in available open-source data and the emergence of open science (Fecher and Friesike, 2014) and citizen science (Vohland *et al.*, 2021).

"Not I, but the city teaches."

Σωκράτης

6. Conclusions and future work

This dissertation asked:

Which spatial relationships, as expressed through densification patterns and transport energy networks, are identified through spatial configuration analyses with software tools for geocomputation?

The aim was to provide insights into how space in cities, through its structures and forms, drives a variety of urban phenomena (such as urban densification patterns, and the locational aspects of transport and energy networks) as expressed through spatial relationships. This chapter highlights the findings and contributions of the research, the implications for urban design and planning, and remaining challenges for potential future geocomputational research.

6.1. Highlights of findings

In this dissertation, the identification of spatial relationships was explored through the spatial analysis of spatial configuration expressions of i) densification patterns in the city of Bergen, Norway and ii) transport networks and energy usage in Bergen, Norway and Zürich, Switzerland. An innovative exploration of methods was used combining identification approaches from the study of the logic of space with Space Syntax in combination with methods for studying urban form. Findings within the dissertation show that the patterns of densification, land use mix and the ensuing mobility choices for movement can be understood through this combined approach to spatial analysis. Spatial configuration can be represented by axial and segment lines. The rational values can be combined with i) building densities within a given proximity expressed as FSI and GSI, ii) land use mix as expressed through the ratio of amenities, offices, and housing, and iii) transport energy usage derived from traffic speed and traffic volume.

To answer the main question, the following subsequent questions were raised and answered:

How does spatial configuration affect densification patterns? SRQ1

Spatial configuration affects densification patterns in the areas of study through the types of land use functions and mixes located at a certain specific area in relation to the values of the spatial configuration of the entire study area. This corroborates the theory of natural urban transformation. For example, areas with high spatial integration values tend to attract more public functions and support higher building densities and more activities. Areas with lower spatial configuration values have potential for densification if local networks can be improved. Thus, well-integrated areas (mostly found in the urban core, local centres and adjacent neighbourhoods) support higher building densities and economic activities. Conversely, more segregated areas, mostly found in suburbs and urban fringes, have high potential for densifying with residential functions whilst improving local street network connections (see A1).

How does spatial configuration affect transport energy usage? SRQ2

Transport energy usage in cities is affected by its spatial configuration. The correlation found is that denser and more compact urban structures display more concentrated and efficient energy usage (see B1, B2). Spatial configurations with high integration values at the local scale (i.e. street networks more suitable for walking) exhibit lower amounts of energy usage than those with high values at a citywide scale (i.e. more car-oriented environments). Analysis shows that the local integration values impact transport energy usage more than global (citywide) integration values. In both Bergen and Zürich, high local integration values correspond with a reduction in energy usage, whereas low local integration values correspond with higher energy usage (see B1).

Understanding the relationship between spatial configuration and transport energy usage is important for achieving more sustainable development. In compact cities where local centres with high building densities and function mix are connected by highly integrated transportation networks, transport use is more energy-efficient than in mono-functional neighbourhoods with low building densities and segregated street networks. The spatial configuration of mobility networks can therefore influence building densities and the distribution of land uses (attractors) which in return generates movement. These collective movements reflect individual mobility choices. Therefore, spatial configurations influence route choice and mode choice (mobility choices), affecting transport energy usage through the available mobility choices (see B1).

How can analyses of spatial relationships be conducted and improved using geocomputational software? SRQ3

Geocomputation in GIS involves performing computational tasks such as arithmetic operations applied to tabular data, within queries and map layers (de Smith *et al.*, 2007, p. 127) to select and compare various data with a spatial relation to each other. This allows for the investigation of spatial relationships through identification of potential correlations. The researcher is subsequently able to make inferences of spatial relationships that can corroborate or expand on existing theories (Hillier, 1996, 2009; Hillier and Hanson, 1984; Hillier *et al.*, 1993; van Nes *et al.*, 2012; Ye and van Nes, 2013, 2014). However, a key challenge is streamlining the process of data input and performing calculations when transferring analyses across different software tools. Within GIS, the use of a VPL allows the researcher to build an executable model to align data inputs and automate analytical processes for gaining insights into spatial relationships of urban areas (Longley and Batty, 1996; O'Sullivan and Unwin, 2003; de Smith *et al.*, 2007) (see C1). This can allow domain-specific professionals to develop or execute a scientific workflow to analyse spatial data without having to learn extensive programming skills. The graphical form conceals the underlying code (see Figure 3, p. 10 and Figure 5, p. 16 in C1), which makes it an intuitive and therefore more accessible technology for a variety of domain-specific applications.

This dissertation showed how spatial analysis workflows can be partially automated with software tools for geocomputation and thus standardised (see C1). This automation allows for the analysis of large and complex datasets by individual researchers with basic computing resources. Although the availability of open-source data is growing, the question remains what to do with the amount of information and what the urban designer or spatial planner can learn from it. The proposed and proven application of software tools in this dissertation thereby contributes to enhancing the *reproducibility* of the analysis, the *reliability* of data input and calculations through an automated workflow, the *comparability* through a proposed standardised methodology grounded in spatial theories, and increased *compatibility* between different data types and forms. This is an improvement on the more rudimentary approaches to spatial analysis that are common within the field of geography, spatial planning and urban design (Longley and Batty, 1996; de Smith *et al.*, 2007) (see C1).

In conclusion, **the spatial relationships within cities, as expressed through densification patterns and transport energy networks**, are:

Spatial configuration and its analysed values affect densification patterns through the type of functions and land use mix associated with a particular area. Thus, building densities and activities relate to the spatial configuration values. Areas with potential for densification can be identified through spatial configuration analysis (A1). This is true for transport energy usage as well. The denser and more compact the city, the more concentrated and efficient the expected energy usage (B1). Spatial configuration directly influences building densities and the distribution of land uses (attractors) which generates movement. The collective movements are reflective of individuals' mobility choices which translate into transport energy usage. Understanding these relationships can help policy makers and practitioners achieve desired sustainable developments.

These relationships have been **identified through spatial configuration analyses with software tools for geocomputation** by combining spatial configuration data from street networks as axial lines with building density, functions and attractiveness variables (A1), and transport energy usage (B1). Analysis of these large datasets is only feasible with software tools such as DepthmapX and GIS using VPLs to create an executable model (see C1).

6.2. Contributions

This dissertation has contributed to the fields of urban design, spatial and transport planning and computer science by providing:

- new insights into how the spatial properties of the built environment influence the distribution of building densities and land uses and generate patterns of movement between these land uses;
- a systematic approach for identification of the above spatial relationships that builds upon the theories of spatial combinatorics, natural movement and natural urban transformation;
- new data on the cities of Bergen and Zürich combining open-source and proprietary data for spatial analysis;
- nine types of land use and transport patterns to help align how planning choices can lead to more efficient energy usage for transport; and
- insights into executable models to improve geocomputational spatial analysis aided by a VPL in GIS for application on different case studies in various contexts.

Every city is different based on its history, geographical situation, and socio-cultural and political circumstances. Hence, the spatial relationships examined in this dissertation are context dependent: the densification patterns and transport energy usage derived from spatial configuration are influenced by the unique context of each city. However, objectivity, generalisability and generation of insights require a certain abstraction of reality and that the research not be obscured by anecdotal idiosyncrasies. This dissertation has demonstrated that methods exist to systematically analyse how these spatial relationships occur and to gain a better understanding of how these phenomena relate in principle. Building upon the approaches from urban morphology and the urban network theories and methods, these insights can contribute to more evidence-based policymaking in planning and urban design.

This dissertation produced evidence of spatial relationships between spatial configuration, densification patterns and transport energy usage across cases. The spatial relationships identified in this dissertation have led to a framework for understanding how to evaluate areas for potential densification (A1, B2) and which land use and transport patterns lead to more efficient energy usage (B1). For potential densification areas, policymakers can evaluate their built environments and allocate strategies for policy priority and investments with the strategic densification matrix (A1, B2). The spatial configuration of the street networks supports certain densities and land uses. Street networks that support high density land use mix are recommended to be prioritised as development areas. In areas where the street network does not support high density land use mix, efforts to develop should be moderated if they are not supported by improvements to the street network and appropriate street typologies (B1). This is a novel approach to urban planning and design that could widen the narrowed scopes of policymakers, transport planners and road engineers.

The comparison between Bergen and Zürich proved that car-oriented spatial configurations can lead to higher transport energy usage. Given that energy currently is a limited and finite resource, policymakers and practitioners should reconsider investment in car-oriented transport infrastructure and champion more sustainable modes such as walking, cycling, and efficient public transport networks. However, beyond the argument of resources, this dissertation argued that there are more aspects where car-oriented urban structures could hamper truly socially, equitably and ecologically sustainable development.

Finally, the process of using these methods via respective software tools was optimised by the creation of an executable model in GIS. This enhanced reproducibility, reliability, comparability, and compatibility between the different data inputs and outputs. The recorded workflow and the executable model (C1) can be used by other researchers in different contexts with similar data inputs.

6.3. Implications for urban design

Whilst urban morphology and related fields that study how cities work have produced many sound theories and usable knowledge about well-functioning cities, it is difficult to reproduce the sustainable urban qualities that self-organised cities possess. The mechanistic view of the city as a complex of systems of creating order through geometric shapes and designs failed to create the desired structure intrinsic to self-organised cities.

Moving forward, it is desirable to focus on the questions of how cities work and how can we understand them better than we currently do. Only through understanding how cities work can we begin to formulate an answer without getting lost in "naïve language-based descriptions" (Hillier, 2009, p. K01:01) to the question of what sustainable development truly means and what a sustainable city might look like.

This normative question yields for a descriptive approach as provided in this dissertation. Spatial relationships can be understood through spatial analysis with software tools via multiple inter-dependent fields of study such as sociology, spatial planning, geography and economics. However, in this dissertation, the focus is placed on understanding these relationships through structure and form. Some urban morphologists try to understand the city by considering it as a collection of artefacts. However, context-dependency and reliance on language-based descriptions can limit the revelation of complex spatial subtleties at play. Although past experiences may give designers and engineers clues about possible and desirable outcomes of new designs, there is no way to guarantee and replicate success. What is missing is a "…situation where claims made at the drawing board are capable of translation into well-structured and therefore liveable urban places" (Hanson, 1989a, p. 40).

The question is how to plan a city with the desired and beneficial physical and spatial properties. This dissertation argues that densification patterns and transport energy usage are important indicators for the degree of sustainability in cities and has demonstrated that answers can be found by systematically studying its spatial structures, the subsequent effects on the location of public and commercial functions and the resulting movement and social interaction. It was discussed how spatial structure affects how humans experience the city (Hillier, 2005, p. 19), and thus how they move through it and perform activities in it. In other words, the patterns of integration and segregation of the urban spatial structure on different levels of scale influence movement patterns. This also applies to vehicular movement, and thus transport energy usage (de Koning and van Nes, 2019). In addition, examining the effects of spatial structure on densification patterns revealed that building density and land use mix naturally follow both configuration and movement patterns. Therefore, every new street connection alters the spatial configuration of the street network and thus potential densification patterns and the natural pattern of movement through it. Hence, if the desire exists to develop a specific area to support natural movement, as was the case in (de Koning et al., 2020a), then the pattern of streets need to support the desired movement between land uses naturally by providing the appropriate spatial configuration. This 'appropriateness' can be measured and evaluated with the urban network approach and associated methods. Accurate predictions can be made about changes in spatial configuration caused by changes in the street network and the implications for building densities, land use mix and movement can be predicted (de Koning *et al.*, 2020a; Maiullari *et al.*, 2019). Therefore, knowledge of spatial relationships is invaluable for testing, evaluating, and optimising plans to ensure the desired result is spatially facilitated. In summary, the lessons that were deduced from this research imply that well-designed urban structures ought to:

- have a mix of highly integrated and less integrated areas locally;
- be well-integrated between different levels of scale; in other words: locally integrated areas need to be integrated into the citywide network as well;
- have sufficiently dense street networks locally to support higher building densities and land use mix and, by extension, promote shorter trips (i.e., walking);
- consist of various typologies of streets, not roads, designed to reflect and accommodate the dominant mode of travel.

The above qualities of urban structures can be measured quantitatively via the geocomputational tools presented in this dissertation. As Hillier notes, it is rather remarkable that "the key human subtleties of space only reveal themselves through patterns of numbers (albeit translated into colours)" (2009, p. 18), and that to be able to describe these patterns, human language needed to be abandoned and replaced with (visual) programming languages instead.

6.4. Challenges for future research

The choice of studying densification patterns and transport energy usage and their spatial relationships is fuelled by an interest into how cities could be organised better than they are at present given that space and energy are precious and limited resources in current human society. The conscious choice to focus on the two sectors that can have the most impact on sustainable development for urban areas is in line with international sustainable mobility policies to reduce pollution, congestion and emissions from transport (European Commission (EC), 2016). The spatial relationships identified with spatial configuration, densification patterns and transport energy data are supportive of rhetoric for sustainable mobility. However, many other factors weigh in such as the spatial quality of the public spaces and the presence or absence of people or (un)pleasant sensory experiences (Gehl, 2011), the diverse cultures of usage across different cities (see for example: Levine and Norenzayan, 1999) and the effects of perceived and objective safety as a factor of the natural social surveillance mechanism (Jacobs, 1961; van Nes and López, 2010, 2013; Newman, 1972). Furthermore, it is recommended to expand the scope of research to include natural environmental qualities such as ecology, biodiversity, and food production potential for studying densification patterns and strategies, as well as the study of goods transport, and life cycle assessments of plans, policies and deployed technologies that claim to contribute to sustainability. Future research on urban space could and should combine sociological and environmental theories and concepts such as place identity and placemaking, Urban Ecosystem Services (UESs) (Gómez-Baggethun and Barton, 2012), permaculture design (Veteto and Lockyer, 2008), biogeometry (Karim, 2010; Wafik *et al.*, 2022) and local community building (Cnaan and Milofsky, 2008).

The trick here is to achieve a balance between a descriptive and yet objective representation of spatial configuration data and how to analyse it. Advancements in qualitative GIS, open science and citizen science are good directions forward. However, it is not yet possible to capture every aspect of cities and the spatial relationships they carry in a model. This dissertation used recent mainstreamed advancements in spatial analysis via software tools to come to a workable proxy for researching the synergy between the physical structure and form of the built environment, and various settlement and mobility patterns. The limitations on this front include i) data availability (preference for open-source data), ii) programming skills requirement (using VPL to build the model instead of coding) and iii) the processing capacity of the resulting datasets.

As technology progresses, the next ‘big thing’ is the use of ‘digital twins’ that can transcend the limitations mentioned (Yamu *et al.*, 2023). Nevertheless, it needs to be acknowledged that a model is only and always an abstraction of reality (Brambilla *et al.*, 2017). No matter how close a model gets to represent a real-life situation, it can never reflect all the variables and subtleties at play. Even if the computing resources allow for it, what can be gained in terms of knowledge from a virtual simulation of the city is still to be debated. Yet again, the question remains whether the effort of making models more comprehensive and complex is proportionate to the intended purpose of learning how spatial relations in cities occur and how these areas should be organised. It remains to be seen whether more data and more complex models to manage these provides added value for our ability to understand the relationships under investigation – how cities should be organised for humans and nature to thrive in harmony and abundance for many generations.

This dissertation presented only a specific aspect and approach for gaining a better understanding of spatial relationships in cities. The objective spatial data on spatial configurations provide a basis for asking the right questions and “…making the city and the building speak, rather than speaking on their behalf” (Hillier, 2009, p. K01:01). By standardising the analysis of spatial elements relating to densification patterns and transport energy usage through a partial automation of the workflow, the knowledge of how cities work could be made more accessible to non-domain experts.

Understanding sustainable cities

By analysing spatial relations of urban structures, commonalities of built environments regardless of geographical, cultural or social differences are found. Space Syntax reveals that movement is a natural phenomenon and "...the fundamental purpose of the grid is to structure movement" (Hillier *et al.*, 1993, p. 64). In self-organised cities (as defined in Section 2.3.2), the urban structure facilitates movement as efficient as possible (Hillier, 2009, p. K01:01) suited to its geographical conditions and the conveyances of a respective period. This is an unambiguous 'natural' phenomenon developed and refined in human settlements through many centuries. The ensuing cadastral pattern of ownership is highly adaptable to changes in building demands over time (Carmona, 2021, p. 203; Conzen, 1960). This adaptability on plot level allows changes to be made on the microlevel (i.e. the building level) without major interventions elsewhere (i.e. the street network). Rådberg indeed advocated this as a sustainable planning approach for achieving sustainable urban form, emphasising how strategic adjustments are much easier to implement on the microlevel (Rådberg, 1996, p. 385). These are fundamental workings of self-organising cities where certain hierarchies and relationships are present.

In planned cities built in the last hundred years, traffic and road engineers dictated a majority of how these were to be organised (Hall, 2014). This led to plans that contributed to urban sprawl of low-density, mono-functional neighbourhoods and increased car-dependency. Buildings that facilitated car-based road network lack the natural incentive to communicate with (i.e. constitute) the public domain. This leads to anti-urban properties, too low or too high building densities, and public land uses that do not necessarily locate themselves in metrical proximity to its users in a natural way. The lower population densities associated with car-based areas supported lesser economic activity, and thus fewer social activities. Such neighbourhoods are prone to being socially unsustainable promoting social alienation and isolation.

A holistic approach is needed for urban planning and design that strives to structure movement as effectively as in self-organised cities, without prioritising one modality over another. Plainly said, increasing road capacities will induce more car traffic. To create people-friendly cities, people-oriented street networks need to be prioritised where densification, land use distribution and movement all occur in the most effective way. This dissertation argues that a greater understanding of spatial configurations with these properties will aid in creating sustainable spatial relationships in cities. These insights can be generated through applying software tools for geocomputation rather than calculating by hand or going by intuition. This dissertation demonstrates that it is possible to provide easy-to-use software tools for processing complex digital data to understand spatial relationships and support informed decisions about how to improve cities spatially. The available open-source data and analytical tools provided insights into how to advance more sustainable developments via urban densification patterns and reduced energy consumption from transport.

In conclusion, as society struggles with finite space and resources to the point of threatening the survival of our species, we should make optimal use of the possibilities offered by technological advances at disposal. However, we should not be overly reliant on machines as the only solution for our grand challenges. Instead, efforts should be concentrated on (re)discovering the spatial conditions that can advance our transition into truly sustainable communities.

Epilogue: Space against the machine

The unbridled growth of cities into agglomerations and megacities may seem inevitable and it potentially could be, given the current population growth predicted. However, the author of this dissertation claims that there is some universal descriptive knowledge that is powerfully shaped by and engrained in natural processes around us, which limit the growth thresholds. We should acknowledge and embrace the opportunities that IT offers and give credit for the achievements that are made with the technologies at disposal. The conveniences offered by IT enable us to discover how and if built structures follow natural spatial laws. Geocomputational software tools offer the opportunity to move beyond rationalistic planning and advance implementation of evidence-based policies that understand these natural spatial relationships at play. This dissertation revealed a framework of study that may increase our understanding of how cities work. This might allow the pursuit of sustainable development that is guided by a proper understanding of the natural mechanisms of spatial relations to achieve a more sustainable lifestyle for all.

Whilst acknowledging the valuable contribution that software tools for geocomputation bring to spatial analysis, it is equally important to be aware of possible threats and acknowledge its limitations. Besides potential moral and ethical objections to unbridled data collection, one can in fact ask to what end it is necessary to model the world around us. On the one hand, as cities and societies become more complex, the associated societal challenges are increasing in complexity and magnitude. The compact city concept came about as a reaction against urban sprawl, and the green city concept as a reaction to overcrowded, polluted cities. In turn, the urgency of sustainable development is a reaction to bad planning and design decisions from the past. Likewise, the lack of evaluation of policies and plans in postmodern planning in the 90s called for evidence-based policies. On the other hand, humanity has evidently thrived for millennia before the transistor was invented. Self-organising cities before the dawn of IT did not need to be analysed to produce street networks that structure movement efficiently. Since movement was restricted to sustainable modalities: travelling on foot, by horse or by ship, there was a natural incentive to keep travel distances short to keep proximity to basic services. Thus, cities were not inclined to sprawl but grew in a naturally compact fashion. This "concurrence and coexistence of meeting place, traffic and market place" (Gehl *et al.*, 2006; Salingaros, 2005a, p. 185) is of course a basic property and perhaps the definition of a city. Similarly, the limits on the dimensions of built structures were determined by the strength of the naturally available building materials.

However, the transport-energy reducing property of compact cities does not imply to build as dense as possible with the currently available technology. This illustrates the essence of the density paradox: achieving sustainable development through building compact cities can be achieved in a satisfactory way if and only if the qualities of the green city can be implemented successfully and completely in the same space at the same time. Amongst these qualities are spaces for biodiversity, ecology, water management, and recreation, but more importantly the production of foods and goods. So, a more fitting approach for achieving truly sustainable development is to structure cities in a way that allows its inhabitants' environmental footprint to not supersede their physical footprint. This can be approached better when its spatial configurations are appropriate for promoting localised economies in safe, walkable, resilient, and socially inclusive human habitats.

Although motorised transport is a valuable technology that raised the standard of living in some cases, it is difficult to ignore its role in catalysing the exponential growth of the industrial-economic complex that led to the global crises the world is facing today and might face in the near future. Self-driving cars and 'smart' devices will aggravate these problems rather than solve them. The argument of convenience does not suffice when introducing 'smart' solutions in cities. Its potential pitfalls cannot be ignored as the well-meaning modernists did when planning car-oriented cities.

It might sound ironic that years of research on a high-tech computer were needed to conclude that the way in which space and resources were used in naturally evolved cities before the advent of modern technology was organised more effectively. Inhabitants of these naturally evolved cities managed to fulfil the needs of their time in a way that allowed future generations – us – to fulfil our needs. They did not own electric cars or 'smart' devices, and they certainly did not need computers to figure out whether they were living sustainably or not. It seems that some of the common knowledge that was natural in the pre-machine era has been forgotten – but not lost. Cities carry this message in their remnant spatial configurations. This dissertation has provided insights into the natural property of cities spatially organising movement and all other urban activities as effectively as possible. Hence, naturally evolved cities that matured with rudimentary technology escaped the haphazard rationales of enlightened technocrats to self-organise space in a sustainable manner. With all the technical powers and conveniences at our disposal today, this generation has not nearly been as successful yet. We may perhaps not need more machines to fulfil our needs without preventing future generations to fulfil theirs but it did require several to arrive at this conclusion.

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Part II: Publications

"Though the problems of the world are increasingly complex, the solutions remain embarrassingly simple."

– Bill Mollison

sustainability

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Article

A Scientific Approach to the Densification Debate in Bergen Centre in Norway

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Abstract: The municipality of Bergen in Norway aims to densify fifty per cent of new housing within the city's central parts. The Ministry of Local Government and Modernisation ordered and financed an investigation to be carried out by the Western Norway University of Applied Sciences and the consulting firm Asplan Viak to give research-based input to the densification strategy debate in Bergen. This article demonstrates how the Space Syntax method can be applied to urban densification strategies in urban planning and policy making. The Geographical Information System (GIS) is used to obtain, select, and aggregate operational information. First, the spatial attributes that constitute an area's attractiveness were registered. Then, this analysis was modelled after the Spacescape® method. Next, the Space Syntax methodology was applied to predict to-movement and through-movement flow potentials. Finally, through weighting the relevant parameters, including impediments such as land ownership, twelve areas were identified as having major potential for transformation based on their overall score. As it turns out, the spatial structure of the street and road network is the underlying driver for how and where to densify. Now, the challenge is how to apply this knowledge into current planning practice.

Keywords: densification; urban transformation; Space Syntax; planning strategies

1. Introduction

What kind of scientifically grounded analysis tools can be used for making densification strategies in cities? At present, the municipality of Bergen in Norway has launched a new urban development strategy of densification, that is, fifty per cent of the total needs for new housing should be realised within Bergen's central parts. This strategy is radically different from previous strategies that facilitated urban sprawl, car dependency and, consequently, low socioeconomic interaction and anti-urban neighbourhoods. These strategies have been generally employed in most Norwegian towns and cities. The recent shift in policy reflects a global trend of moving towards low-carbon, low-emission cities in the battle against climate change, global warming, and dwindling resources. Subsequent national and local objectives aim at reducing urban sprawl into the countryside, as well as transporting energy usage by investing in public transport and increasing the building intensity and land-use mix around these public transport lines. In the following, first, we provide an overview of the recent planning history of Bergen. Next, we present the current planning challenges and approaches to deal with them. Finally, we present the results with the Space Syntax approach.

After thirty years of urban planning with an emphasis on facilitating private car accessibility, in 1990, the Bergen Municipality in Norway changed their planning focus on urban public space by transforming the inner-city public spaces from car-dominated to pedestrian-friendly areas. The challenge was to identify the basic spatial characteristics that could generate urban areas with pedestrian-friendly public spaces and street life. A study was conducted showing the overall and local relationships among the natural landscape, built-up environment, and public spaces. The method had a place-phenomenological approach, inspired by the work of Christian Norberg-Schulz [1,2]. The place analyses of Bergen consisted of handmade sketches carried out by various architects [3], as shown in Figure 1. The knowledge gained was important for establishing a successful long-term process of transforming dilapidated public areas into attractive, lively urban places with a view to understand and strengthen Bergen's place identity. The municipality of Bergen received several national awards for this turn-around operation, such as the Bolig og byplanprisen (1994), Norsk forms hederspris (1995), Statens byggeskikkspris for byrom i Bergen (2002), and the new light rail was awarded with the following prizes: Kollektivprisen (2012), Boby - byutviklingspris (2012), Vegdirektørens pris for vakre veger (2012), and the international award Worldwide project of the year (2011).

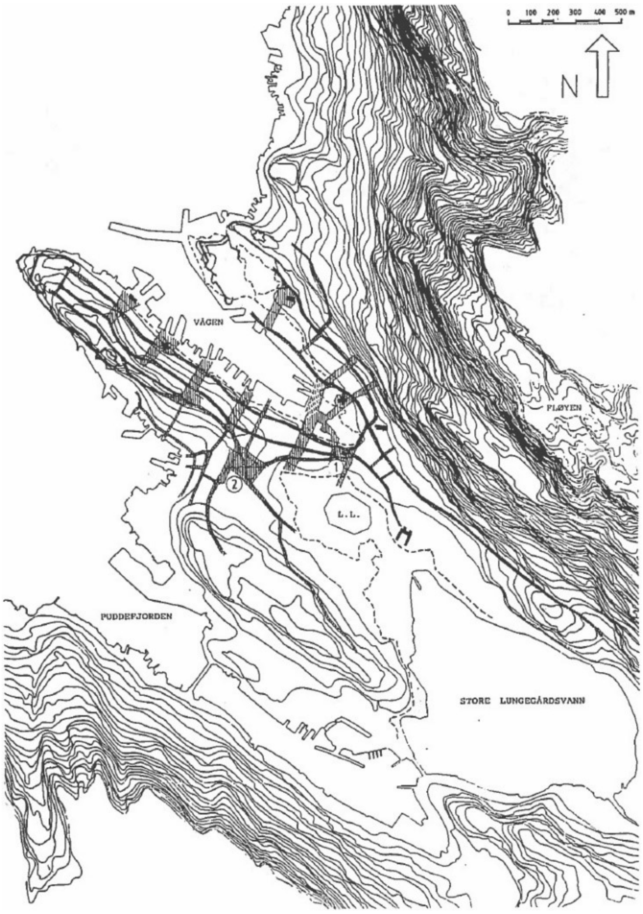


Figure 1. The character of Bergen's public spaces and landscapes.

Today, new planning challenges and opportunities are emerging. On the one hand, in light of sustainable urban development, the task is to discover where and how to densify the built mass in a sensible and environmentally friendly manner, whilst maintaining profitability. On the other hand, a revolution has taken place regarding the automation and availability of data and digital maps. In addition, a number of scientifically grounded spatial analysis methods and tools have been developed. Thus, instead of registrations on handmade maps, we have a number of electronic tools at our disposal for analysing complex environmental situations.

In Bergen, several resolutions have been adopted to improve the urban environment. The primary goals are to stop the growth of private car use and reduce greenhouse gas emissions [4]. The municipality tries to achieve these goals by changing their policies from an urban sprawl strategy to a compact city strategy focusing on the city's central parts, as shown in Figure 2 (left). This is meant to improve walkability and support effective and reliable public transport. The reasoning is that short walking distances and a well-functioning public transport system yield high numbers of users, which in turn requires high building densities and a high degree of land use diversity.

The central areas of Bergen, shown in Figure 3, make up 12% of the total built-up areas in the Bergen municipality. At present, the population density of the whole municipality of Bergen is 630 inhabitants per km^2, whilst the central areas have a population density of 2111 inhabitants per km^2. The municipality of Bergen has 281,190 inhabitants, of which 83,669 live in these central areas.

The central parts of Bergen are expected to facilitate almost half of the new housing stock, which would account for approximately 10,000 new dwellings by 2030. This area is already largely filled with different building types and a large variation of urban functions. Bergen's city centre contains protected heritage objects of local, national, and international importance. The city centre's dense structure results from its topographical situation, sandwiched between steep mountains and the fjord. This forms the basis for Bergen's unique place identity that is treasured and admired by visitors and locals alike. The remainder of the densification area covers the areas from Sandviken and Laksevåg on the seafront to Fantoft and Paradis up into the valley. These neighbourhoods have a predominantly suburban settlement pattern with many low-density buildings surrounded by trees and vegetation. There are few urban centres outside the historic city core, and the low-density residential neighbourhoods are heavily car dependent.

2. Current Paradigm in Urban Planning

Current planning policies in Europe put ″smart″ growth, high building density, and high diversity of urban functions within short walking distances on the agenda to create compact cities (see for example [5,6]). However, the social and environmental sustainability of building a compact urban form is disputed [7] (p. 385). The compact city has the advantage of providing short walking distances between destinations. The ecological footprint for mobility per capita is relatively small as compared with sprawling urban areas. There are advantages to social and economic intensity, such as a high number of people living relatively close to each other paves the way for more social and economic interaction and, from an environmental perspective, less infrastructure is needed per user, and energy usage for transport between destinations in compact cities is low. However, compact urban form often leads to a lack of green spaces for recreation, biodiversity, runoff water management, and food production.

Conversely, the concept of a green city carries positive connotations in terms of well-being and attractiveness. A green city has the advantage of being able to provide its inhabitants with space for outdoor recreation and the possibility to enjoy nature, produce food, and manage water runoff. However, since green cities tend to have low building density, they contribute to urban sprawl into the countryside as the city expands. Moreover, the amount of infrastructure per user is high, and the potential for social and economic activity is low. The contradictions between green cities and compact cities continue to cause a lack of understanding about what constitutes a sustainable city within the fields of urban design and planning to this day [7].

If density is one of the requirements for urban quality, namely high social and economic interaction, then urban development projects should always facilitate maintaining, and where desirable increasing, the level of building density. High building density is considered to contribute to sustainable development because, on the one hand, it implies the sharing of buildable space, facilities, and infrastructure, and on the other hand, the reduction of travelling distances. This sharing implies that the amount of land and energy resources required to perform all urban activities is reduced. Therefore, the degree of this sharing's success can be seen as an indicator of urban quality. Jane Jacobs [8] and Jan Gehl [9] argued that sufficient density with a large variation of land use was one requirement for life between buildings. More importantly, life between buildings was ″potentially a self-reinforcing process″, in which, ″once this process has begun, the total activity is nearly always greater and more complex than the sum of the originally involved component activities″ [9] (p. 73). In other words, a successful urban area is self-propelling by merit of the amount and duration of outdoor activities that it generates.

The Local Context

The background for the research is a project initiated by the Bergen municipality that intends to explore where and how to densify existing urban areas. The aim is to use the outcomes in future land use and policy planning as a strategy for densification in the central areas of Bergen. On the basis of the ”Denser Stockholm” project, an analysis was made to identify both the need for densification and the suitable places for densification. With the GIS-based method, various types of densification were identified and classified depending on different driving forces such as political and legal systems, the need for space versus available space, and accessibility to adjacent functions and services [10].

Successful densification is determined by natural movement patterns that result from the spatial configuration of the street network and public transport coverage. Streets with high amounts of people moving through them are most suitable for densification. Space Syntax methodology can make predictions of movement patterns and, as such, determine where natural urban transformation is likely and desirable to occur [11,12].

The Norwegian Ministry of Local Government and Modernisation financed this inquiry to test out the analysis tools on Bergen and reveal various densification potentials. The Ministry expressed particular interest in whether or not, and how, the Space Syntax and Spacescape methods could be integrated into one common method for identifying densification potential in the study area. Because context-independent methods were used, it was possible to conduct an independent comparison of data to search for possible co-relations between spatial configuration and socioeconomic parameters related to city planning. The study formed the background and outcome for a feasibility study, on the densification strategy of the central parts of Bergen [13].

Complex legal issues related to private property rights pose a serious problem for large scale urban planning and transformation of urban areas in Norway. As stated in paragraph 105 of the Norwegian Constitutional Law of 1814, “no one should be dispossessed of their private property, and if so, they should be given full compensation” [14] (p. 12). This explains why urban expansions in Norway tend to take place on large plots where one only has to deal with a few property owners. Conversely, large-scale urban renewal or transformation projects involve time-consuming negotiations with property owners. In some cases, property borders need to be adjusted.

Since 1980, Bergen’s demographics have changed dramatically. Between 1980 and 2000, the centre population decreased by 7000, despite large investments for upgrading and renewing the city centre. However, between 2000 and 2017, the population of Bergen’s inner-city areas increased by 15,000. This was a result of improved housing standards during the 1980s and 1990s, which contributed to an improvement in Bergen’s city centre image. In addition, various environmental measures were carried out from 2000 onward, and a number of higher education institutions were reinforced or established. All these efforts contributed to an increase in the number of residents living in Bergen’s city centre.

Figure 3 shows a survey of migration within the municipality. The municipality of Bergen consists of eight districts. Two of these districts are situated within the study area (Bergenhus and Årstad). The vast majority of people moving to the municipality prefer to live in one of these two districts. For the other six, the net population changes between 2000 and 2015 were marginal. Most of the new inhabitants are students, young couples, and single households [13].

During this inquiry, a change took place in the municipality’s land use policy. Figure 2 shows two different proposals for the municipality’s land use strategy for Bergen’s central areas. Figure 2 (right) is the land use strategy from 1980 [15] and Figure 2 (left) is the current strategy from 2016 [13]. The 1980′s plan still supported car-based urban sprawl by proposing building sites in the peripheral areas (coloured in light yellow). There was no plan for a public transport network. In the years leading up to the current strategy from 2016, a proposal was made to densify in existing built-up areas instead. A new light rail line was opened in 2010 and extended in 2013 and 2017. Thus, strategies were put in place to open up for densification around areas served by light rail transport. Most of these areas are already urbanised.

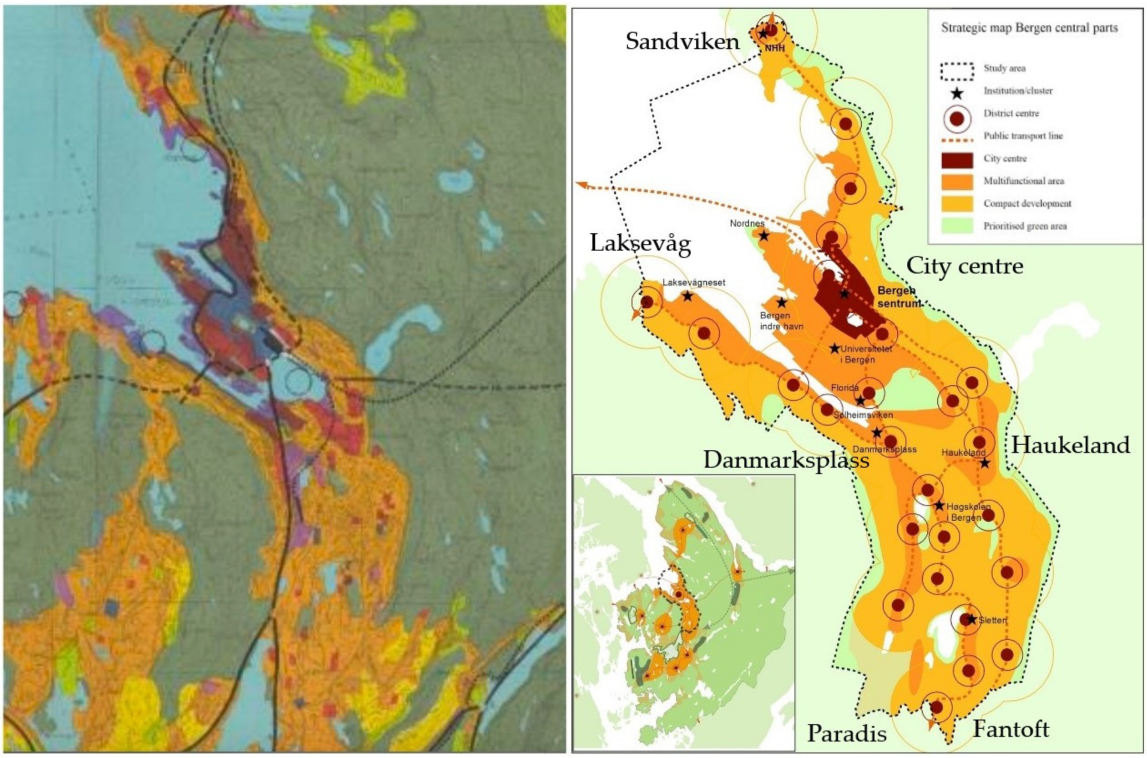


Figure 2. (**right**) Municipal land use plan from 1980; (**left**) Strategic spatial planning map for Bergen's central parts from 2016.

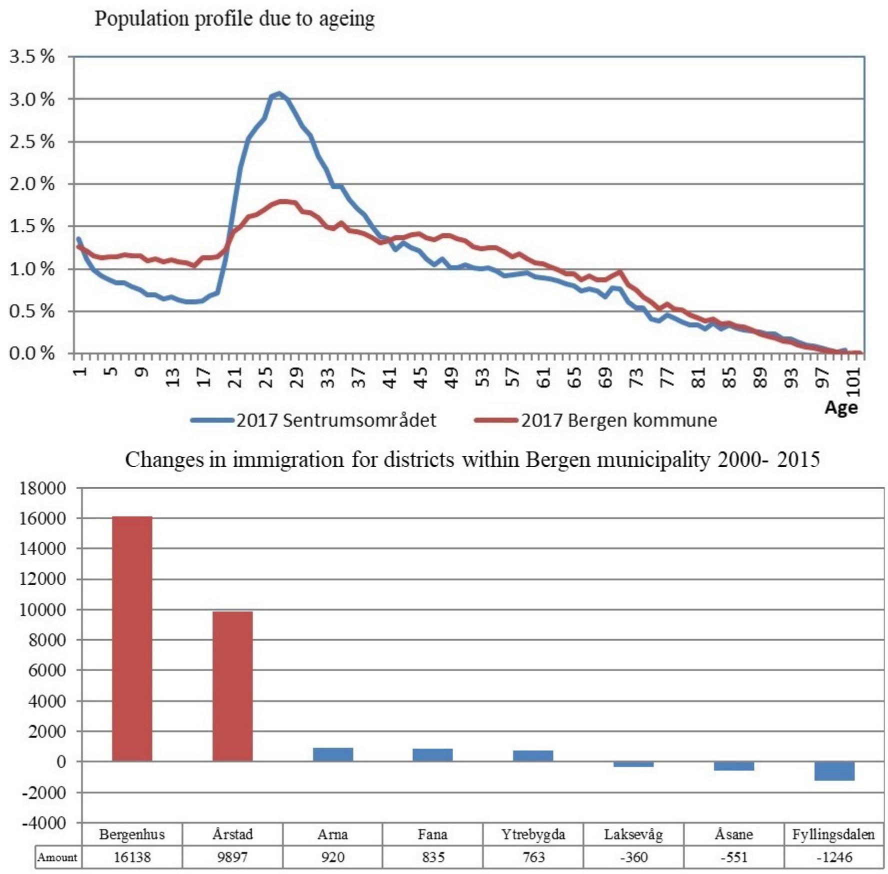


Figure 3. (**Top**) Population profile due to aging for the study area (red) and Bergen municipality (blue); (**Bottom**) Changes in immigration for districts within Bergen municipality 2000–2015.

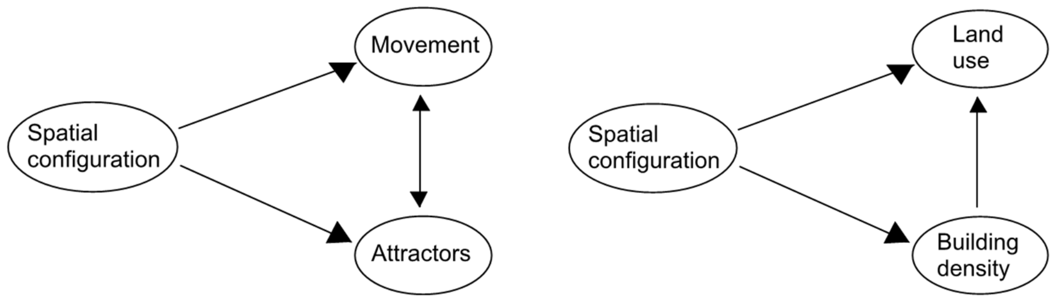
If density is a prerequisite for sustainable use, and the number of outdoor activities is an indicator of the degree of success for performing these activities, then, a spatially integrated urban street network is the primary generator of sustainability in the context presented here [16]. In this inquiry, we show how the degree of street network and public transport accessibility play a role in the natural urban transformation process. The effect of the light rail, for example, is that property prices near the stops are increasing. Presently, however, these densification processes are taking place without an overall plan.

3. Current Theories and Methods on Urban Space

The approach for finding densification possibilities in Bergen was to consult work from similar studies and apply current urban research practices on the relationships among urban space, urban morphology, and land use. First, a baseline study was made of the existing situation to assess the relation between the spatial configuration of the street and road network, as well as the type of built mass density and the degree of land use diversity. Next, the results from the baseline study were used to formulate sustainable, strategic densification proposals.

3.1. Space Syntax

At present, there are two theories on how cities transform based on Space Syntax research, i.e., the theory of the natural movement economic process [17,18] and the theory of the natural urban transformation process [12]. The theory of the natural movement economic process states that the degree of the street and road network's spatial integration affects patterns of movement, as well as the location of commercial activities such as shops and retail. The theory of the natural urban transformation process states that the degree of building density and land use diversity is also affected by the degree of the street and road network's spatial integration. Figure 4 shows diagrams of these two theories, which are able to explain the relationship between cause and effect based on the spatial configuration of the street and road network [19]. The higher the degree of spatial integration of the street network, the higher the density of the built mass and degree of land use mixture. Measuring the degree of the street network's spatial integration is done by applying the Space Syntax methodology.

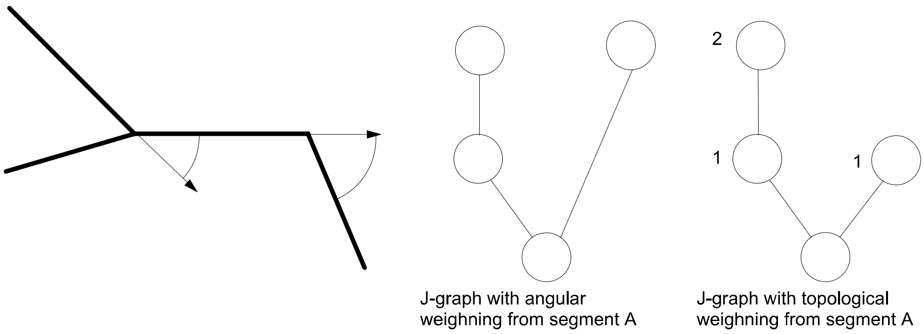


(**a**) (**b**)

Figure 4. (**a**) The theory of the natural movement economic process; (**b**) The theory of the natural urban transformation process.

Space Syntax is a form of accessibility analysis. The Space Syntax method allows for calculating how every street segment relates to all others based on the total number of directional changes (called topological distance) and the degree of angular deviation (called geometrical distance). This can be analysed on different scale levels, i.e., local centralities and main centres can be identified by calculating topological distance with respectively low or high metric radii. This is the street and road network's "to-movement potential". Likewise, the main routes for pedestrians and car traffic can be identified by calculating the geometrical distance with various metric radii. This yields the network's "through-movement potential". For both analyses, a radius of 500 m is used to identify the most vital pedestrian-based streets, whereas a radius of 5000 m will detect the main routes, which are mainly car-based streets or potential main routes for public transport. These two radii correspond with approximately 5–6 min walking (500 m) or driving (5000 m).

Figure 5a shows an example of four street segments and Figure 5b,c shows two different justified graphs. Both justified graphs show how street segment A relates to the other street segments B, C. and D. Figure 5a,b is redrawn from Turner [20], while Figure 5c is taken from van Nes and Yamu [21]. The graph in Figure 5b shows the degree of angular deviation, whereas the graph in Figure 5c shows only the number of direction changes from segment A to the other three street segments.



(**a**) (**b**) (**c**)

Figure 5. Two different manners of weighting distance in Space Syntax methodology. (**a**) Example of four street segments A–D; (**b**) Justified graph with angular weighting from segment A; (**c**) Justified graph with topological weighting from segment A.

The most recent Space Syntax calculations applied in this project are the angular choice and angular integration analyses for each street and road segment [22]. These calculations are based on the angular weighting from Figure 5. The formula of angular choice C of a segment *i* is as follows [23] (p. 64):

$$C_i = \sum_j \sum_k g_{jk}^{(i)} / g_{jk}^{(j<k)} \quad (1)$$

where *gjk* (*i*) is the number of shortest paths between segment *j* and *k* containing *i*, and *gjk* is the number of all shortest paths between *j* and *k*. The angular choice shows the through-movement potentials for each street segment in relation to all others.

The formula for the angular integration (AI) of a segment x is:

$$AI_x = \frac{1}{n}\sum_{i=1}^{n} d_\theta(x,i) \quad (2)$$

where *n* is the number of segments and d_θ the angle between any two segments on the shortest path on a segment *x* and when adding the length *l* of segments [23] (p. 66):

$$AI_x^l = \frac{\sum_{i=1}^{n} d_\theta(x,i) l(i)}{\sum_{i=1}^{n} l\,(i)} \quad (3)$$

The angular integration analyses show the potential to-movement potentials. Shops and commercial activities tend to seek for locations with both high to-, as well as through-movement, potentials [21].

3.2. Urban Morphology: Spacematrix

The latest contribution to the urban morphology approach is Johan Rådberg's method of simultaneously quantifying building density and building form. Rådberg created a matrix where building intensity (or Floor Space Index, FSI) was correlated with plot coverage (or Ground Space Index, GSI). With this matrix, a classification of various types of building morphology could be made [7]. Through later application of the methodology in PhD research, the method was renamed Spacematrix [24].

Depending on the number of floors, building density is categorised into low-rise, mid-rise, and high-rise density. The categories of building type are furthermore separated into point type, strip type, and block type, depending on the building's form. Therefore, the entire built environment can be divided into nine categories, as described in Table 1.

Table 1. Categorisation of the built environment.

	G High-rise point	H High-rise strip	I High-rise block
Building height	D Mid-rise point	E Mid-rise strip	F Mid-rise block
	A Low-rise point	B Low-rise strip	C Low-rise block
	Land use of the urban block		

Figure 6a shows a simple illustration of how types of building volumes in relation to their plots are placed in a Spacematrix scheme. Figure 6b shows a Spacematrix analysis applied on Bergen's city centre. Most of these building types can be found in every major town or city. The analysis is conducted manually, with the help of Google Earth and Google Street view, or by querying two georeferenced shapefiles containing FSI (building) and GSI (plot) data. Then, Spacematrix describes both the intensity of the built mass (through FSI) and plot coverage (through GSI), as well as the spaciousness of the non-built space (through OSR, open space ratio), quantitatively. This makes differentiating between urban forms more accurate and more efficient than before [7].

(**a**) (**b**)

Figure 6. (**a**) The principles of the Spacematrix method. (**b**) An analysis of Bergen's city centre (right).

Figure 7 is adapted from Rådberg [7] and shows how different building types can be accurately and objectively categorised according to building intensity (FSI, on the y-axis), plot coverage (GSI, on the x-axis), and the total number of floors (L).

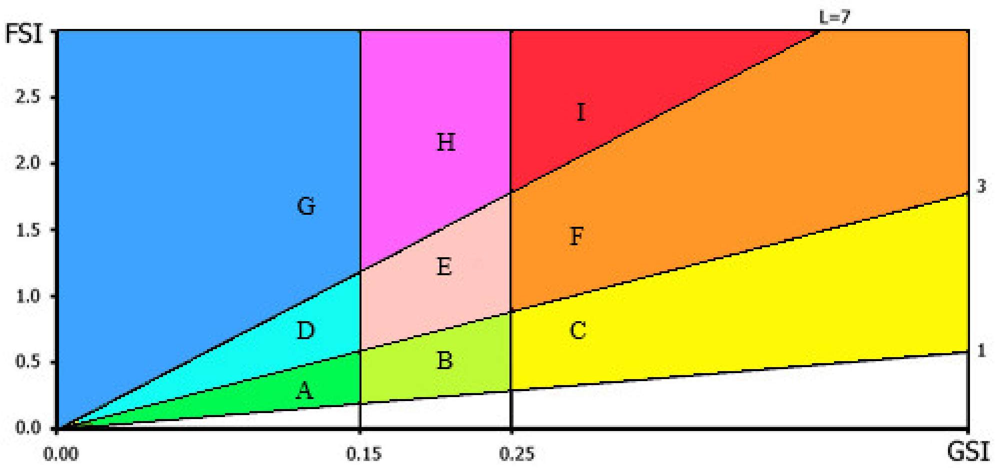


Figure 7. Building morphology categorisation based on FSI (y-axis), GSI (x-axis), and number of floors (L).

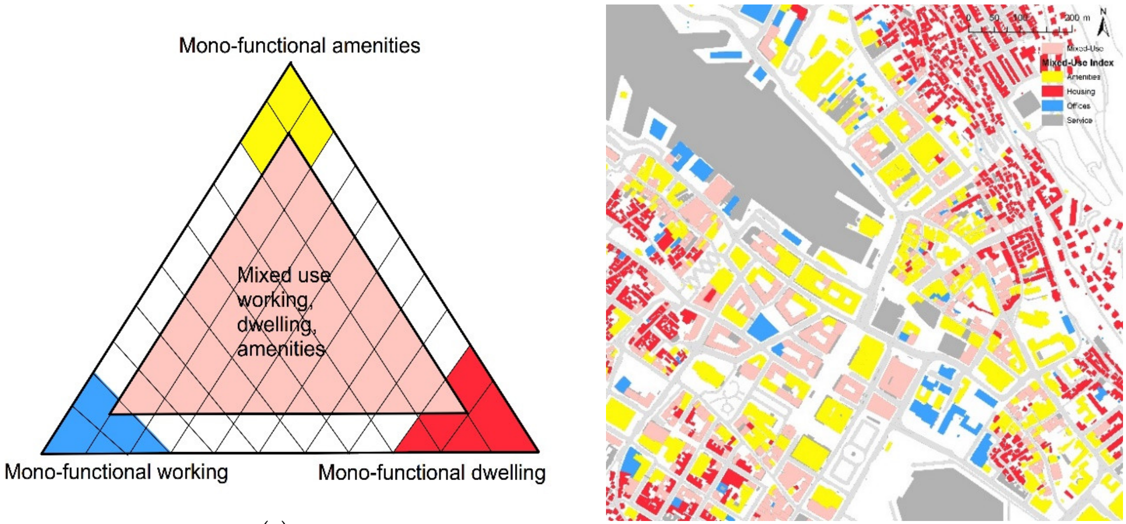
3.3. Functional Diversity: The Mixed Land Use Index

Van der Hoek developed a triangle matrix with that could be used to quantify land use diversity. The method is named the mixed land use index (MXI). Buildings that have only a single function, such as dwellings, working places (industrial areas or offices parks), or amenities (leisure activities such as sports, shopping, etc.) are defined to be monofunctional. Buildings are bifunctional when two of these three functions are present, and they are multifunctional when all three functions are present [25].

The original MXI model measures the percentage of housing, working space, and amenities occupying urban blocks. The function "housing" includes various residential dwellings, such as apartments, condominiums, and townhouses. The function "working" encompasses workplaces such as offices, factories, and laboratories. The function "amenities" covers commercial facilities such as shops, leisure facilities such as sporting arenas, cinemas, concert halls, and museums, and social amenities such as healthcare facilities, educational institutions, and community centres. Consisting of three variables, MXI is defined as the percentage of each variable and sums to a constant:

$$MXI = (\%Housing/\%Working/\%Amenities) \quad (4)$$

The weakness of this matrix is that the categorisation can be ambiguous. For example, a shop or a sports centre can be considered to be an amenity for the customers, whereas it is a workplace for the employees. As Dovey and Pavka also pointed out, a distinction between the level of attraction or the temporal distribution of activities was lacking [26] (p. 255). Improvements are needed to fine-tune this definition for the MXI method. Despite its shortcomings, however, the mixed land use index is a useful method for describing the degree of monofunctionality versus multifunctionality. Figure 8a is a ternary plot, a graphic depiction of the ratios of the three MXI variables as positions in an equilateral triangle. Monofunctional areas wind up at the edges of the triangle, whereas multifunctional areas are categorised in the middle of the triangle. Historical town or city centres tend to have a balanced mixture of dwellings, working places, and amenities; this is also the case in Bergen's city centre. As can be seen in Figure 8b, there are various multifunctional buildings in the historic centre, as well as many amenities and workplaces. Conversely, many modernist urban areas tend to have a strict separation of functions, resulting in predominantly monofunctional areas.



(**a**) (**b**)

Figure 8. (**a**) The principle of the MXI method; (**b**) The analysis of Bergen's city centre.

4. Approach and Application for Bergen

The project started with an identification of the types of densification actions. Following Sandkjær Hansen [27], three types were identified, i.e., intensification, transformation and expansion. Intensification entails densifying the built mass in existing urban areas by, for example, enlarging building volumes upon renewal or renovation. The transformation strategy concerns identifying and assessing the densification potentials of larger urban areas that would require a comprehensive functional transformation, such as harbour fronts, goods terminals, and industrial estates. The expansion strategy utilises densification opportunities in previously unbuilt areas within city limits. In the Bergen case, the latter were often found on mountain slopes, where development had not previously been considered due to costly technical challenges. The area of investigation is located in a valley of about 7 km in length and 2 km across, between steep mountainsides and the fjord. All major communication lines are located at the lower parts of the valley. It proved to be difficult to establish suitable areas for city expansion on the mountainsides. Regarding expansion towards the waterfront, most suitable areas have already come under development expansion projects. Possibilities for intensification are addressed at a later stage (see Section 6). The task for this study was, therefore, to focus on identifying and analysing potential transformation areas.

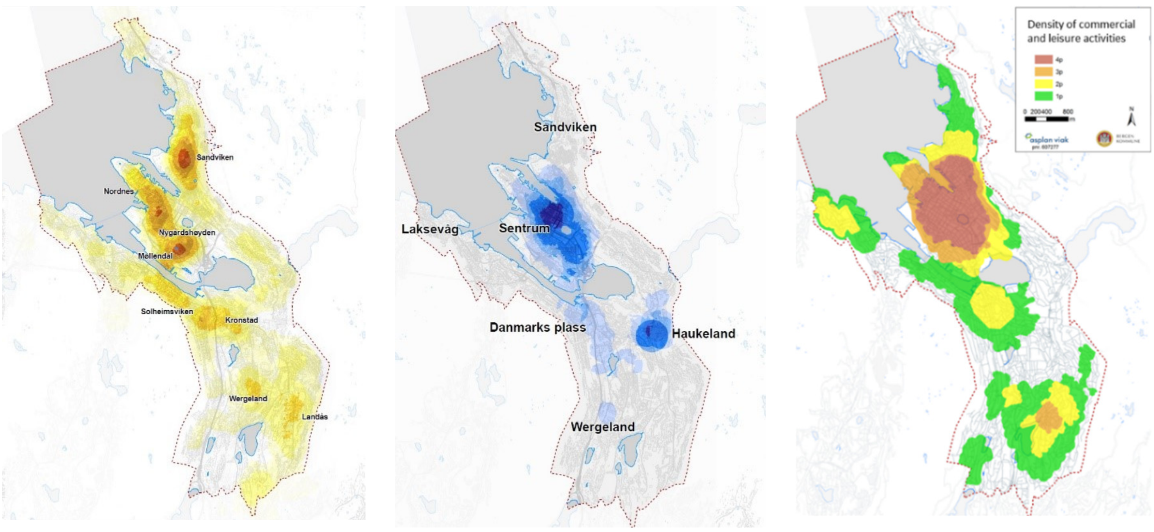
A base map was created from 160 basic statistic units (called grunnkrets). Each of these units could be referred to and conveyed data from the National Statistics Agency and planning and property information with the municipality of Bergen as a source. Maps based on these statistical units made it possible to compare the results of various spatial analyses. One challenge was to assess what kind of information was relevant for co-relating, with a view to gain relevant new knowledge. The second challenge related to the amount of information that could be shown in one map. A map that contained too much information lost its meaning and readability.

The results from the baseline studies followed the theories on the natural movement economic process and natural urban transformation process. The highest densification pressure was found around the spatially integrated main routes, the various spatially integrated local centres, and near the public transport stops. This densification pressure was reflected in the average square meter price in the property market. Currently, the average square meter price for an apartment in the city centre is approximately 57,000 NOK (€5760) and in the suburbs around 35,000 NOK (€3500). Locally, discrepancies may be found, which can likely be attributed to unique landscape elements such as the mountain slopes and fjords surrounding the city. This challenging topography is also responsible for the characteristic capricious road pattern, which follows height lines to keep gradients acceptable from a road-engineering point of view.

5. Results

In the following, we present the results from the Spacescape report and various spatial analyses, i.e., Space Syntax, Spacematrix and function mix (MXI), for Bergen's central areas. The methods used in the Spacescape report consist of overlapping thematic GIS registrations using an aggregate map that summarises the results of all these themes. Topics that were examined included the density of working places and housing, frequency of public transport, local axial integration of the street network, and commercial and service activities. Figure 9 shows the most useful thematic maps. The higher the concentration of various facilities, the higher the attractiveness and desirability to live in or near these areas. This is mirrored in the property prices, where the highest square meter prices can be found in the city centre.

Three thematic maps that address functionality and density were juxtaposed with each other. Figure 9 shows housing density (Figure 9a), density of working activities (Figure 9b), and density of commercial and leisure activities such as trade, public and private service, culture, and education (Figure 9c). According to most writings on compact cities, a compact city has a high density of built mass, a high degree of land use diversity, a high number of services, and a high accessibility and frequency of public transport [28–30]. The maps of Figure 9 seem to confirm that the historical city centre is the most compact part within the study area, followed by Danmarksplass. These areas also have good public transport accessibility.



(**a**) (**b**) (**c**)

Figure 9. (**a**) Housing density; (**b**) Workplace density; (**c**) Density of amenities.

To analyse the attractiveness of Bergen, eight variables were mapped. These are listed in Table 2. The Spacescape method operates with seven variables. The difference is that, contrary to Bergen, sun conditions were deemed irrelevant for Stockholm. Furthermore, a regular street structure was considered to be important for Stockholm, whilst Bergen has a more pluralistic urban structure. In addition, the population's socioeconomic status and living conditions were considered to be relevant for Bergen but not for Stockholm.

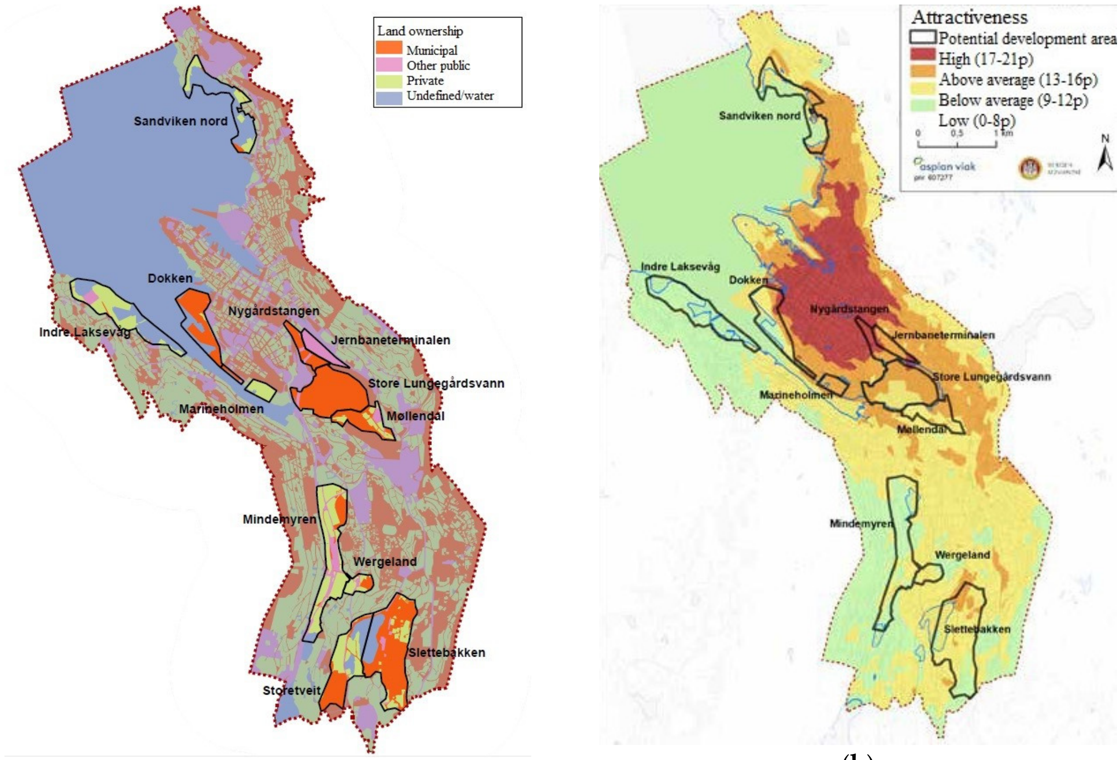
Table 2. Attractiveness variables.

Topic	Weighting
Proximity to the city centre core	Very important 0–4 points (17%)
Proximity to urban businesses	Very important 0–4 points (17%)
Proximity to public transportation hub	Important 0–3 points (13%)
Exposure to sunlight	Important 0–3 points (13%)
Socioeconomic living conditions	Important 0–3 points (13%)
Proximity to a waterfront or vista	Moderately important 0–2 points (9%)
Access to a park	Moderately important 0–2 points (9%)
Proximity to an integrated street structure	Moderately important 0–2 points (9%)

Twelve major transformation areas were identified through overlapping the attractiveness variables from Table 2. These areas were analysed according to attractiveness, ongoing planning activities, ownership, potential obstructions related to implementation, and capacity. The total capacity for the twelve development areas was summed up. The potential turned out to be considerable, with room for realising approximately 10,000 new dwellings and a 1,000,000 m^2 public programme. On the basis of a discretionary assessment, a division was made into 50% dwellings and 50% urban functions. This could increase the total housing stock by as much as 25%, which would, in turn, trigger the need for new social and commercial amenities.

When it comes to implementation, all densification projects are difficult. Moreover, some areas face critical obstructing factors such as unclear ownership or underlying diffuse agreements outside the power and authority of the municipality. Such areas are considered to be immature with regard to starting a planning process, let alone programming. Figure 10a provides an overview of land ownership in Bergen, with the twelve development areas marked out. In some development areas, the public sector is the dominant owner. Regarding the others, the land is predominantly privately owned. When it comes to planning and implementation, the strategy that deals with privately owned land is quite demanding with respect to fulfilling public goals, in this case cross-sectoral goals specified by the municipality. A challenge the municipality faces is that the central government has organised its activities into a large number of companies acting as if they are private and with economic income as a prime objective. Due to the strong property rights in Norway, it is the local owners who decide whether they will densify or not. However, if property prices rise due to the increased accessibility of the road, street, and public transport network, it acts as an incitement for property owners to densify.

The summary map of all themes, shown in Figure 10b, demonstrates a great variety in the attractiveness of the twelve development areas. According to the overall score, the centre and its immediate surroundings to the north and east have high and above average attractiveness. The other areas, in yellow, have below average attractiveness, with the lowest attractiveness found to the west and southwest. There is a clear concurrence between the most attractive areas and the compactness of Bergen, i.e., the more compact the area, the higher the overall score on the scale of attractiveness. Furthermore, Bergen has a clear, more attractive ”east end” and less attractive ”west end”. Especially in winter, the east side has far better sun exposure than the neighbourhoods on the shaded slopes to the west. This is reflected by the area’s socioeconomic performance.



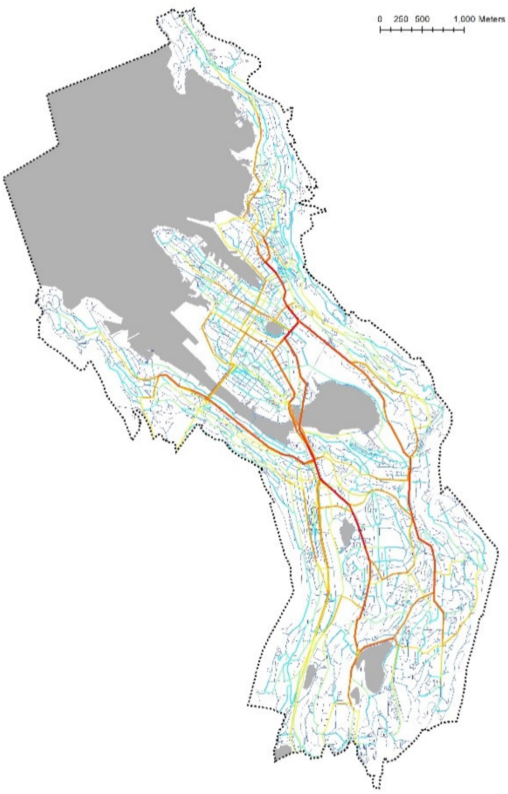
(**a**) (**b**)

Figure 10. (**a**) Development areas overlapped on land ownership; (**b**) Summary map of attractiveness variables.

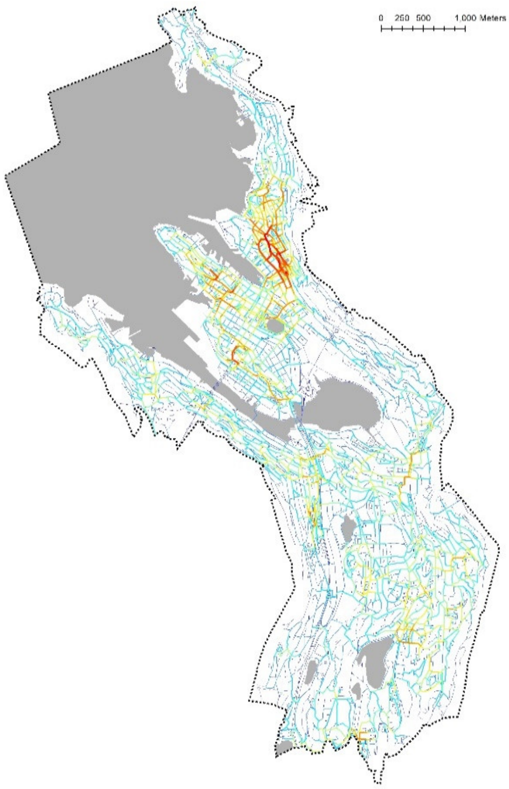
So far, twelve densification areas were identified around the city centre. The next step is to find out how to densify. Here a more robust and objective method is required than the discretionary assessment method used earlier. To that end, the latest Space Syntax analyses of to-movement and through-movement potentials [30] were added to this inquiry.

According to the theory of the natural movement economic process and theory of the natural urban transformation process, the spatial configuration of the street and road network matters. When the street network is integrated on all scale levels, the densification pressure is higher, and if a high degree of land use diversity is facilitated, walking distances between the various functions become shorter. To this end, we wanted to add a more objective approach to identify how and where to densify, in addition to the subjective discretionary approaches used previously. For this, we aggregate the land use mix, building density, and spatial integration of the street and road network into one model. The basis for these three analysis methods is the Space Syntax analyses. Where the spatial integration of the street network is high, on both a citywide and local scale, the degree of building density and land use diversity is also high.

Figure 11 shows the through-movement potential on a citywide scale with a radius of 5000 m, or 5–6 min driving at 50 km/h (Figure 11a), and on a local scale with a radius of 500 m, or 5–6 min walking at 5 km/h (Figure 11b). The red, orange, and yellow streets are the most integrated streets. This indicates that these streets are expected to have relatively high amounts of through traffic. Green and blue shades indicate streets that are relatively segregated from the rest of the street network. On the citywide scale, the main routes stand out. These main routes run largely parallel to the valley and connect the different districts with each other. Car traffic is dominant on these streets. On the local scale, small clusters of locally well-integrated streets are highlighted by the analysis. These streets are likely to be used by pedestrians. Most well-integrated streets are found in the city centre, especially in the Stølen/Indre Sandviken area. Conversely, the dominant green and blue street segments outside the city centre indicate that the street pattern here does not favour pedestrian traffic.



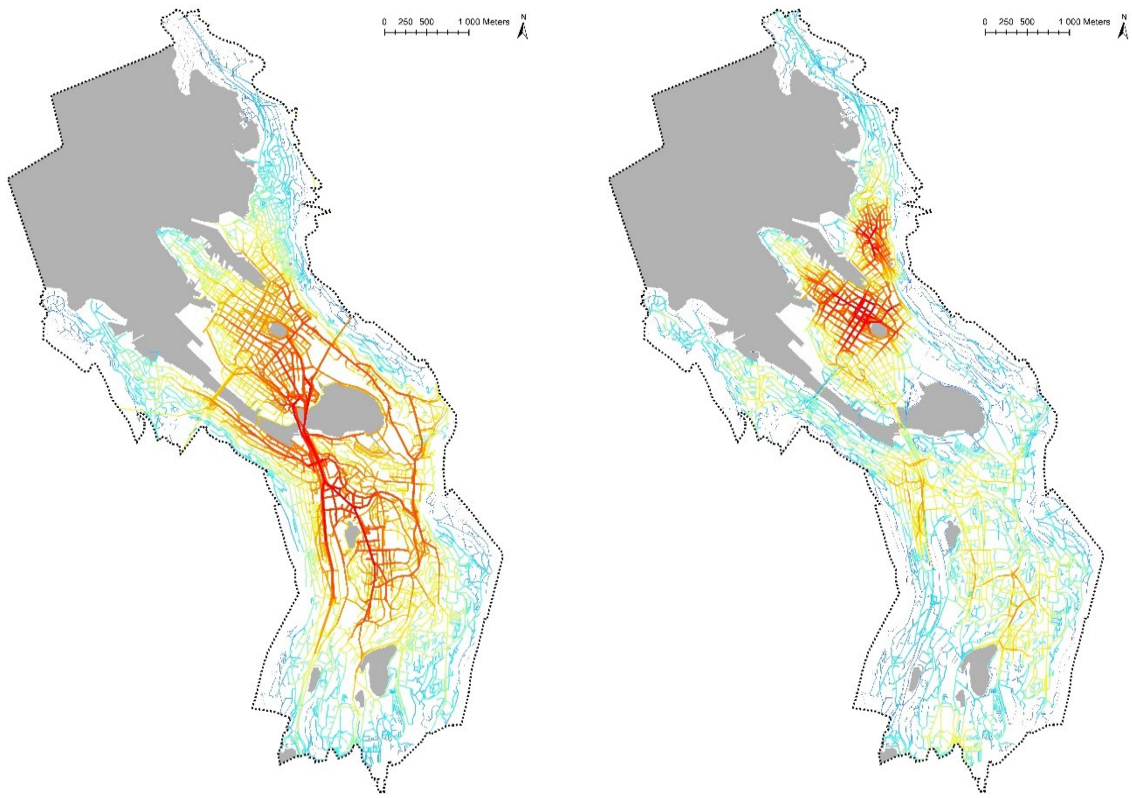
(**a**)



(**b**)

Figure 11. Space Syntax analyses of through-movement potentials. (**a**) Angular choice with high radius (R = 5000 m); (**b**) Angular choice with low radius (R = 500 m).

Figure 12 shows to-movement potentials for Bergen's city centre with a radius of 5000 m, or 5–6 min driving at 50 km/h (Figure 12a), and a radius of 500 m, or 5–6 min walking at 5 km/h (Figure 12b). Here, too, the analysis with a high radius shows the to-movement potentials on a citywide scale, whereas the analysis with a low radius shows the to-movement potentials on a local scale. Whereas the through-movement potential analyses indicate the potential for the flow of movement throughout a city, the to-movement potential indicates streets that, based on the spatial configuration of the street pattern, are likely to be a destination. On a citywide scale, many streets adjacent to or near the main routes that lead out of the city centre have high to-movement potential. Locally, the orthogonal street network in the city centre scores high, as well as the Stølen/Indre Sandviken area that is highlighted in the local Angular Choice analysis of Figure 11b.



(**a**) (**b**)

Figure 12. Space Syntax analyses of to-movement potentials. (**a**) Angular segment integration with high radius (R = 5000 m); (**b**) Angular segment integration with low radius (R = 500 m).

The Spacematrix analysis, shown in Figure 13, reveals that the city centre has medium to high density and predominantly closed building blocks. The areas outside the centre core are a mix of low and medium building densities with a large variation in building types. The greater the distance from streets with high through- and to-movement potential, the lower the building density. The analysis shows that the highest FSI and GSI are found in areas with the highest values on all Space Syntax analyses.

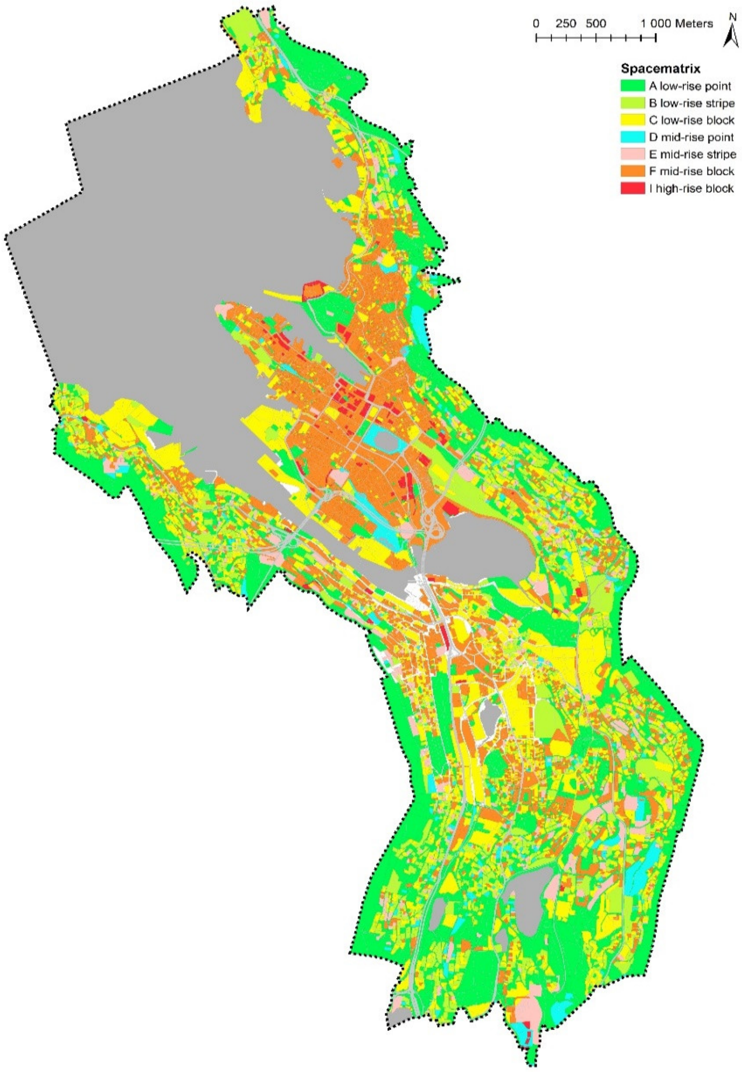


Figure 13. Spacematrix analysis of building densities and typologies.

Through the MXI analysis shown in Figure 14, it becomes clear that the city centre, with its high to-movement potential on different scale levels, also has the highest concentration of amenities and multifunctional buildings. Outside the centre core, most amenities are situated around Haukeland university hospital, Sletten, and Danmarksplass. Offices and industry are concentrated along the waterfront, the railway line, and at Mindemyren.

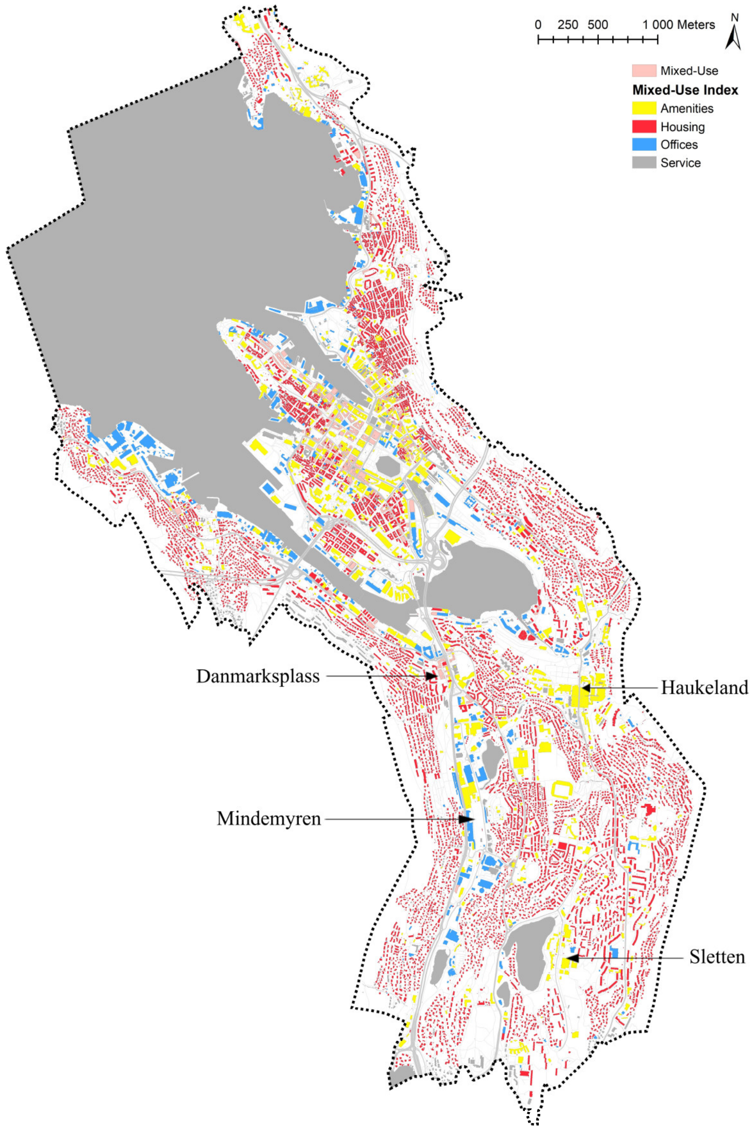


Figure 14. Mixed land use index analysis of the distribution of functions.

As the Space Syntax, Spacematrix, and MXI analyses of the baseline study of Bergen's city centre show, the spatial configuration of the street and road network seems to affect the degree of land use mixture and building densities. These results shape the basis for new densification strategies in a more informed and refined manner than proposed in earlier reports.

6. A New Approach for Making Densification Strategies

If the street network really matters for how cities transform naturally [12], how can the Space Syntax approach be used to formulate densification strategies? Here, we aggregate the angular choice value measures with two different radii with one another using the latest Space Syntax method. Building density takes place on plots located along streets. Therefore, the various Space Syntax variables were added to each adjacent plot for every street segment. For the plots surrounded with several street segments with different integration values, the segment with the highest integration value decided the plot value. The next step was to aggregate the Space Syntax measures with low and high metrical radii.

These correlations became useful for formulating recommendations to the Bergen municipality on where and how to densify. If the street network configuration influences how cities transform naturally, some long-term strategies can be made. Evidently, the street network configuration influences the degree of building density and degree of function mix [11,12]. Figure 15 shows how the following four types of densification strategies were identified based on street network integration on the local level (vertical axis) and citywide level (horizontal axis):

Type A, high local and high citywide integration of the street and road network

Where extra space becomes available, these areas can be transformed with a high density of built mass. The aim is to provide land use plans that allow intensive utilisation of space with a wide range of different public functions, particularly on the ground floor level. Areas suitable for this kind of development in Bergen are the city centre, the harbour areas around the city centre, Danmarksplass, and the industrial area Mindemyren.

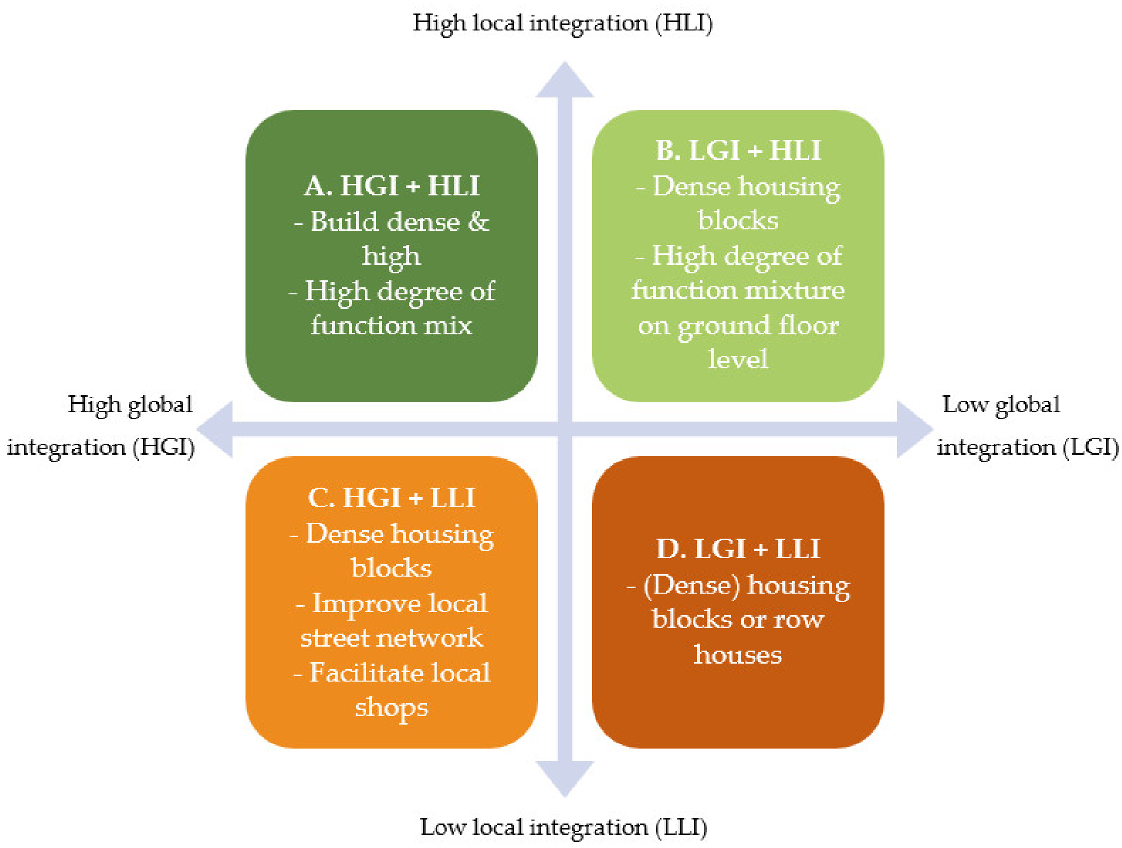


Figure 15. Strategic densification matrix.

Type B, high local, but low citywide integration of the street and road network

Where there is space, these areas can facilitate the high density of dwellings with ground floor spaces for shops, small businesses, and services. Depending on the local circumstances, high-rise buildings can be considered to be an option. As an example, the Sandviken area has many two to three floor high old wooden houses. The type and style of buildings give this area a particular place identity. New buildings will have to adjust to the existing building stock in scale and style to avoid damaging the place identity of the area. Areas suitable for this kind of densification are the various local centres outside Bergen's city centre. Most of these small local centres are situated along the main routes leading through various urban areas. Areas located along the light rail line also belong in this category.

Type C, low local, but high citywide integration of the street and road network

These locations are suitable for high densities of housing. Where possibilities exist to improve the local street network by improving connections or densifying the street network, local shops on the ground floor can be facilitated. An example of such an area is the southern part of the transformation area Mindemyren.

Type D, low local and low citywide integration of the street and road network

Where there is space to develop, increased densities of only dwellings are desirable. These areas with a low degree of accessibility do not likely have many users, and therefore are not very attractive to shop owners. Examples of these kinds of areas are found on the sloped parts on the edges of the study area.

Figure 16 shows the principles on where and how to densify in one map. It shows that the most highly accessible areas on both scale levels (coloured in dark green) are located in the historic city centre and local centres in the suburbs. Where land is available inside these areas, the pressure to build from various project developers is high. Conversely, in areas with low values (coloured in red), the densification pressure is low due to the high costs of constructing roads up in the mountains and steep hills. On the one hand, for the areas with high global integration but low local integration, the challenge is to make a local, inter-accessible street network with the intention to establish pedestrian-friendly neighbourhoods. This responsibility must be taken on the municipal level. On the other hand, areas with high local integration values but low global integration values, require strategies to enhance social infrastructure before densification can take place.

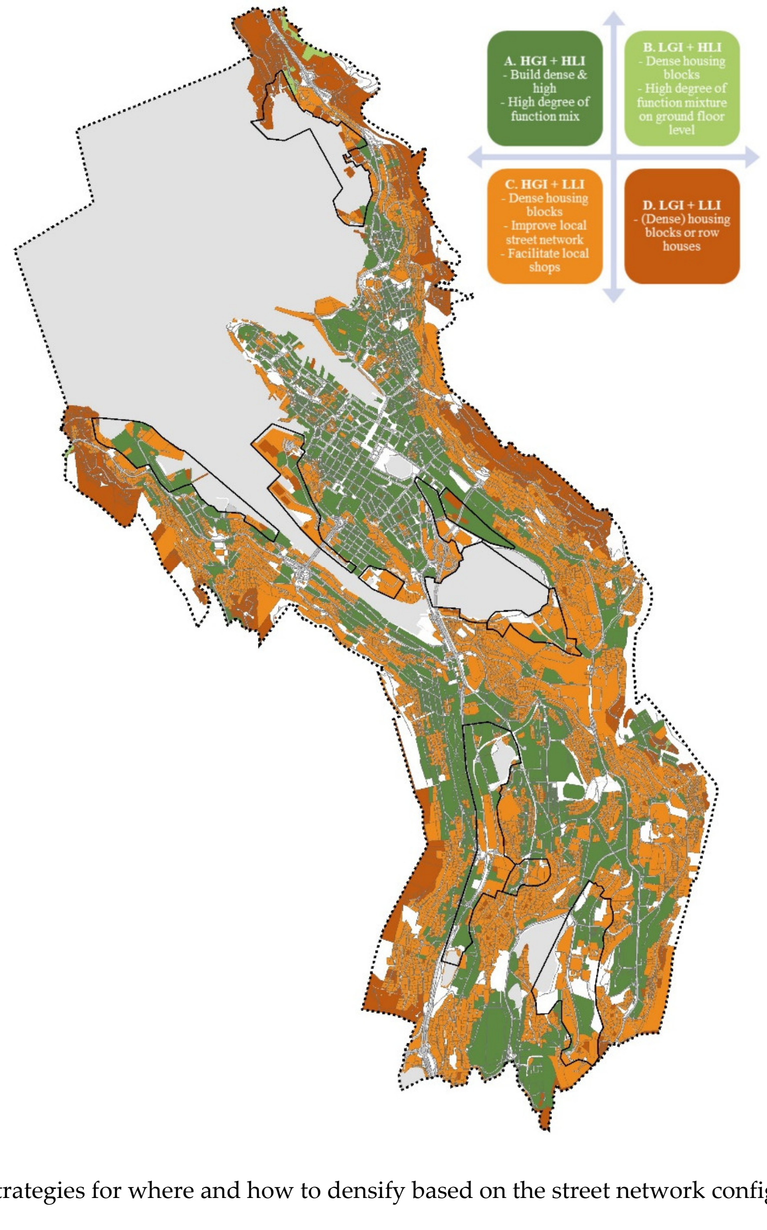


Figure 16. Strategies for where and how to densify based on the street network configuration.

The launched densification strategy offers new opportunities for politicians and citizens within the municipality to discuss expectations, preferences, and priorities, and subsequently build programmes for each of the development areas seen in a long-term and holistic perspective. By using the latest Space Syntax calculations and aggregating the results with one another, we have attempted to contribute to the densification debate with new knowledge in line with the theory of the natural urban transformation process.

7. Conclusions

In comparison with other European cities that have a similar number of inhabitants, Bergen has a small urban core. Therefore, attention should be paid to areas outside, but adjacent to, the compact city centre, specifically, the three semi-compact areas, public transportation hubs, and low-density neighbourhoods in general.

The first recommendation for the local government is to concentrate attention and efforts for densification strategies on the identified twelve major development areas. This is where the greatest potentials for development are and where the long-term benefits will be the highest. This applies to the use of administrative competence and capacity, as well as the effect of planning efforts. Second, a systematic implementation strategy with a timeline is recommended. The areas that are facing critical obstacles concerning implementation do not have this priority. The time horizon for implementation is recommended to be extended from 2030 to 2050.

Setting a hard target of densifying the compact urban valley by building 10,000 new dwellings, and thus increasing the number of residences in the Bergen valley by 25% within ten years, could have a negative impact on the standards of quality that are desired. There are still too many examples of densification projects with poor urban qualities being implemented. Building permissions are given on the ground that they are in line with the overall aim to densify, but an overall plan is lacking. Furthermore, a long-term strategy ought to be rooted in coordinated, long-term public budgets. In Norway, many planning activities are initiated by the private sector, leading to an increasing number of ″bad″ densification projects with anti-urban properties and a lack of proper social infrastructure. If the initial densification projects fail to manifest good urban qualities and create enthusiasm among citizens, decision makers, and politicians, the whole densification strategy can fall and end up propelling an anti-urban sprawl practice. Given that the real estate market is getting more market driven, in combination with strong property rights in Norway, the most significant challenge in current planning practice is to negotiate towards an equitable solution for all stakeholders, property owners, and users.

The map showing great varieties of attractiveness within the twelve development areas (Figure 10b) sends an important message to the involved stakeholders, both investors and planning authorities. By deconstructing the attractiveness map, we can uncover which factors score high or low, and thereby which factors should be refined or strengthened to raise the attractiveness of the various densification areas. While topological aspects such as steep slopes, as well as reduced sun exposure and view are difficult to alter, others, such as accessibility, diversity, and access to amenities, public transport, and green areas can be improved. For areas with lower attractiveness, these factors deserve extra attention, higher economic efforts, and creative, widely supported solutions.

All the aspects mentioned above raise a major challenge. One basic prerequisite for urban transformation in the Norwegian planning context is that developers, mostly private parties, are obliged to cover the expenses of necessary new infrastructure. This is enshrined in a so-called predictability decision, a decision that gives the municipality a mandate to demand financial contributions from the developers through a formalised economic development deal. Here, one is confronted with a dilemma. For the most attractive areas, it is expected that the developer is willing to accept relatively large investments in new infrastructure. Attractive areas will become more attractive. The situation is different for areas with low attractiveness. It is expected that the opportunities for profit are lower and, as a result, the opportunities for greater joint contributions to lift the quality of the public domain could be lower. This can result in a negative spiral where the areas that require the most efforts and resources will receive the least. This finding can contribute to the debate on relations between transformation, the predictability of decisions, and living conditions. Previously, the central government had a policy and rather high budget for improving living conditions. Grants for public investment in socioeconomically vulnerable areas were considerable. Now, however, the central governments have almost abdicated their earlier obligations and left the responsibility for planning and financing almost entirely to the municipalities and private investors. This could lead to a fragmented and incoherent urban densification process with poor urban qualities, a shortage of social infrastructure, and private car dependent street profiles. Seemingly, compact urban forms promote social equity, giving access to jobs for those who cannot afford a car. Creating compact cities with lively urban streets, therefore, requires an overall plan and spatial strategies, something which must be organised on both the national and municipal level. To that end, scientifically grounded spatial tools such as those recommended in this inquiry are needed, both for making strategic plans and for evaluating submitted densification proposals from project developers.

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Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities

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Abstract: Energy usage in cities is intertwined with its spatial configuration—the denser and more compact the city, the more concentrated and efficient the energy usage is to be expected. To achieve sustainable communities, cities (and their inhabitants) must reconsider its spatial configurations in the context of rapid urbanisation and growth in light of limited resources and conflicting spatial claims. This article seeks to understand how spatial configurations affect transport energy usage in cities and propose an integrated assessment approach factoring spatial configurational analysis in relation to transport energy usage at the micro- and macroscale. Comparing Bergen, Norway, and Zürich, Switzerland, findings showed that spatial configurations were positively correlated to transport energy usage. Street structures suitable for walking and less suitable for car traffic tended to exhibit lower amounts of energy usage. Following this, nine typologies of transport and land use patterns are described to support planning for more sustainable means of transport.

Keywords: transport energy usage; sustainable mobility; space syntax; natural movement; natural urban transformation

1. Introduction

Challenges to sustainable development in the form of rapid urbanisation and the emergence of very dense megacities and metropolises have increased pressure on land use and transportation networks and corresponding energy resource limitations [1]. As cities grow, the need to maintain a feasible level of service in the transportation network while ensuring liveability increases with mounting difficulties. Urban planners and city managers have to balance the need for efficient traffic flow and increased network capacity as urban areas increase in size while ensuring that they still function at a human scale to offer accessibility to all.

In addition to the challenges of complexity and competition for space, the global threat of climate change has led to an escalating urgency to reduce our ecological footprint and make responsible choices regarding our decisions and the goods and services we use. The transport sector is responsible for 20% of EU-28 greenhouse gas emissions (excluding international aviation and maritime emissions) [2] and is estimated to account for anywhere from between 20–50% to one-third of its total energy usage depending on the source. It is important to reconsider how we assess and structure our cities to make them less car-oriented and translate this into actionable knowledge for sustainable development.

The recent Sustainable Development Goals (SDGs) are indicative of the challenge above [3]. Although set-up as stand-alone goals, each SDG has an explicit and implicit relationship with each other. Take for example SDG 11—Make cities and human settlements inclusive, safe, resilient, and sustainable—where the focus is on building cities and communities that are equitable but also sustainable, and SDG 7—Ensure access to affordable, reliable, sustainable, and modern energy for all—where the focus is on energy resource resilience and robustness. This is where a fine-tuning of the current assessment methodologies is needed if cities are expected to embrace comprehensive strategies to reduce fluctuations in energy resources or decreased levels of services.

Concerning the relationship between urban form and energy use, there has been a multitude of research confirming the classic Newman and Kenworthy [4] study on how high-density environments have lower energy usage [5–7]. However, there is a need to understand how different spatial configurations affect transport energy usage and how that can be assessed beyond limited focus on either building units or at a regional scale [5]. This knowledge is needed for planning transport infrastructures that can facilitate and encourage sustainable mobility and reduce energy consumption. This assessment requires a combination of expertise and methods typically separated by domains of traffic engineering which calculate traffic flow and energy use for transport, architects, and urban designers, who analyse urban space and form and spatial planners who can translate indicators into feasible policy.

This article combines the above disciplines to ask the following research questions:

1. How can urban form and movement theories contribute to an integrated assessment methodology for sustainable communities and inform urban planning policy and practice?
2. Which spatial configurations affect transport energy usage of private vehicles in cities and what are the categories observed?

Using the cases of Bergen, Norway, and Zurich, Switzerland, this article presents an analysis of urban spatial configuration (street structures) based on the theory of the natural movement economic process [8,9] with space syntax analyses in relation to transport energy usage modelling with MATSim. These variables are spatially correlated in GIS (Geographical Information Systems) to inform how the spatial configuration of the built environment can influence transport energy usage at the local and the regional scale. We propose to assess six variables (see Table 1) at the micro- and macroscales that inform spatial configurations.

Our findings showed that the relationship between spatial configuration and transport energy usage depends on the various degrees of inter-accessibility at various scale levels, from the local (micro) scale to the city-wide (macro) scale. Comparing both cities, positive and significant co-relations were observed between streets with the space syntax variable "angular choice" with a high metrical radius (macro scale. i.e., suitable for car traffic) and transport energy usage. Our analysis identified nine typologies of spatial configurations through aggregating route choice variables and indicates their suitability in reducing transport energy consumption. This article concludes by proposing transport and land use planning strategies based on these nine typologies to reduce transport energy usage and achieve sustainable urban forms.

2. Theoretical Framework

Urban form has a direct impact on building and transport energy usage and these factors are directly affected by urban planning policies [10] (p. 3). This mutual relationship has been widely researched since the late 1980s [5,6,10–12]. The implementation gap lies in the coupling of an understanding of this relationship at both the local (micro) scale and regional scale [11] (see Figure 1). Here, we turn to Rådberg [13] who studied how a fine-grained deformed street network contributes to lower energy usage for transport and described the density paradox wherein two concepts for the ideal sustainable city clash—the compact city versus the green city. The former implies the sharing of infrastructure, space, and facilities, thereby reducing the total footprint per capita, and the latter has connotations of attractiveness and well-being through its "green" spaces for cultivation, water infiltration, and recreation. The normative nature of these sustainable concepts leaves us lacking the descriptive precision needed to assess and implement an ideal sustainable urban form [13] (p. 385).

Jabareen's [12] review of what these forms could be, identified four types: compact city, eco-city, neotraditional development, and urban containment. However, within these types, the issue of sustainable transport still remained one of the largest challenges [6,10].

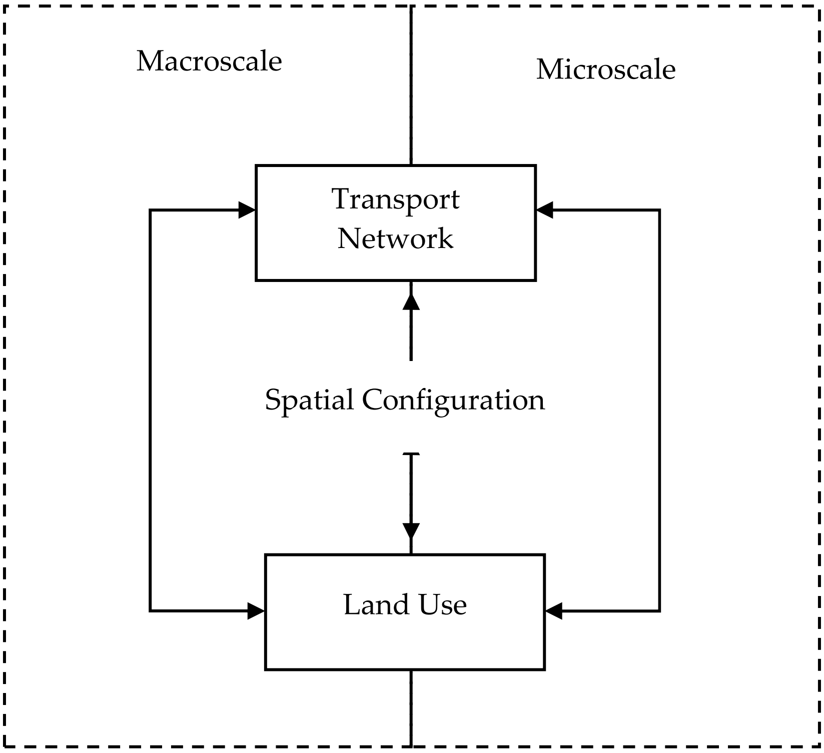

Figure 1. Conceptual framework for understanding spatial configuration.

2.1. *Transport and Land Use Integration at the Macro- and Microscales*

If achieving sustainable cities and communities is the goal, then there is an urgency to adopt integrated policies and plans towards inclusion and resource efficiency (SDG 11.B). There is a need to understand how transport and land use integration can play a role. To do so, access to safe, affordable, accessible, and sustainable transport systems for all must be provided (SDG 11.2). The necessary infrastructure will need to be upgraded to make them sustainable (SDG 9.4) [3]. This holistic approach was also advised as a key ingredient of achieving sustainable mobility [14,15]. A chief culprit to unsustainable transport impact is the use of the private vehicles. Hence, this article will focus on the energy usage related to car usage.

Transport and land use networks mutually influence each other through the amount of accessibility the former allows and the resulting activities that can take place in the latter [16]. They are both determined by and determine the spatial configurations of the environment they are in (Figure 1, centre). Regarding transportation networks (see Figure 1, top), the classic network dilemma plays a role in understanding urban form and its spatial configuration [14,17–19]. An expanded network (i.e., streets or rail) consisting of many nodes and hubs and links and connections that obey a hierarchy developed over time [20]. Such a network might cover more territory and serve a larger user group and be more resilient [17]. However, the more complex and complicated the network becomes, the higher the costs are of utilising and maintaining such a network. For example, as the degree of transfers needed to get from A to B increases, so does time delays and energy usage [6]. The challenge here is therefore to strike for a balance between transport accessibility and sustainability at both the micro- and macroscale (see Figure 1, left and right). As for land use patterns (see Figure 1, bottom), density and diversity (mixed land use) are critical factors for sustainable outcomes [12]. The general understanding is that higher density urban environments will lead to less energy consumption. These factors can, however be relative to the context such as building typology and average household size [5,6]. It is therefore important to consider the socioeconomic effects of urban spatial configuration on land use in the form of activities available and how accessible this is for various demographic groups [16].

Critics say that although parts of this relationship (density and trip length) seem straightforward, other factors remain obscure [11]. Those factors tend to concern choice, particularly that of individual mobility choice or residential location choice [21]. However, these factors will not be modelled directly due to the fact of our focus on spatial configurations of the street and road network. Travel behaviour choice (i.e., route and mode) determined spatially could be derived from the spatial configuration analysis derived from the space syntax approach [8,9], whereby the higher spatial integration of the network, the higher flow of movement. This is where we apply the space syntax method for identifying the spatial parameters in relation to transport energy consumption.

2.2. Understanding Spatial Configurations with Space Syntax

Methods for describing and measuring urban space stem from an analytical understanding of physical components developed in the 1950s amongst urban morphologists [22]. However, methods for analysing spatial configuration—space syntax—defined as the spaces between the physical objects have been consistently developed since the 1970s [8,9]. This method [8,23–27] helps in the development of precise definitions of the spatial elements focusing on *extrinsic* properties of space in terms of pure spatial relationships, and in developing theories on space and spatial relationships, on space and flow of movement, and economic attractiveness. Texture, shapes and form of the built environment is not at issue here. With current technology and software development and computer capacities, application of this analysis on large metropolises has become possible and widely utilised worldwide by an international community resulting in a substantial database confirming the method and its findings [28].

Space syntax consists of four theories: (i) the theory of natural movement [23], (ii) the theory of the natural movement economic process [24,29], (iii) theories of spatial combinatorics [8]; and (iv) the theory of the natural urban transformation process [29–31] that describe and predict effects of spatial configuration. The theory of the natural movement states that the flow of human movement in built environments depends on the degree of *spatial integration* (i.e., normalised distance from one point to all points [9]) of the street network. The higher spatial integration on various scale levels, the higher the flow of human movement [32]. The theory of the natural movement economic process states that the spatial configuration of the street network influences the flow of human movement and thereby the type, number, and location of shops [24,29,32]. The theory of the spatial combinatorics shows how an object placed in space contributes to integrate or to segregate urban spaces [8]. The theory of the natural urban transformation process shows that the spatial configuration of the street network steers building density and the degree of land use diversity in urban areas [29–31].

As research has shown, the spatial configuration of the street network is the underlying driving force for the densification processes of the built mass, the degree of land use diversity, the degree of movement flows through the street and road networks, and the dispersal of economic/commercial activities [27]. These theories allow us to calculate spatial inter-relationships based on three types of distance: *topological* (the number of direction changes), *geometrical* (the number of angular deviation) and *metrical* (the travelled distance), and correlate resulting spatial data with place bounded socioeconomic data (such as movement flow, property prices, distribution of crime, human behaviour in urban space etc.) [26,27,29,30].

The measures within space syntax that best capture spatial configurations are [8,9];

- Potential to-movement: how likely a street is to be a destination of a route. Angular segment integration analyses (i.e., how close each segment is to all others in terms of the sum of angular changes that are made on each route);

- Potential through-movement: how likely a street is used as part of a route. Angular choice analysis (i.e., counting the number of times each street segment falls on the shortest path—least angular deviation—between all pairs of segments within a selected distance or radius).

In any urban environment, considering only spatial configuration and, ceteris paribus, route choice is determined primarily by, to and through movement. The other choice factor at play would be then mode choice, which is affected mainly by transport supply (i.e., if certain networks per modality are available), and resulting travel distances and travel times. Although these choices are subjective, both are factors in how transport energy usage is related to spatial configuration [6,7,10,11]. Therefore, by analysing spatial configurations and correlating it to transport energy consumption, the sustainability of urban forms can be assessed. The following section will deal with what inputs and variables are needed to implement such an assessment.

3. Methodology

To examine how and which spatial configurations affect energy usage (transport) in cities, this article proposed an integrated assessment method based on quantitative data on two levels of scale simultaneously (i.e., micro and macro). Two avenues of data and corresponding methods are needed to combine spatial configuration data analyses with space syntax and energy usage data via MATSim.

3.1. Cases: Bergen and Zürich

Two developed European cities with (i) dense transport networks (streets and transit), (ii) dense urban spatial configurations and (iii) situated in valleys between geological formations were selected due to the fact of their anticipated similar urban settlement patterns (see Figure 2).

The city of Bergen, located in western Norway, has a dense public transport network in its city centre. However, coverage decreases sharply after a couple of kilometres. Thereafter, there is a high dependency on private vehicle usage. This is reflected in its modal split (car—55%, public transport—16%, cycling—3% and walking—26%) [33]. The most used public transport mode is the bus, followed by the newly established light rail system which runs through the valley leading away from the city centre. A second light rail line is expected by 2023.

The city of Zürich, in north-central Switzerland, is well known for its dense public transport network consisting of a wide range of modes that operate in tune with each other: trams, (trolleys) buses, local, regional and (inter)national trains, even a few boat services over the lake and funicular trains leading up the hills. This is reflected in its modal split (car—25%, public transport—41%, cycling—8% and walking—26%) [34].

Level of Scale

A radius (R) of 500 m was taken for the local or microscale, and 5000 m for the macro or city scale for understanding urban spatial configurations. These distances are pertinent to how easy it is to get to a given location and how likely one is to pass through within certain metrical radiuses. These distances are applicable to the north-western European context [35] (p. 269). The above choices take the angular deviation of each topological step into account. The first radius concerns walkable distances or local accessibility (i.e., walking around 5–6 min at an average speed of 5 km/h), whereas the latter one concerns car-based distances or city scale accessibility (i.e., driving around 5–6 min at an average speed of 50 km/h).

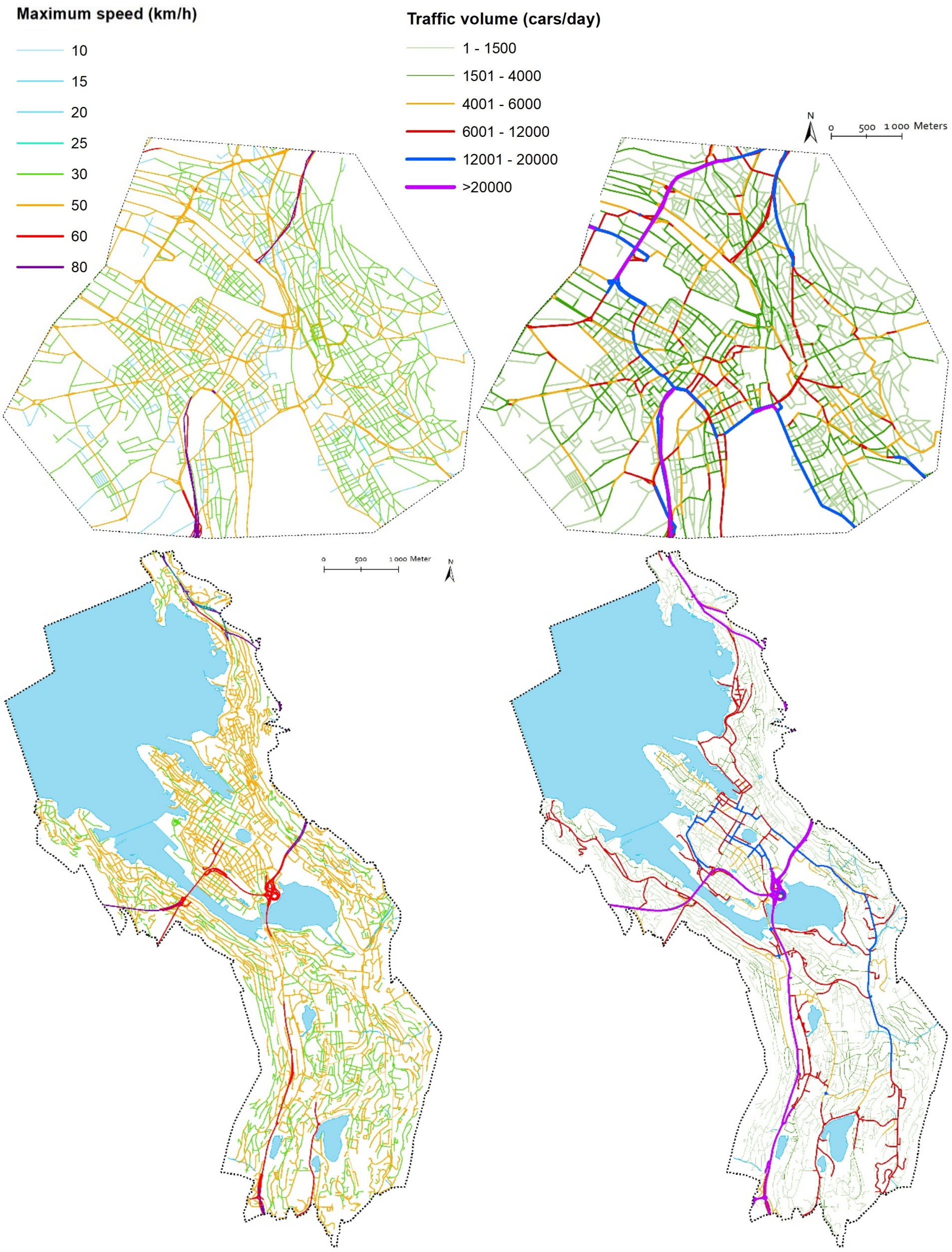

Figure 2. (left) Maximum speed in km/h and (right) traffic volume in cars/day for networks in Zürich (top) and Bergen (bottom). Note that the purple, red and blue colours show the highest values for maximum traffic speed and the amounts of private vehicles, respectively. As can be seen for both Zurich and Bergen, the largest traffic flow of vehicle transport takes place on the roads with the highest speed. These are the motorways connecting the centres with the peripheral areas.

3.2. Variables for Analysis

Understanding that spatial configuration relies on extrinsic properties of space (i.e., structure of street networks) and no meaning is attributed to the built form [36], a combination of macro- and microscale variables was used for analysis (see Table 1). Utilizing the most recent and novel variables of segment integration and angular choice analysis, the topological, geometrical, and metrical properties were considered in calculating spatial configurative relationships of street segments [28]. These variables were selected to best capture potential to movement (integration) and potential through movement (choice) to capture spatial configuration and to reflect transport energy consumption.

Table 1. List of variables used in the model.

Variable	Scale	Description	Metric
Segment Integration (R = 500 m)	Micro	To-movement potential with 500 m metric radius	Numeric
Angular Choice (R = 500 m)	Micro	Through-movement potential with 500 m metric radius	Numeric
Segment Integration (R = 5000 m)	Macro	To-movement potential with 5000 m metric radius	Numeric
Angular Choice (R = 5000 m)	Macro	Through-movement potential with 5000 m metric radius	Numeric
Aggregated Angular Choice	Micro/ Macro	Combination of high and low radius ([C500] × [C5000])	Numeric
Energy consumed without stops	Macro	Total car energy usage per street segment per day (kWh/day)	Numeric

3.3. Data Source and Inputs

To fulfil the list of variables, the following data sources were then prepared and transformed for analysis depending on the respective platform for the necessary list of variables (see Table 2).

Table 2. Data source, input form, and platform.

Data Source	Input form	Platform	Outcomes
OpenStreetMap	Axial Map	DepthMap	Potential to-movement with Angular Choice (Low/High)
OpenStreetMap	Axial Map	DepthMap	Potential through movement with Angular Integration (Low/High)
OpenStreetMap (Zürich case)	Traffic speed and vehicle usage derived from polyline-edges in network	MATSim	Transport energy consumed (Changing Speed, Air Resistance, Rolling Resistance and Heat)
Road data from Norwegian Road Authorities (Bergen case)	Node/Link Network	GIS	

3.4. Variables for Spatial Configuration

The spatial structure of the street network forms the basis of the space Syntax analyses. The data of street networks per case were sourced from OpenStreetMap (OSM) between April–June 2016 for Bergen and July–September 2017 for Zürich. Georeferenced, axial maps were drawn during the same period and confirmed using a combination of Google Street View and OSM road centre line data using ArcMap. The axial maps follow the principle that the fewest and longest set of axial sight lines of visibility and accessibility cover all convex spaces in a spatial system [28] (p. 13). It provides the empirical data for calculating segment integration (to-movement), angular choice (through-movement) at both scales, and aggregated angular choice is derived from buffers on each segment.

3.4.1. Segment Integration (Potential To-Movement)

With the input of the axial map, DepthMap is used to calculate the topological depth from one axis to all others—the total number of direction changes from one axis *to* all others. The integration (I) of an axial line (i) is a function of its depth related to all other axes calculated as [37] (p. 64):

$$I_i = \frac{2\Big(n\Big(log_2\Big(\frac{n+2}{3}\Big) - 1\Big) + 1\Big) / (n-1)(n-2)}{2\big(\big(\frac{\sum_{j=1}^{n} d_{ij}}{n-1}\big) / (n-2)} \quad (1)$$

where n is the number of segments, d_{ij} is the shortest distance (fewest number of direction changes) between two segments i and j. The greater the number of steps (d_{ij}) between streets axes, the lower the integration values gets.

Segment integration of a street shows how easy it is to get to a segment from all other segments. In the segment analyses, the axial lines are broken up where they cross each other [28]. It calculates the to-movement potentials. Segment integration can be compared across systems. It measures how close each segment is to all others in terms of the sum of angular changes that are made on each route [37] (pp. 475–490). Angular segment choice is calculated by counting the number of times each street segment falls on the shortest path between all pairs of segments within a selected distance (termed "radius"). The "shortest path" refers to the path of least angular deviation (namely, the straightest route) through the system [37] (p. 475).

The angular integration (AI) of a segment x is:

$$AI_x = \frac{1}{n}\sum_{i=1}^{n} d_\theta(x,i) \tag{2}$$

where n is the number of segments and dθ the angle between any two segments on the shortest path on a segment x and when adding the length "l" of segments [37] (p. 66):

$$AI_x^l = \frac{\sum_{i=1}^{n} d_\theta(x,i)l(i)}{\sum_{i=1}^{n} l\,(i)} \tag{3}$$

3.4.2. Angular Choice (Potential Through-Movement)

Angular choice, or how likely one is to pass *through* that axis when moving around in a built environment, measures the degree of betweenness and measures the through-movement potentials. The formula of angular choice (C) of an axis (i) is as follows [37] (p. 64):

$$C_i = \sum_j \sum_k g_{jk}^{(i)} / g_{jk}^{(j<k)} \tag{4}$$

where *gjk* (*i*) is the number of shortest paths between segment *j* and *k* containing *i*, and *gjk* is the number of all shortest paths between *j* and *k*.

3.4.3. Aggregated Angular Choice

Values generated by angular choice analyses are aggregated per case with a 35 m buffer around each segment, creating aggregated areas for each integration level. This value is based on various research concluding that a dense street network with a fine mesh size of between 60–80 m performs better than larger blocks, both when it comes to increased circulation and the exploitation possibilities of the urban block [28]. Showing angular choice for high and low radius simultaneously helps to find out which areas are well integrated into the local street network and enjoy good accessibility on the city scale. The natural break—or Jenks—method is applied to classify the resulting spatial values from angular choice as low (L), medium (M) or high (H). This allows for a combination of nine aggregated choice categories that represent typologies of routes (see Table 3).

3.5. Variables for Transport Energy Usage

Focusing on energy usage for private vehicles, data were generated via MATSim—an agent-based program for making large-scale transportation simulations. Agents, representing residents, are assigned a home address and a job or study location. Daily activity schedules can be appointed or generated, after which the agents will choose a travel itinerary based on the transportation options available. The agents' route-choice and mode-choice between their origins and destinations are then made based on travel time and costs through an iterative optimisation process. The simulation accuracy depends on the amount of detail of the parameters programmed into the model [38].

Table 3. Aggregated choice categories matrix. High values have a dark shade, and colour red if angular choice values at city-wide scale (global) are higher than local scale choice values and green if local scale choice values are higher than city scale choice values.

		Angular Choice with Low Radius (R = 500 m)		
		Low	Medium	High
Angular Choice with High Radius (R = 5000 m)	Low	LL	LM	LH
	Medium	ML	MM	MH
	High	HL	HM	H

3.5.1. Simulating Energy Usage

In this paper, the choice to focus on energy data from private car use was due to the following reasons, (i) only accurate car traffic data could be obtained for both cities, (ii) public transport lines are subject to non-rational planning choices and do not always follow the most integrated, fastest or shortest routes, whereas private car drivers do, (iii) the current data availability for both cities made it is difficult to determine the itinerary of passengers, and therefore it was impossible to estimate how many trips a bus line represents. On the contrary, for cars, one trip was (assumed) equal to one. Since pedestrians and cyclists move around using energy they "produce themselves", the energy usage by cars is the one mode that is most practical for comparing energy usage with to-movement and through-movement potentials of spatial configurations. Agent-based simulations can assist in demonstrating a change in the agents' choice of mode of transportation, for example, if a change occurs in the public transport network or a change in the road network. In this article, the focus remained with private vehicles usage.

Energy consumption was calculated per street segment and relevant parameters giving information about the amounts of vehicles that used a specific street segment and how much energy each vehicle potentially consumed. For the Zürich analysis, data were generated through an agent-based simulation program (MATsim). This input data were maximum traffic speed (see Figure 2, left) and amount of (private) vehicles observed (see Figure 2, right). For the Bergen analysis, the actual data were sourced from the national road authorities.

The following calculations were used to estimate the amount of energy usage per vehicle (E_{car}) from one point to another: kinetic energy in changing speed (and direction), air (swirl) resistance (E_{air}), rolling resistance (E_{roll}) and heat loss (E_{heat}). Without the amount of energy that the industry needs to produce the car and the fuel itself, the total amount of energy that a driving car's engine produces was converted to other forms of energy under the influence of the following [38]:

3.5.2. Changing Speed (and Direction)

After a vehicle with mass m speeds up to a velocity v, the built-up kinetic energy is converted by the brakes into heat at stopping points such as traffic lights and pedestrian crossings. Kinetic energy is calculated by the formula:

$$E_k = \frac{1}{2}mv^2 \tag{5}$$

The problem with the parameter for distance is that the way the segments are split up in the model, this formula would assume that each car comes to a full stop at the end of each street segment. The model, thus far, lacks the data on stopping points. However, it is also not possible to calculate the aggregated losses from, amongst others, subtler braking, taking turns, and sloped terrain accurately. To eliminate this inaccuracy, the kinetic energy for braking is left out of the equation. The final estimation of energy usage will therefore be modest, at best, compared to the actual numbers.

3.5.3. Air Resistance

The swirl of air around the car causes a drag, the coefficient of which, c, is depending on the cross-sectional area, size and shape of the vehicle. Following MacKay [39], we here assumed an average car drag value of 0.33. The effective area A_{air} of the air swirl (resistance) was calculated by multiplying the cross-sectional area A_{car} of the vehicle by this drag-coefficient:

$$A_{air} = c \,.\, A_{car} \tag{6}$$

For air resistance, the kinetic energy of the swirl of the air was calculated. The mass is found by multiplying the density by volume. The volume of the tube of air was obtained by multiplying the effective area A by the length of the tube, obtained by vt. The mass of the tube of air is then:

$$\text{Mass} = \text{density} \cdot \text{volume} = \rho A v t \tag{7}$$

where ρ is the density of air, which is 1.3 kg/m^3 at sea level. The kinetic energy of the air swirl is then:

$$E_{air} = \frac{1}{2} m_{air} v^2 = \frac{1}{2} \rho A v t v^2 \tag{8}$$

which per time unit comes down to:

$$\frac{\rho A v t v^2}{t} = \rho A v^3 \tag{9}$$

3.5.4. Rolling Resistance

This is a constant coefficient that depends on the vehicle's mass and is typically 0.01 for cars. A 1000 kg car with a 0.01 rolling resistance coefficient then requires 0.01 · 1000 = 100 N. With: power = force · velocity, rolling resistance is directly related to the speed in m/s by a factor 100:

$$E_{roll} = 100\ v \tag{10}$$

3.5.5. Heat

The poor energy-converting capabilities of conventional fossil-fuel engine cars makes that approximately three-quarters of energy which is lost to heat. Whilst modern cars are fortunately becoming increasingly efficient, a factor of 4 is usually assigned to car engine heat loss. So, when we count with 75 % heat loss, an average mass of a car of 1000 kg and an average cross-sectional area of 2.4 m^2, the formula for the total amount of energy (E_{car}) consumed by one driving car is:

$$\begin{aligned} E_{car} &= (E_{air} + E_{roll}) \cdot E_{heat} \\ &= (\tfrac{1}{2}\rho A v^3 + 100\ v) \cdot 4 \\ &= 4 \cdot (\tfrac{1}{2} \cdot 1.3 \cdot 0.8 \cdot v^3 + 100\ v) \\ &= 4 \cdot (0.52\ v^3 + 100\ v) \\ &= 2.08\ v^3 + 400\ v \end{aligned} \tag{11}$$

Now, we can generate results per street segment. The total amount of energy E_{tot} used by a given number of vehicles that drives through a certain street per day at a certain speed (v) is:

$$E_{tot} = (\text{number of cars per day}) \cdot (2.08 \cdot (\text{traffic speed})^3 + 400 \cdot (\text{traffic speed})) \tag{12}$$

The above energy usage results are then linked with the georeferenced street segments with traffic speed as inputs as represented in Figure 2.

3.6. Integrated Assessment Approach

The integrated assessment approach consists of three cascading steps:

1. Generating aggregated angular choice buffers resulting in route typologies (see Table 3, Figure 7, left and Figure 8, left);
2. Spatial configuration and energy-use overlay (see Figures 3–6) for to- and through-movement;
3. Testing for co-relation between spatial configuration variables (see Table 1).

Step 1 was done by grouping the values of angular choice for each scale level into three categories: low (L), medium (M) and high (H) using the natural break method, creating aggregated areas for each category by generating a 35 m buffer around the segments.

Step 2 aggregated the categorised angular choice values (AC) on the high (R = 5000) and low (R = 500) radius by permutation as shown in Table 3 corresponding to the buffers created in Step 1. The high local values are emphasised in red and local values in green.

Step 3 was achieved by spatially overlaying the layer containing the energy values and subsequently running a bivariate analysis of the dependent variable for energy (energy consumed, E_{tot}) and the independent spatial configuration variables of the aggregated segment values of angular choice (AC) on both the micro- and macroscales.

Steps 1–3 allows for analysis of the spatial configuration's relationship to energy usage and allows us to identify types of routes that might be present. This allows for statistical and visual–spatial understanding of that relationship on both micro- and macro-scale levels. Step 3 in particular provides typologies which can further inform planning policy and practice. These outcomes are demonstrated in the findings for both cases.

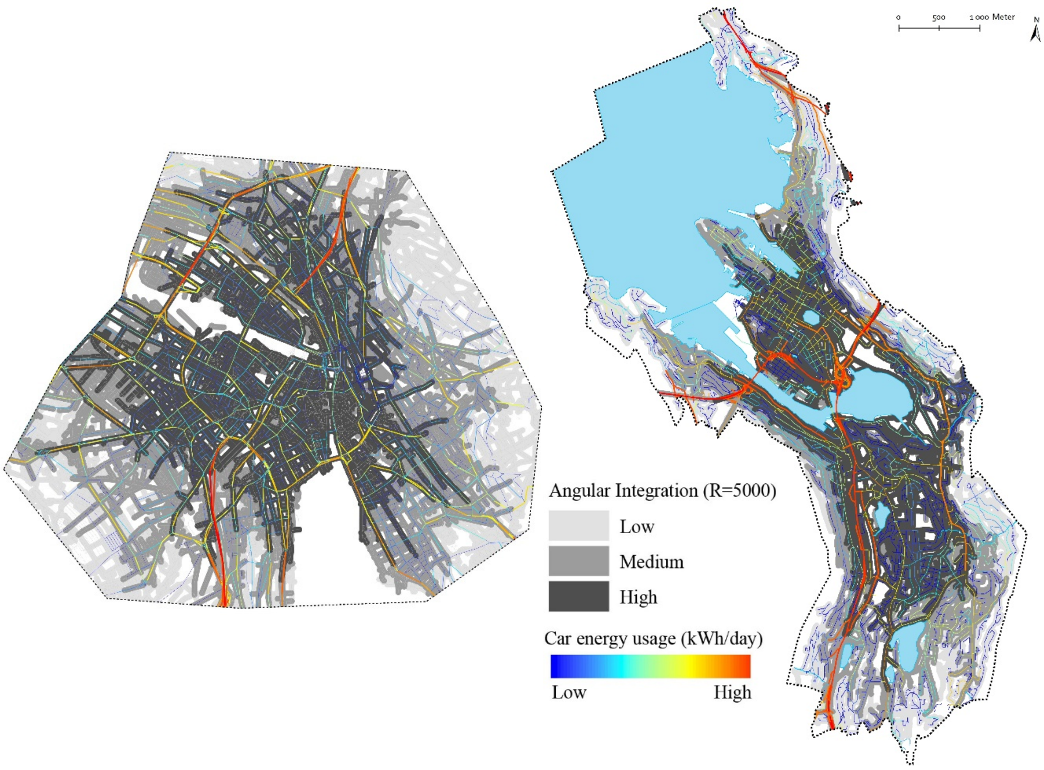

Figure 3. Energy usage from cars overlapped on segment integration analyses with a high metrical radius (R = 5000 m).

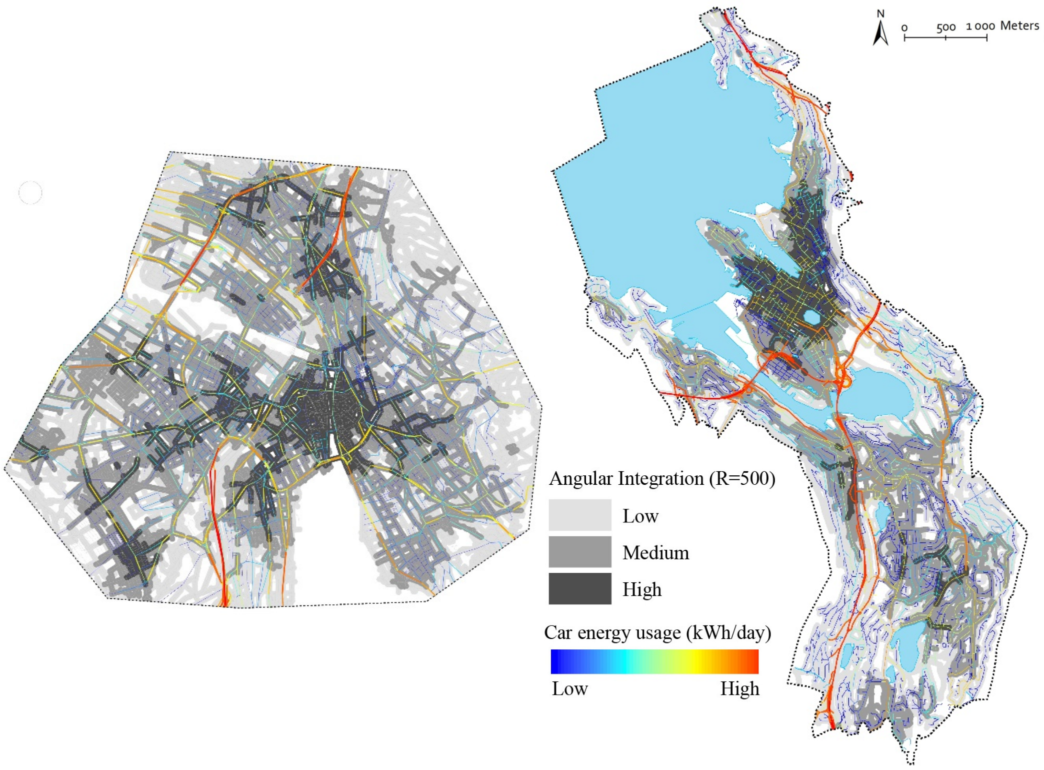

Figure 4. Energy usage from cars overlapped on segment integration analyses with a low metrical radius.

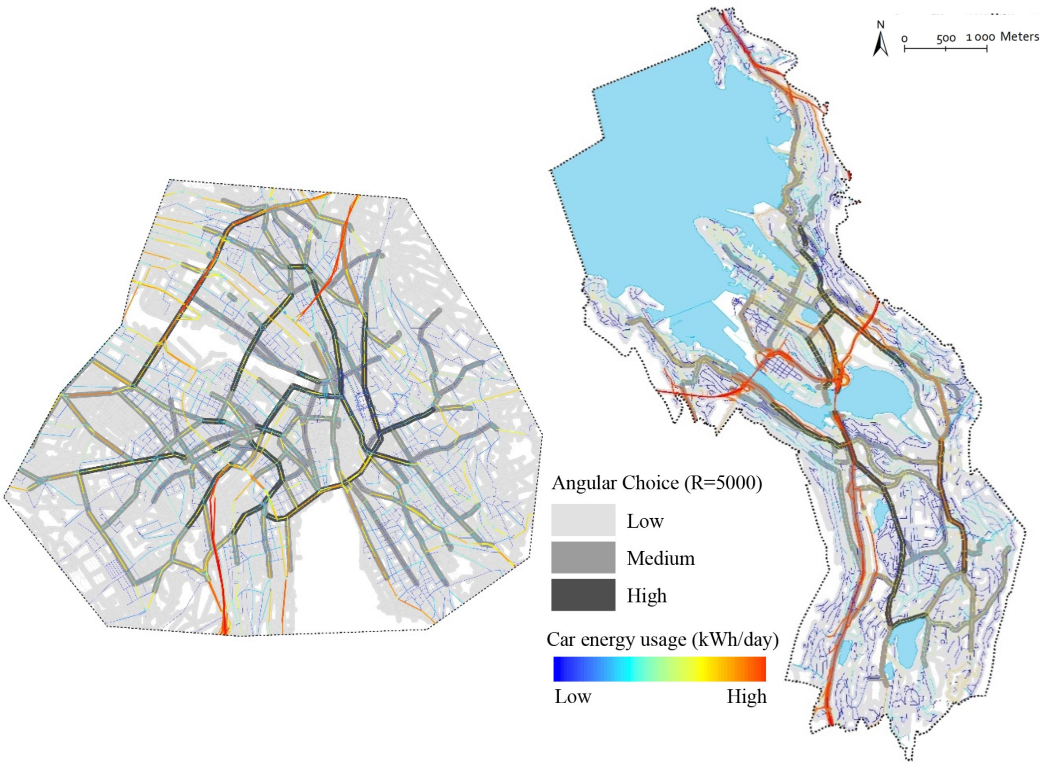

Figure 5. Energy usage from cars overlapped on angular choice analyses with a high metrical radius at city scale.

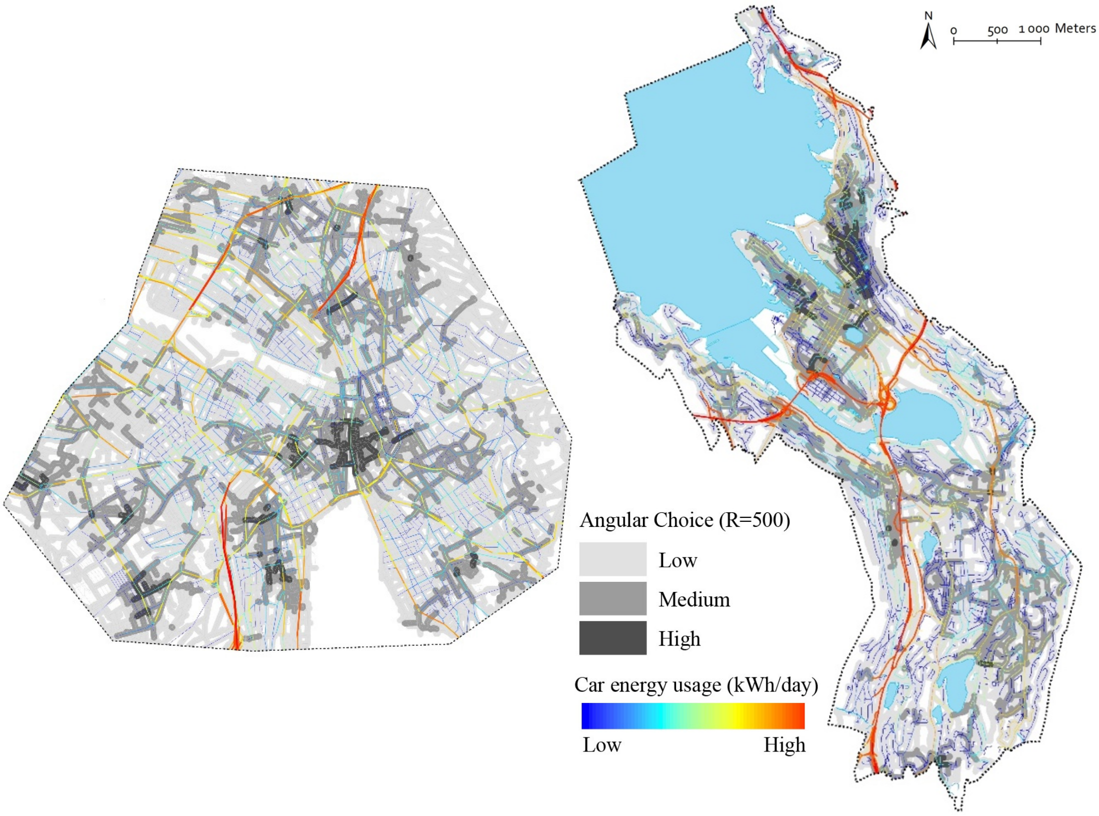

Figure 6. Energy usage from cars overlapped on angular choice analyses with a low metrical radius at local scale.

4. Findings

Statistical correlation between spatial configurations and transport energy usage indicate a positive relationship between all variables for Zürich and Bergen with the exception of segment integration at local scale for Bergen (see Table 4). When comparing the aggregate angular choice of both cities, segments with high values for local integration (i.e., walkable areas) tend to use less energy than areas with high values at a city-wide scale (i.e., car-oriented). The following sections will discuss these key findings in detail before discussing the typologies of routes from these findings.

Table 4. Relating spatial configuration variables (segment integration and angular choice) at micro- and macroscale to transport energy usage.

	Bergen				**Zurich** [#]			
	Sample		N = 2174		Sample		N = 7027	
Analysis	Segment Integration		Angular Choice		Segment Integration		Angular Choice	
Radius (m)	500	5000	500	5000	500	5000	500	5000
Pearson correlation	**−0.061** **	0.129 **	0.053 *	0.149 **	0.079 **	0.113 **	0.024 *	0.073 **
Significance	0.005	0.000	0.013	0.000	0.000	0.000	0.047	0.000

* Correlation is significant at the 0.05 level (two-tailed). ** Correlation is significant at the 0.01 level (two-tailed).
[#] Outliers due to the motorway removed (10% of energy consumption). −0.061 is an outlier value

4.1. Correlating Spatial Configurations to Transport Energy Usage

Spatial configuration analysis generated a database for potential to- (segment integration) and through-movement (angular choice) per segment for both cases. Segment size differ between Bergen (N = 2174) and Zurich (N = 7027) as evidenced by the different city forms (see Figure 3). Table 4 shows the correlation between energy usage for transport and segment integration and angular choice with both low (R = 500, micro scale) and high (R = 500, macro scale) metrical radius for Bergen and Zürich.

All correlations are significant for both cases. Positive correlations were found between spatial configuration variables and energy usage for transport except for integration at low metrical radius (local scale) for Bergen.

- In terms of to-movement (i.e., how likely a street is a destination, measured through Angular Integration), Bergen shows a negative correlation at the local or micro scale but a positive correlation at the city-wide or macroscale. This means that in Bergen, the less a street is a walkable destination (lower integration value), the higher the transport energy use. Whereas in streets that are accessible destinations for vehicular traffic (integration at macro scale), a higher transport energy use is expected;
- In terms of to-movement for Zürich, for both the micro- and macro-scale, a positive correlation for segment integration was observed. This means that in Zürich, the more walkable destinations (the higher the choice value), the higher transport energy use was observed, contrary to literature [10,11,40]. A possible explanation for this may be the difference between car usage in Bergen (55%) and Zürich (25%) [33,34]. Having relatively low care ownership in Zürich compared to Bergen may exacerbate the share of local traffic in the agent-based simulation when correlating with the segment values. In addition, Zürich's pedestrian zones (streets such as Augustinergasse) are not completely blocked off and still accommodate private vehicles or goods delivery vehicles;
- In terms of through-movement (i.e., how likely a street is a part of route, measured through Angular Choice), Bergen and Zürich both showed a positive, albeit weak, significant correlation on both scale levels. Therein, the more a street was likely to be part of a route choice (the higher the angular choice value), the higher the energy use for transport was expected. This was more so for the city scale than the local scale. Both cities have limited, continuous pedestrianized zones (within a one-kilometre radius) where cars are limited. This might affect the segments with high angular choice values that could be dominant, prioritised, and potentially historical routes in the city as they naturally become extensions into major roads [20,41]. Next, the adjacent areas to these pedestrian zones tend to have walking pavements parallel to roads allowing vehicular traffic. Even though these routes are likely to be chosen, they facilitate both pedestrian and vehicular traffic simultaneously.

4.1.1. Segment Integration (To-Movement or Destination)

If transport energy use, the degree of land use diversity and building density depend on the spatial configurations of the street and road networks, then it follows that areas where the largest function mixture and the largest building density is present, less transport energy is consumed. In Zürich centre, both walkability (26%) and public transport (41%) usage were high [34]. In Figure 3 we see that as soon as the integration values drop (dark grey to light grey) towards the edge of the inner city, the energy usage for transport increases (orange and red). This is even more observable in areas that enjoy a high integration values at the city scale, but low integration values at the local scale as seen in comparing Figures 3 and 4.

4.1.2. Angular Choice (Through-Movement or Route Choice)

Streets segments that have a high angular choice value at the local scale and a high transport energy consumption, also have high or medium angular choice values at the city scale. It is clearly visible in how the "aortae" of high energy usage "feed" and connect the areas of high local through-movement (see Figures 5 and 6). This corresponds to path dependencies of cities in which historically important routes retain a high level of use and recognisability for the population and eventually evolve into major traffic thoroughfares that facilitate private vehicle usage [41].

4.1.3. Aggregated Angular Choice

Figure 7 (left) is a representation of aggregated and buffered choice values on both the local and the city-wide scale for Bergen. High values have a dark shade, and colour red if angular choice values at city-wide scale (global) are higher than local scale choice values and green if local scale choice values are higher than city scale choice values. Correlating the maps in Figure 7 (left) and (right), areas with high or medium local scale values present lower energy usage. High values at the city scale present higher energy usage. Areas with high global and low local angular choice values (HL) (bright red) scores marginally higher in energy usage than medium global and medium local (MM) (dark grey) integration. It seems that high angular choice values for local scale have a bigger impact on energy reduction than global values in Bergen.

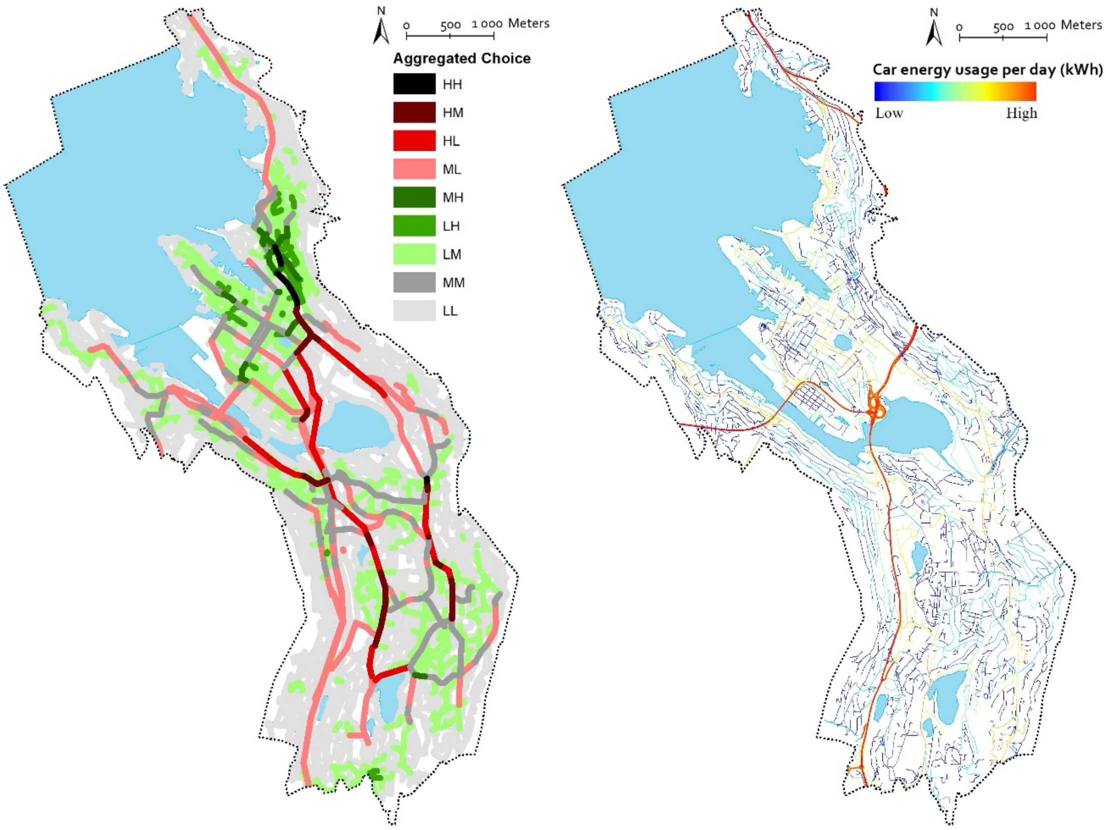

Figure 7. Aggregated angular choice (**left**) and energy usage for cars (**right**) in Bergen.

Figure 8 (left) is a representation of aggregated and buffered choice values on both the local and the city wide (global) scale for Zürich. Correlating with energy use represented in Figure 8 (right) and the spatial configuration (Figure 8, left), it shows a similar pattern in Zürich as for Bergen. It can be observed that areas with high or medium local values score lowest in energy usage. In Zürich, segments with low values at global scale and medium values at local scale (LM) show a higher energy usage than those with medium values at global scale and low values at local scale (ML). Likewise, segments with high values at global scale and medium values at local scale (HM) has higher energy usage values than those with high values at global scale and low value at local scale (HL).

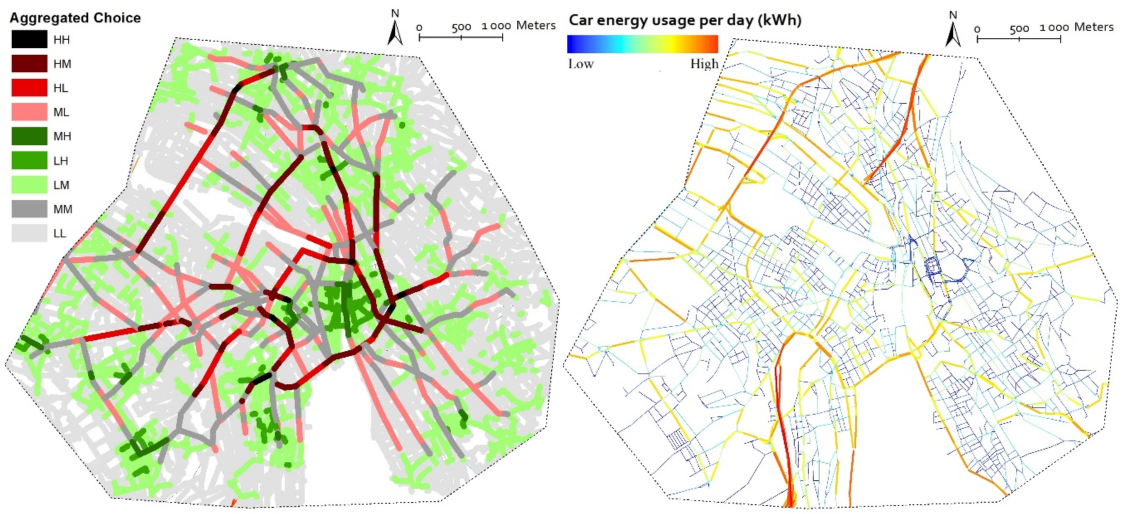

Figure 8. Aggregated angular choice (**left**) and energy usage for cars (**right**) in Zürich.

The similarities between both cities are however evident: all areas with high local integration, (LH), (MH) and (HH) present as lowest in energy usage. Areas with low local integration values tended to present as high in energy usage.

4.2. Identifying and Understanding Route Typologies

Knowing the local and city-wide scale integration and choice values of the cities in relation to their energy usage provides the opportunity to relate this to typical transport and land use typologies. Interpreting the results from correlating spatial configurations and energy usage, the resulting typologies can be identified:

- High global, high local choice values (HH): Major road—Connects city districts, often supporting high volumes of traffic. When possible also used intensely by local pedestrians and cyclists;
- High global, medium local choice values (HM): Central road connecting city districts and the wider region; supports high volumes of regional traffic, and moderate local traffic;
- High global, low local choice values (HL): Regional road, often a motorway or boulevard; supports high speed, large volumes of traffic; little to no local traffic;
- Medium global, high local choice values (MH): District road, connecting neighbourhoods; moderate to high traffic volume, intensely used by pedestrians and cyclists;
- Medium global, medium local choice values (MM): District or local street that supports moderate traffic, often a mix of motorised traffic, pedestrians and cyclists;
- Medium global, low local choice values (ML): District or local road, predominantly for local motorised traffic travelling within and in between neighbourhoods;
- Low global, High local values (LH): Central street within or in between neighbourhoods; high intensity of local traffic, often non-motorised;
- Low global, medium local values (LM): Neighbourhood street with mixed functions, moderate traffic intensity, mostly for local residents;
- Low global, low local values (LL): Local road or street serving only the immediate surrounding properties.

This interpretation allows for an understanding of what these typologies in relation to spatial configurational values may represent in reality. However, since the analysis of spatial configuration merely describes the extrinsic properties of space these typologies still need to be controlled in the field. For example, in Bergen some of the most highly integrated segments (HH) (e.g., Stølegaten, Øvregaten), are in fact narrow which do not support large volumes of vehicular traffic. Conversely, some of the most spatially segregated segments (LL) experience heavy traffic (e.g., Sjøgaten, Møllendalsveien) and could be better typified as district roads (MM/ML). This discrepancy is useful for planning policies and strategies as it indicates the potential that a segment might not match or complement its current usage pattern. This would be helpful for planners to identify routes that might need upgrading (increase in capacity) or change in function (car-oriented to pedestrian-oriented).

5. Conclusions

To understand how spatial configurations can affect transport energy usage in cities, this article correlated six spatial and energy-usage variables (see Table 1) across the city of Bergen and Zürich. The values of integration (to-movement) and route choice (through-movement) at both the local and city-wide scales were determined using space syntax analyses of axial maps of both cities based on OpenStreetMap. This was then correlated statistically and spatially to transport energy-usage derived from data from the local municipality in Bergen and an agent-based model for Zürich based on traffic speed and volume.

5.1. Spatial Configurations Affecting Transport Energy Usage

Our findings indicate that the spatial structure of urban space affects transport energy usage. In general, there were weak but positive correlations to transport usage between segment integration and angular choice values at both local (low metrical radius, R = 500 m) and city-wide (high metrical radius, R = 5000 m) scales for both cities (see Table 1). The correlation was stronger for both integration and choice at the city-wide scale, indicating that these routes which favoured vehicles tended to exhibit high transport energy usage. The exception here is that of segment integration at the local scale. Bergen showed this with a weak, negative relationship to transport energy usage. This indicates that the more "walkable" areas of Bergen showed less transport energy usage. Across both cities, correlation at the local scale was lower than correlation at the city-wide scale. This indicates that even though "walkable" or pedestrian-oriented areas (local scale) still exhibited a positive relationship to transport energy use, the coefficients were less than those of areas (city-wide scale) facilitating vehicles which are more car-oriented.

5.1.1. High Transport Energy Usage for Car-Oriented Spatial Configurations

The private car in particular is a major contributor to transport energy usage. As shown in the energy usage equation, longer and high-speed car trips consumed exponentially more energy. This is visible in Figure 3, where the high-energy usage areas were at the periphery of the medium-to-low values of segment integration at a city-wide scale. This is even more visible on a local scale (see Figure 4). These areas with less potential as destinations (to-movement), typically suburbs, urban peripheries or industrial zones, tended to see higher transport energy usage due to the higher car use or speeds permitted as opposed to denser city centres which might be pedestrianised or had lower speed limits. Examples include Mindemyren in Bergen and Industriequartier in Zürich. In Figure 5, the street segments with high angular choice values exhibit high transport energy usage. These arterial routes have the highest potential as chosen routes and attract high amounts of traffic and corresponding energy usage. Here, path dependencies might be at play as historically important routes tend to be routes that develop for vehicular traffic in modern times.

5.1.2. Low Transport Energy Usage for Pedestrian-Oriented Spatial Configurations

On a local scale (see Figure 6, the inverse is true. These segments with high angular choice at local scale tend to indicate a high degree of "walkability" in streets and attract less vehicular traffic and transport energy usage. Segments with high angular choice values at both scales but not high transport energy usage indicating an efficient public transport system for tram, buses or light rail commonly found in Bergen and in Zürich. Areas such as the peripheries of Byparken in Bergen and Altstadt in Zürich are where local scale high to-movement networks (segment integration) are enmeshed with the global scale high through-movement (angular choice) networks (see Figures 4 and 5). These areas reflect lower transport energy usage as private car usage is available but discouraged. Here, walking and cycling seem to become a natural choice for shorter, local destination trips. When these segments have the presence of a well-integrated and diverse public transport systems, these local destination trips have the potential to extend towards car-free regional trips, too, reducing energy usage further.

5.2. Integrated Assessment for Transport and Land Use Planning

This article proposed an integrated assessment approach consisting of three steps: (i) generation of aggregated angular choice buffers resulting in route typologies, (ii) spatial comparison of spatial configurations and energy usage via overlay and (iii) statistical correlation of spatial configurations and transport energy usage. Our findings indicated a clear correlation between spatial configurations and transport energy usage as depicted through nine common typologies. These typologies as discussed below exemplify how urban form and movement theories contribute to transport and land use planning policy and practice.

5.2.1. Typologies for Transport and Land Use

Combining angular choice for high and low radius identified which areas are well integrated into the local street network and enjoy good accessibility on the city scale. Nine typologies were identified based on the aggregate choice matrix (see Table 3). In Bergen, routes such as Fjøsangerveien with medium-to-high transport energy usage corresponds to routes with medium-to-high values for angular choice at a city-wide scale with medium-to-low angular choice values at local scale (types HM, ML, and HL). This is similar for Zürich (e.g., Utoquai) as well. The variable of angular choice shows through-movement potential or route-choice likeliness at the city-wide scale (R = 5000 m). Regardless of to-movement potential or destination likeliness, these tended to emphasize common routes or arterial roads where large volume of traffic (usually private vehicles) travel through. These major, central, and regional roads are main flows for both person and goods transportation and the high energy usage due to the volume and speeds reflect this.

The inverse was also true. Areas in both cities with many streets with medium-to-low angular choice values at city-wide scale and medium to high values at local scale (R = 500 m) enjoyed a lower energy usage pattern. These areas typically contain narrow streets and economic attractive areas for pedestrian, residential, and retail activities. The Sandviken area in Bergen and the Altstadt in Zürich are examples of these district roads, central and neighbourhood streets (types MH, LH, LM).

5.2.2. Contributions to Policy and Practice

This approach allows for a clarification of the relation between spatial configurations and transport energy usage. The use of space syntax allows for a value free evaluation of a city and to correlate it to simulated and real-time transport energy usage. By combining the results from the latest space syntax analyses techniques with energy use for transport, and reveal the results with the theory of the natural movement [28,32] and the natural urban transformation process, the findings highlight what kinds of spatial configurations of the street network that are the necessary conditions to support and facilitate sustainable transport and land use patterns in existing cities. This assessment approach allows policymakers and practitioners to (i) identify potential locations in their cities to support such modes and what to avoid, and (ii) to provide insights into what type of spatial configurations would facilitate vibrant and lively urban areas.

Spatial configurations that facilitate and accommodate vehicular traffic tend towards higher transport energy usage while those that facilitate pedestrian activities or cycling or public transport tend towards lower transport energy usage. The former areas with low local scale angular choice values perpetuate private vehicle dependency and monofunctional areas of low density that become part of the urban sprawl. This creates complex and unsustainable transport patterns for travel for work, shopping, leisure activities and home. In addition, this might exacerbate transport inequalities for those who have access to private vehicles and those who do not [21,41]. The latter are areas with short urban blocks and tend to enjoy both high segment integration and angular choice values.

In line with Jane Jacobs [42], short urban blocks enhance walking or cycling as a transportation mode. Walking and cycling are modes with the lowest energy usage. Both modes are highly sought after in most cities in their pursuit of sustainable development. Both cases show that short urban blocks (or a fine-grained urban structure at local scale) with main routes running through them are necessary conditions for public transport and walkability. Areas with these conditions are highly sought after for enhancing sustainable transport outcomes. These areas also tend to evolve naturally into vibrant, highly urban areas with high building density and high degree of land use diversity supporting retail, commerce and social interaction [31,43]. Planners and policy makers therefore need to veer away from establishing new routes for heavy vehicular traffic only within the city core and enhance walkability (and slower modes) in current and potential socioeconomic centres. Concretely, this can be achieved by retrofitting current urban fabrics with the introduction of short urban blocks and fine meshed street networks [11,20,43].

6. Discussion and Reflection

The above approach and findings contribute to novel insights to current academic discussions on transport and land use patterns in relation to energy consumption. The findings verify a positive correlation of car-oriented spatial configurations having higher energy usage. This is a critical element of addressing sustainability concerns, particularly in view of the energy transitions anticipated in the coming decades. In addition, the verification of what necessary conditions are required to support walkable, liveable and vital urban areas for those with and without access to private vehicles contributes to larger societal goals of creating and maintaining sustainable communities and cities. space syntax, which stems from precise concepts of urban space, applicable independent of cultural, economic, social or aesthetic contexts, allows for a value-free evaluation of the city. Moreover, it is possible to calculate spatial relationships independent from socioeconomic data with the space Syntax method. The MATSim model aggregates traffic data on the mobility network based on the place-bounded data regarding the location of urban functions. Therefore, overlapping and correlating these two models contributes to knowledge on the relation between urban spatial configuration and energy use for transport.

Planners and policy makers can use the findings to understand how spatial configurations affect transport energy usage. In addition, the approach using predominantly open sourced map data can be applied in various cities and regions across the world. Knowing the necessary conditions for walkable and liveable areas enables practitioners to plan and design for more integrated streets, differentiate which streets are desirable and which are less, and contribute additional savings in energy usage when the desired change is implemented. What the findings from Bergen and Zürich show, is that urban areas with short urban blocks or a fine-meshed street network with a well-connected main route running through these areas enhance low energy use for transport. The disclosure of high or low energy usage streets and areas based on a value-free evaluation of the city can also promote institutional innovation towards more sustainable mobility [44].

6.1. Limitations

The proposed approach experiences limitations in (i) the availability of transport energy data in different contexts for different modes, (ii) the simulation accuracy of energy data, (iii) complex operations in the joining of analysis across multiple platforms and (iv) replicability of results due to the previous limitations.

Data on energy registrations for walking and cycling are limited. Walking as a transportation mode is more complex than vehicular transport. A challenge for future research is to add registrations for pedestrian flow into the current approach and simulation models. Likewise, energy use per person for public transport such as trams and busses are more complex but need to eventually to be considered.

As calculations will differ between private cars and transport of public goods or public transport or walking, the challenge is to build an aggregated model that does not become overly complex, if the data are available in the first place. In this article, Bergen data acquired were proprietary and only available to the authors as part of a research project. Whereas in Zürich, the data had to be simulated as it was otherwise not available.

Regarding the energy usage simulations, they are at best an approximation of actual consumption. As discussed in selecting variables for transport energy usage, energy losses for braking and changing speed and direction at stops, turns, inclines and more were left out of the equation. Vehicle production energy usage and other costs were also left out. In this simulation, only passenger transport was considered and not goods transport. The latter is a key cause of pollution and emissions in the EU and should be considered in future studies. From this perspective, it could be that real values could turn out to be (much) higher. On the other hand, current technological innovations have also led to more energy-efficient cars, which may result in lower values. The agent-based simulation's accuracy is therefore highly dependent on available input. This may explain slight differences in correlation significance between Bergen and Zürich, as measured traffic data was used in Bergen instead of a simulation. Further research could include dynamic, real-time traffic observations to resolve this limitation.

The novel contribution in correlating spatial configurations to transport energy usage required a complex, cross-platform analysis. The spatial configurations were analysed in DepthMap, the traffic values in MATSim and then both combined and geo-referenced in ArcMap. The analysis is therefore limited by potential join errors and data transference between platforms. Both Bergen and Zürich have one or more arterial roads that lead into or through the city via a tunnel. On some occasions, the terrain above is built up with streets and buildings, leading to errors in the spatial join operation where the energy values from the tunnel road were joined instead to the residential streets above. This had to be manually sieved out by the authors and the inaccuracy was (at least partly) corrected by taking out the 10% outliers in Zürich, see Table 4.

The cross-comparison between cities allows for external validation of the findings. Although the approach operates from the value-free Space Syntax method, it is impossible to interpret the findings without local knowledge and field confirmation of the findings. Both case cities are similar in their historical development, urban structure and territorial conditions. To make the findings more robust, it is advisable to test the replicability of the approach in more cities and regions. This is of course subjected to data availability and access to the analytical tools used.

6.2. Reflections

The foremost use of the integrated assessment approach presented in this paper is a first step to build an energy classification for different street and road types. However, this model needs testing on other cities before making it operational for evaluating and diagnosing urban plans. At the very least, this model is a first step to understanding what the necessary conditions are for certain spatial configurations to achieve sustainable mobility for sustainable communities and cities.

It is not the intention of this article to villainize those who own and use private vehicles or to blame planning decisions for reinforcing unsustainable travel patterns and high energy consumption. In fact, one of the most vital transport flows i.e., goods and services have been unfortunately neglected due to lack of data availability. As long as the forces of a free market society prioritize profit-maximizing, mass-production, outsourcing and monoculture over energy efficiency, local economy, ecological diversity and social equity, a simple correlation of spatial configuration to energy usage remains limited in its ability to change the status quo. Here, the approach neglects who (a blue-collar worker or a CEO) is consuming transport energy.

In light of equity, health and well-being discussions in the SDGs, a potential future avenue of research would be to focus on who benefits and who pays in our current transportation system. With a shift towards thinking more in terms of local production and consumption in mind, further research should provide new insights how to achieve the Sustainable Development Goals within the transport and land use systems that we currently have.

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STRATEGIES FOR INTEGRATED DENSIFICATION WITH URBAN QUALITIES

Combining Space Syntax with building density, land usage, public transport and property rights in Bergen city.

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ABSTRACT

Bergen city in Norway is presently undergoing an enormous population growth. In this respect, Bergen municipality wanted to identify all the possibilities for densification in the current situation. Therefore, the following issues were evaluated: street network and public transport accessibility, building density, degree of functional diversity, restrictions on (private) properties and current land use plans.

Our approach is to analyse the central areas in Bergen in the current situation to discover how the urban transformation takes place in a natural way. Firstly, we studied the relationship between street network accessibility (with the Space Syntax method), degrees of FSI and GSI on building density (with the Spacematrix method) and degrees of function mix (with the MXI method). Secondly, we wanted to reveal the legal issues that arise from the strong Norwegian property rights. Thirdly, we added the accessibility of public transport lines through the angular step depth in the Space Syntax analysis. We combined all these issues by using GIS. Unlike in earlier research (Ye and van Nes, 2013 and 2014), the buffer line function in GIS was used to correlate building density, function mix and degree of spatial integration.

It turns out that the degree of street network integration affects the location of commercial activities and the degree of building density and function mix. When the street network accessibility increases on a local and global level, property owners start to submit plans that exploit their properties to the utmost. The same occurs around public transport stops with frequently running light rail trams. As follows from the theory of the natural urban transformation process, densification can thus be steered by improving the street network accessibility on multiple scale levels, combined with high public transport accessibility.

KEYWORDS

Building density, land use mix, property rights, public transport, natural urban transformation.

1. INTRODUCTION

During the last years, the use of GIS has contributed to combine the results from spatial analyses with place-bound socio-economic data. GIS has made it possible to operate with big data and to combine them with one another. The combination of building density (the correlation between FSI with GSI), degree of function mix (MXI) and Space Syntax in old and new towns has contributed to knowledge on how these aspects are interrelated (Ye and van Nes 2013 and 2014; van Nes et al., 2012). Already now, an outline is formulated for a theory of the natural urban transformation process. According to this theory, the spatial configuration of the street and road network influences the degree of building density and the degree of multi-functionality in the natural transformation processes in neighbourhoods over time (Ye and van Nes 2014). Lively and vital urban environments are thus dependent on a combination of a highly spatially integrated and well-connected street pattern, high building densities and a high degree of function mix.

Current planning policies in Europe are putting smart growth, high building density and high diversity of urban functions within short walking distances on the agenda to create compact cities. However, the social and environmental sustainability of building a compact urban form is disputed (Rådberg 1996:385). The compact city has the advantage of short walking distances between buildings containing its various activities. The ecological footprint is relatively small due to a reduction of urban sprawl. There are advantages to social and economic intensity because a high number of people live close to each other. From an environmental perspective, energy usage of transport between functions in compact cities is low. However, there is a lack of green spaces for recreation or for agricultural activities. Green and sustainable cities on the other hand have positive connotations in terms of well-being, attractiveness and sociability. The green city has the advantage of being able to provide its inhabitants with recreation and possibilities to produce food. In contrast, green cities contribute to urban sprawl into the countryside when the city expands. This contradiction between green cities and compact cities continues to prevail in urban design and practice (Rådberg 1996).

High building density is considered to contribute to sustainable development because it implies sharing of buildable space, facilities and infrastructure, as well as the reduction of travelling distances. This sharing implies a reduction of land use and energy resources required to perform all kinds of urban activities. The degree of success of this sharing can thus be seen as an indicator for an area's degree of urban quality.

If density is desirable as one of the requirements for urban quality, then urban development projects should always facilitate for maintaining, and where possible, further increasing density. Jane Jacobs (2000) and Jan Gehl (2011) argue that sufficient density is a requirement for life between buildings. More importantly, life between buildings is "potentially a self-reinforcing process", in which, "once this process has begun, the total activity is nearly always greater and more complex than the sum of the originally involved component activities" (Gehl, 2011:73). In other words, a successful urban area is self-propelling by merit of the amount and duration of outdoor activities, which requires both sufficient density and high-quality public spaces to ensure that a high number of people enjoy using these spaces.

Therefore, if density is a prerequisite for sustainable use and the amount of outdoor activities an indicator for the degree of success of performing these activities, then a spatially integrated urban street network is the primary generator of sustainability in the context set out here (see also: Hillier et al., 1993).

The next step is now to reveal how public transport accessibility plays a role in the natural urban transformation process. In 2009, Bergen city in Norway opened a light rail connection. The line was extended in 2016 and the last part of it will be opened summer 2017. The effect of the light rail is that surrounding property prices are increasing. For that reason, public transport accessibility was included in the calculations of street network accessibility by mapping the angular step depth from public transport stops.

One obstacle for large scale urban planning and transformation of urban areas in Norway is the strong legal issues related to private property rights. It is even stated in paragraph 105 of the Norwegian constitution law from 1814 that no one should be dispossessed of their private property, and if so, they should be given full compensation (Backer and Bull 2016, p. 12). Therefore, urban expansions in Norway tend to take place on large plots where one has to deal with a low number of property owners. Large-scale urban renewal projects or big inner city transformations thus involve time-consuming negotiations with property owners and adjustment of property borders, as well as high costs of changing property borders when a large number of owners are involved.

The background for the research is a project set up by Bergen municipality that intends to explore where and how to densify in existing urban areas. The aim is to use the outcomes in future land use and policy planning as a strategy for densification in the central areas of Bergen. Inspired by the 'Denser Stockholm' project (Spacescape 2013), a Spacescape analysis is made using a densification rose to identify both the need for densification and there where there is freedom to do so. How to densify in those areas depends on the degree of accessibility of the street network and public transport, as this inquiry shows. To that end, the Space Syntax method is included in the research project.

The project started with an identification of the types of densification actions proposed by the municipality. Three types of densification actions were identified: intensification, transformation and expansion. The intensification strategy entails identifying densification potentials in existing urban areas without changing the whole built environment. The transformation strategy concerns identifying and assessing densification potentials of larger urban areas that would require a functional transformation, such as harbour fronts, goods terminals and industrial estates. The expansion strategy intends to find densification opportunities in previously unbuilt areas within the city boarders. In the Bergen case, these are often found on the mountain slopes, where development had not previously been considered due to costly technical challenges.

Following the theory of the natural movement economic process (Hillier et.al, 1993 and 1998), it is to be expected that the highest potentials for densification outside the city centre are found around the main routes, the local centres and the public transport stops. Local discrepancies may be found which can likely be attributed to the unique landscape elements such as the mountain slopes and fjords surrounding the city. They are also responsible for the characteristic capricious road pattern, which follows height lines in order to keep gradients acceptable from a road-engineering point of view.

2. DATASETS AND METHODS

With the aim of producing maps in which Space Syntax, Spacematrix, Mixed-Use Index and property ownership data are combined, two new ways of visualising integration levels have been tested. This method goes further than the raster method introduced by van Nes, Ye and Mashhoodi (van Nes et al., 2012; Ye and van Nes, 2013, 2014) (see figure 1).

With the first method, the integration levels contained within the line segments are projected onto the building plots adjacent to these segments. This is achieved using an Overlay operation in ArcMap. The method is chosen because the building plots themselves contain the data that the integration levels are aimed to be combined with, i.e. the data on density and functional use as well as information on ownership of the plots.

The second method combines Space Syntax data with Spacematrix and the Mixed-Use Index with a buffer area around the line segments, since there are a number of inaccuracies in the initial results from the grid-based method. The overlay method works well for smaller plots, especially if they are connected to only one or two line segments. However, in particular on larger plots, values are found that often do not represent the actual degree of integration based on their position in relation to the street network.

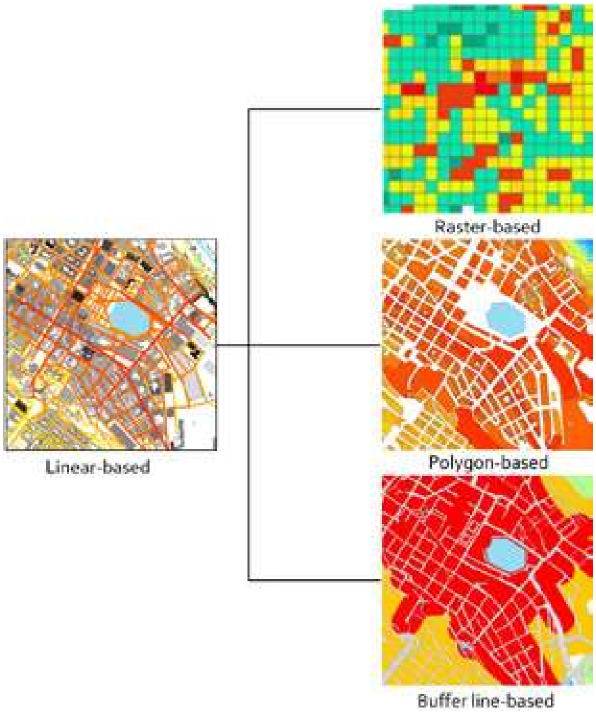

Figure 1 - Examples of raster-based, polygon-based and buffer line-based Space Syntax maps in GIS

The best example of this inaccuracy is the plot belonging to the goods terminal east of Bergen's railway station (figure 2). Directly connected to the globally and locally highly integrated street Strømgaten, this large plot thus receives a "highly integrated" classification. In reality, however, the plot is for the larger part flanked by line segments with much lower integration values than the map suggests. Moreover, the plot today is isolated and difficult to approach, and elongated to such an extent that only a limited percentage of people would approach it from Strømgaten, but most others from other streets located closer by.

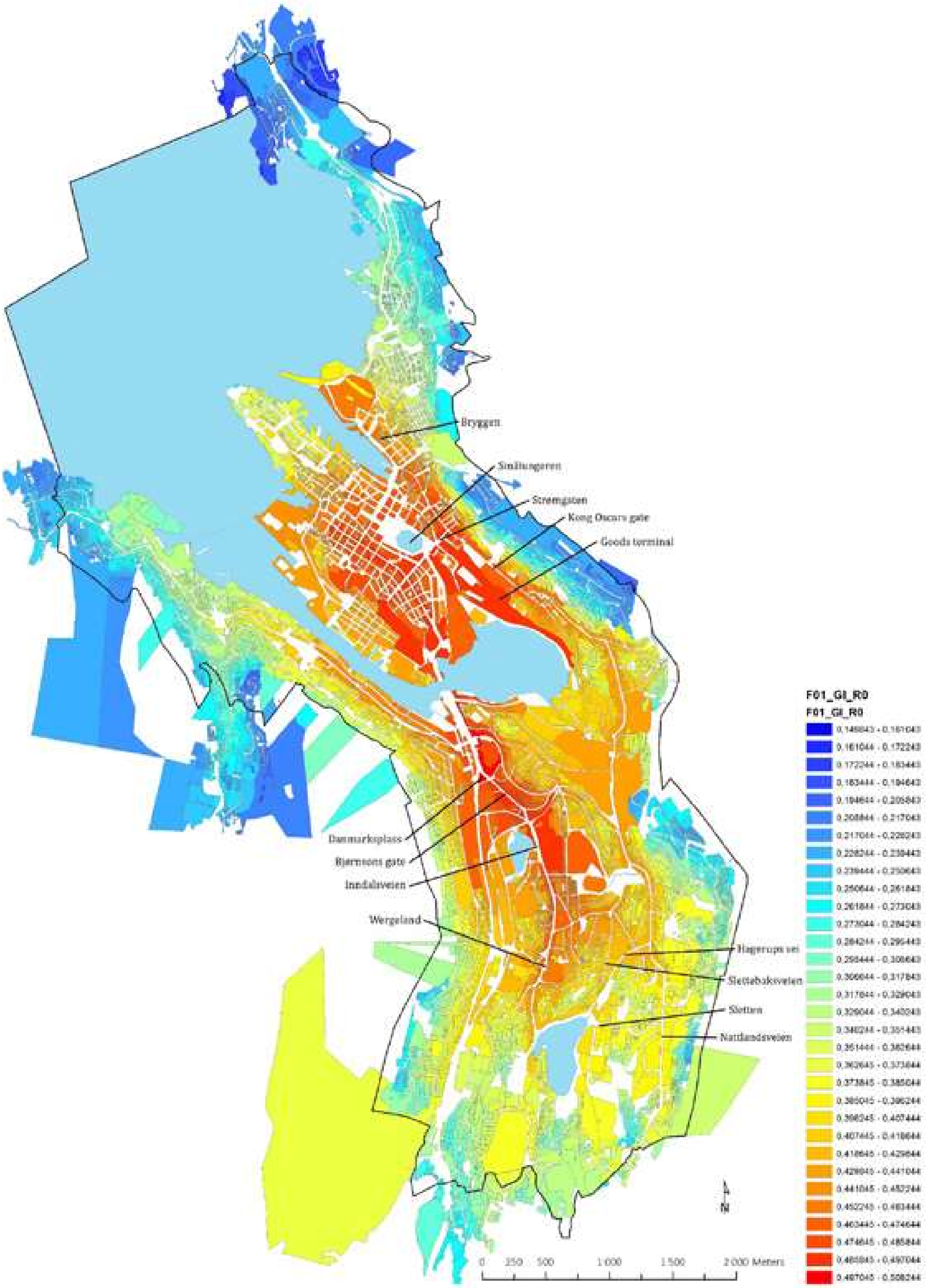

Figure 2 - Global integration map projected on building plots

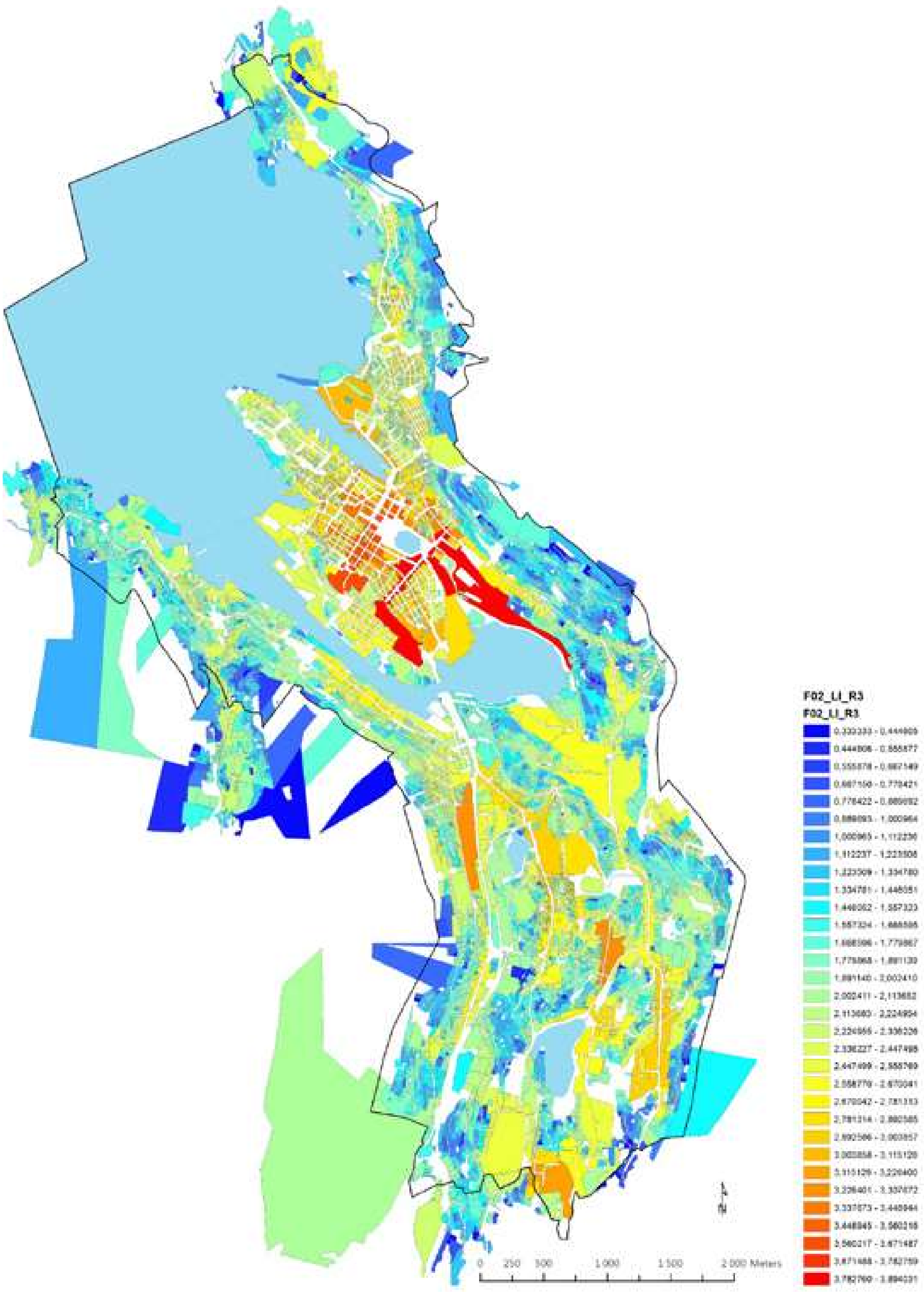

Figure 3 - Local integration map projected on building plots.

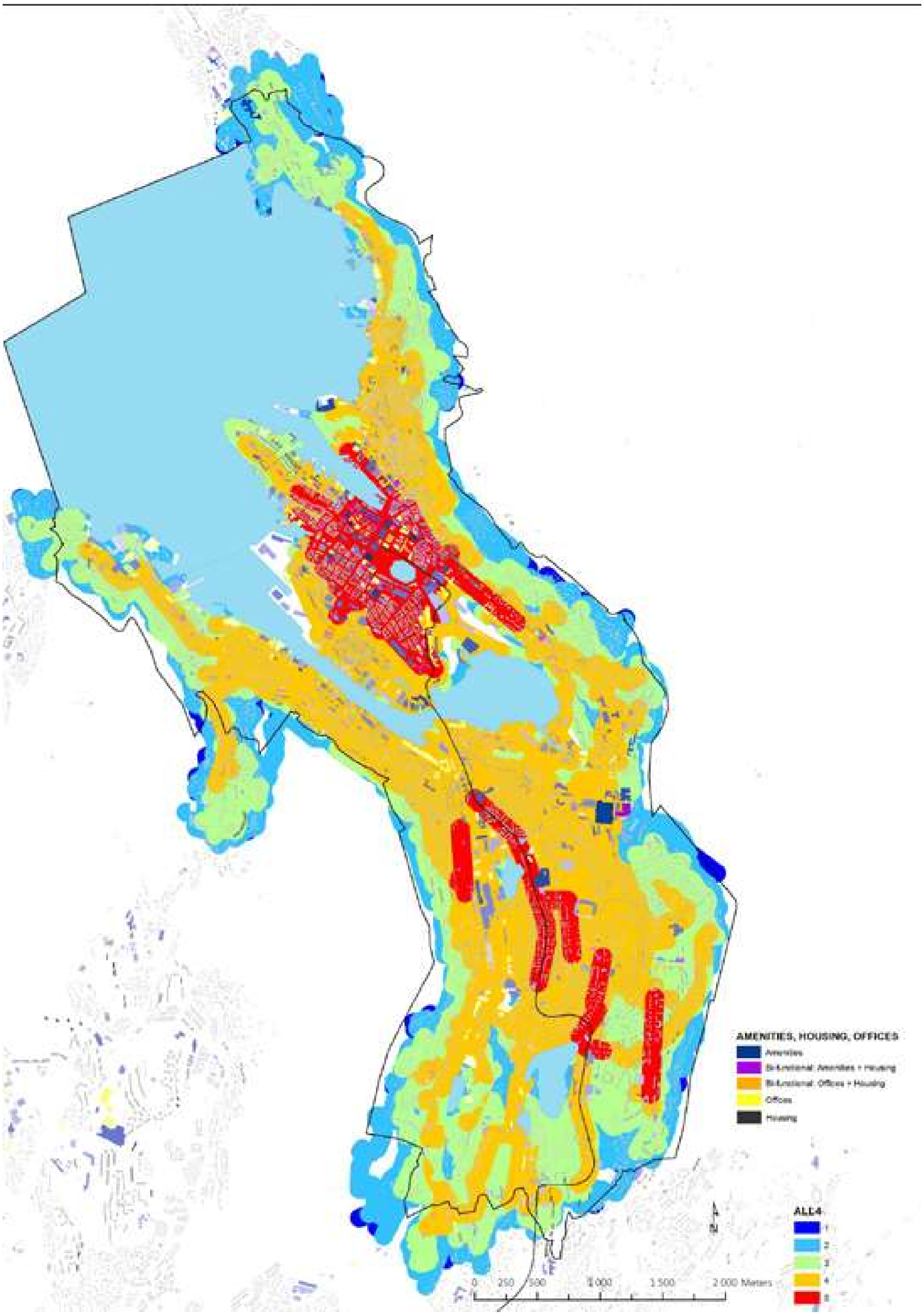

Figure 4 - Aggregated integration map using 75m buffer lines

To avoid this deviation from actual integration values on larger plots, a buffer operation is tested out as a second method. With a buffer of 75 meter around each line segment, a surface area is created that contains the corresponding integration value of that segment.

To identify the segments with high potential for both to- and through-movement, the global and local integration values have been multiplied with each other and combined with the multiplied metric step depth values with both high and low radii. The result is an aggregated map that reveals the overall integration values based on the location in relation to the street network. In addition, the building function is visualised by colour according to the Mixed-use Index and simultaneously, the building height is indicated by the gradient of the colour in question.

3. RESULTS

In figure 2 and 3, the global and local integration values have been projected onto the building plots. The highest global values are found in the city centre area where there is an orthogonal street structure, introduced in the first decade of the twentieth century. The high values extend out of the centre along the main axis that leads past the Danmarksplass area. This axis has evolved over time by different road upgrades to facilitate the rapid growth of vehicle transport. Since 2009, Bergen's first light rail line runs parallel with the highway. The highest density and degree of function mix is found along this highway axis.

The orthogonal street network structure yields the highest local integration values in the city centre around the Smålungeren area (figure 3). However, there are no other local areas outside the city centre where equally high values are found. This lack is not only limited to the built-up slopes, where both the road structure becomes more parallel to limit the gradient and there is an edge effect, but is also found throughout the urbanised valley.

It becomes clear that the street pattern throughout the city (outside of the city centre) has been constructed for facilitating car traffic through the large topographic variations in the landscape. This has produced a curvier road pattern with fewer cross connections than in cities located in a flat landscape. Moreover, road engineers have the largest influence in Norwegian urban planning. In detailed land use plans, all new streets and roads are planned in detail, whereas the land usage along these streets and roads is merely indicated with a function and with a degree of building density.

Taking into account that Bergen's street pattern is imposed on an extreme sloping landscape, the aggregated map in figure 4 was produced to reveal the areas with the best accessibility on both city level and local level, whilst including choice of route based on angular deviation. Again, the highest values are found in the city centre. Moreover, several main streets are well-integrated on a local level, such as Bryggen and Kong Oscars gate in the centre, Bjørnsons gate and Inndalsveien leading up to Wergeland, Slettebaksveien and Hagerups vei north of Sletten, and Nattlandsveien as the main road on the east side of the valley.

These red areas are undergoing a considerable degree of urban transformation in terms of increased density of the built mass. Ground prices in these areas are rising. New building projects have larger floor space and more storeys than the old buildings. The amount of commercial establishments is also increasing. The trajectory of the light rail line has subsequently connected these centres with each other. Most areas around these centres, marked in orange, are relatively well-integrated, although further away, the values drop sharply.

As a test of the method, a close-up study was done of the area around Danmarksplass, an area that has developed incrementally over the last 80 years without any overall urban planning. The goal is to reveal how building density and degree of multi-functionality are strongly influenced by the degree of spatial accessibility of the street and road network. The local centre on Danmarksplass is located along one of the main routes leading towards Bergen centre.

Figure 5 Metric step depth with a high metrical radius at the Danmarksplass area with registrations of building height and degree of function mix

Figure 5 shows the metric step depth analysis with a high metric radius combined with the degree of function mix. Here, the main routes through and between various neighbourhoods are highlighted. Where the values are high, the degree of function mix and building density are high. Schools, restaurants and shops are located along the eastern side of the busy highway as well as a light rail stop. The narrow pavement on this side of the road is always frequented by a high number of people.

Figure 6 - Metric step depth low radius Danmarksplass

The same features can be seen in the metric step depth analysis with a low metrical radius shown in figure 6. In particular, a high degree of function mix occurs on ground floors of buildings where the values are high. Local supermarkets, food shops and snack bars are located along these locally highly integrated streets. There is a cluster of local grocery shops and retail in a local centre west of Danmarksplass, which has the highest locally integrated street. These shops predominantly serve local residents living in the vicinity. The connections for pedestrians and cyclists between the local shopping centre and the main centre in Danmarksplass, however, are poor. The highway through the area acts as a barrier and the two sides are only connected by two pedestrian subways. There are no pedestrian crossings on street level.

Figure 7 - Angular Step Depth From Public Transport Stops

Figure 8 - Functions projected onto axial lines

Serviced by a few bus lines, analysis of the angular step depth from public transport stops shows that public transport coverage is quite high in the Gyldenpris area west of Danmarksplass. However, the transformation from a suburban to an urban district seems to be hindered due to a segregated street pattern and a low socio-economic status. In contrast, the Kronstadhøyden area on the east side is not locally serviced by public transport at all. The street pattern is more curved. Moreover, the neighbourhood has a higher socio-economic status than the Gyldenpris area. This difference is for a large part due to sun conditions. Whereas the Gyldenpris area is in the shadow of a mountain most of the day, the Kronstadhøyden area has good sun conditions. Some new developments are currently taking place in the Møllendal area to the northeast and the Haukeland area to the east.

As an experiment, the degree of function mix was projected onto the axial lines (figure 8). The correlation between functional mix and integration values seems strong. Amenities (coloured in blue), to which most non-residential functions belong, are predominantly connected to main routes. Offices tend to be located on the side streets of these main roads, ensuring favourable accessibility both by car and by public transport, whilst mono-functional residential streets are clearly clustered away from the main roads.

4. DISCUSSION OF THE RESULTS

It turns out that developments in Bergen city take place in line with the natural urban transformation process. Well-integrated streets have more to- and through-movement than poorly integrated streets. Shops and businesses cluster around these streets and densities increase considerably in comparison to the situation prior to the new situation.

Seemingly, cities in Norway are currently transforming on an "anti-urban" track. Even though the intentions are to make compact cities, there are three drivers for urban sprawl in Norway. For the first part, urban developments are still steered by a strong emphasis on private car accessibility. New buildings are equipped with parking garages in the basement and often at ground floor level. As a result, building projects create poor urban qualities for pedestrians and cyclists. This stands in strong contrast with the municipality's formal ambitions to reduce the growth of car traffic with 50 % by improving the walking and cycling conditions in urban areas.

The second cause for the continuation of the anti-urban tradition is Norwegian property legislation. Although private property developments do result in space-efficient exploitation of building plots with high short-term profits, the flexibility and adaptability to adjust to changes on the long-term is lacking. Moreover, these private owners have the last word concerning the degree of multi-functionality. In addition, property owners tend to plan and build their properties to the current context rather than being future-oriented. Access from the public domain is hardly taken into account and private car accessibility is prioritised. Attitudes like these strongly affect the organisation of public spaces that link the properties to the public street network. Disappointingly, this often results in an incoherent, anti-urban structure with inward oriented buildings that lack active frontages towards the public streets.

The third aspect is the hilly Western-Norwegian landscape. Technical innovations now give way to previously impracticable or unrealisable plans, although they are expensive. Moreover, carrying out functional changes in a later stadium would be much more demanding. Therefore, any possible short-sightedness from private developers could produce a building stock that is hard or expensive to adapt to new uses.

The method of projecting integration values onto building plots can be a useful tool in Norwegian planning. By linking integration values directly to building plots, the authorities can take measures that oblige privately owned properties to be developed with the urban qualities related to accessibility for pedestrians, cyclists and public transport, flexibility, multi-functionality and, in the near future, energy production, smart communication and sustainable mobility means.

The second method, using buffer lines, is more usable to locate densification potentials based on the position in the urban fabric. In addition, this method allows for quick identification of areas that are segregated as a consequence of the street pattern layout. The municipality and road authorities can use this method as input for overall development plans as well as infrastructural improvements, and subsequently predict the effects on building density and degree of diversity of such plans and measures.

The test analysis of public transport stops as a backbone for densification reveals that the influence of bus routes is insignificant in comparison to that of the light rail. This might be due to the comparatively long-term character of light rail lines, creating a certainty of passenger flows along these routes. The municipality is currently developing plans for three new light rail routes aimed at improving the accessibility to and from the city centre to the districts further away. It can therefore be expected that redevelopments will intensify more along these lines than the integration values based on the street pattern would otherwise suggest.

5. CONCLUSIONS

How can this research be used to make recommendations for Bergen municipality on where and how to densify? Evidently, the street network configuration influences the degree of building density and degree of function mix. Four types of urban areas were identified based on street network integration on local and global scales:

Type A: High local and high global integration of the street and road network.

Where extra space becomes available, these areas can be transformed with a high density of built mass. This can include high-rise buildings. The aim is to provide land use plans that allow a wide range of different usages, in particular on ground floor level. Areas suitable for this kind of development in Bergen are the city centre, the harbour areas around the city centre, Danmarksplass and the old industrial area Mindemyren.

Type B: High local, but low global integration of the street and road network.

Where there is space, these areas can facilitate high density of dwellings with ground floor spaces for shops, small businesses and services. Depending on the local circumstances, high-rise buildings can be considered as an option. As an example, the Sandviken area has many 2-3 floors high old wooden houses. The type and style of buildings give this area a particular place

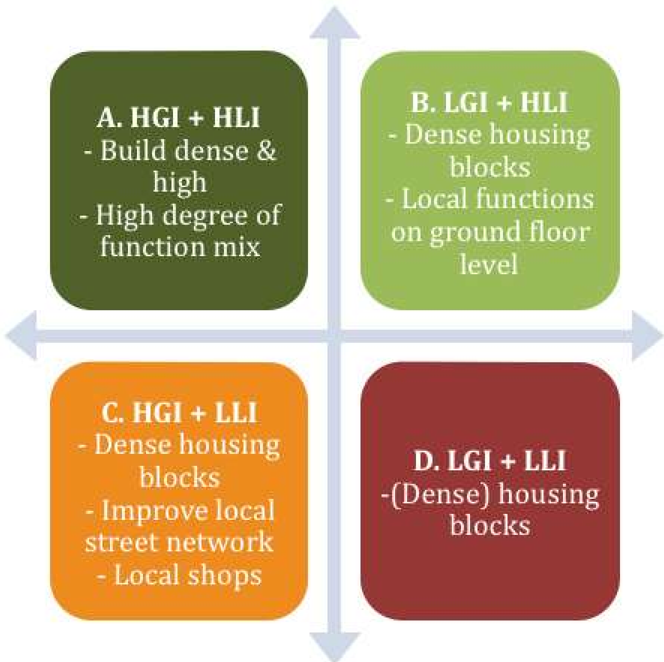

Figure 9 Strategic densification matrix

character. New buildings will have to adjust to the existing building stock in scale and style to avoid damaging the place-identity of that area. Areas suitable for this kind of densification are the various local centres outside Bergen centre. Most of these small local centres are situated along the main routes leading through various urban areas. Areas located along the light rail also belong in this category.

Type C: Low local, but high global integration of the street and road network.

These locations are suitable for high densities of housing. Where possibilities exist to create a locally integrated street network, local shops on the ground floor can be facilitated. An example of such an area is the southern part of industrial area Mindemyren.

Type D: Low local and low global integration of the street and road network.

Where there is space to develop, high densities of only dwellings are desirable. These areas have a low degree of accessibility, and are therefore little attractive for shop owners. Examples of these kinds of areas are found around the lake Store Lundgårdsvannet such as Møllendalsveien, and harbour areas located along the fjord Puddefjorden.

Figure 9 shows the principles on how to densify. The colours in the diagram in figure 9 are applied in the combined integration map of figure 10, showing how and where to densify in one map.

Four groups were used in this inquiry. It is also possible to use nine different groups where high, medium and low values of global and local integration are combined. This would enable the application of more detailed strategies. In this case, however, being in the beginning stage of collaboration with the municipality and in a planning process where multiple NGO's, property owners and stakeholders are involved, operating with four different categories rather than nine is more practical. In addition, the various densification strategies for each of the nine categories would need to be defined.

The experiments with the buffer line method are still in a test stage. The next step is to find ways to combine density, MXI and Space Syntax data into one buffer line model. The raster model is useful for overall strategic land use planning in whole urban regions or in regional planning. Professionals such as spatial planners and urban geographers may find this model useful. The polygon model is useful as a guide for urban designers and architects who work on plot level. Finally, the buffer line model can be useful for road engineers to make them aware of the spatial potentials of their planned road and street links. After all, the degrees of building density and function mix depend on the degree of spatial integration of the street and road network.

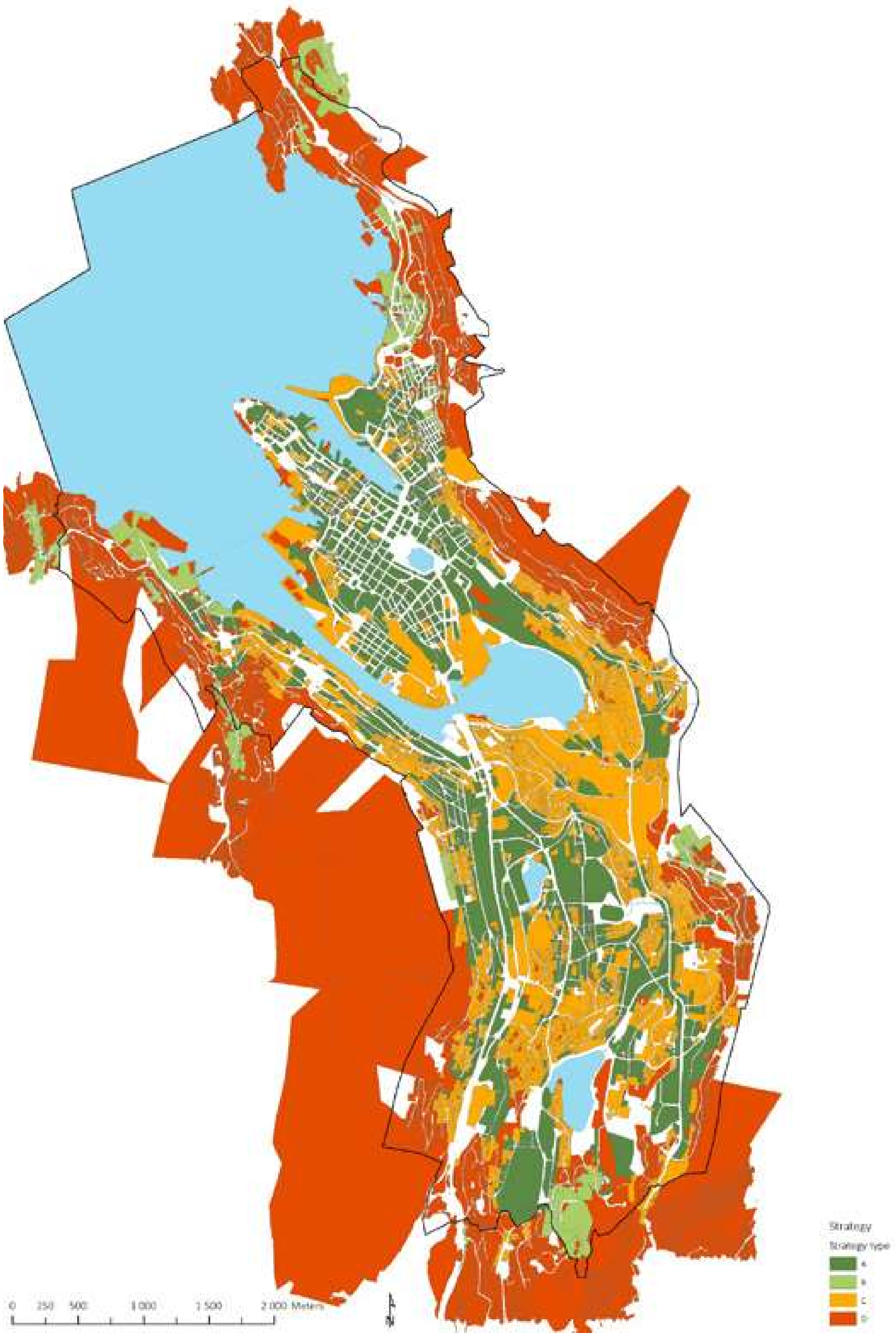

Figure 10 - Strategies for where and how to densify

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Data Article

Spatial data and workflow automation for understanding densification patterns and transport energy networks in urban areas: The cases of Bergen, Norway, and Zürich, Switzerland

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A B S T R A C T

A better understanding of how the spatial configuration of cities, understood as urban structure and forms, can achieve sustainable development is needed. This paper presents spatial data and an automated workflow for studying the urban structures (i.e., road and transportation networks) and forms (i.e., building size, position, function and density) of two medium-sized European cities - Bergen, Norway and Zürich, Switzerland. The data focuses on examining correlations between the densification patterns and transport energy usage of these cities de Koning et al., (2020). Spatial and tabular datasets for (i) urban structures, (ii) urban forms, (iii) building density, (iv) road centre lines and (v) transport energy usage are obtained as georeferenced files from OpenStreetMap (OSM) and upon request from collaborating local and national authorities. Transport energy data is derived from traffic data collected from the Norwegian Public Road Authorities or simulated via a traffic model. Open-source data is used wherever possible. Data gaps within proprietary data are supplemented with proxies or open-source data.

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Hand-drawn axial maps drawn by the authors using the Space Syntax methods and analysed via depthmapX software are a crucial dataset presented here. All analysed data are then returned to a Geographical Information System (GIS) platform and processed via an automated workflow of 19 steps built via the ModelBuilder™ tool in ESRI® ArcGIS. The automated workflow allows for repetitive cross-city comparison and the compilation of diverse spatial data sources for analysis.
In combination with the novel workflow, the dataset can be used for future comparative studies in spatial planning, transport planning and management of energy systems to facilitate informed decision-making towards more sustainable developments.

Specifications Table

Subject	Social Sciences
Specific subject area	Planning and Development
Type of data	Spatial data files (ESRI shapefile) and supporting tables VBA script code ArcGIS Toolbox
How the data were acquired	Part of the spatial data files are georeferenced axial maps hand-drawn by researchers and validated with local experts. The rest were secondary data downloaded from open-source online resources via ArcGIS Editor for OpenStreetMap (OSM). Information on transport capacity and building use were proprietary data provided on request by local authorities (Bergen Kommune) and national authorities (the Norwegian Public Road Administration) and the Institute for Transport Planning and Systems at ETH Zürich as georeferenced shapefiles.
Data format	Shapefile (.SHP), Code Page file (.CPG), dBase Database file (.DBF), Shape Index file (.SHX), Projection file (.PRJ), Extensible Markup Language file (.XML),
Description of data collection	Axial maps were drawn over the street networks of Bergen, Norway and Zürich, Switzerland using the Space Syntax method in ArcGIS. They are exported per city, analysed with depthmapX and then re-imported to GIS. Open-source data for all available street networks, buildings, and plots were downloaded for both cities' geographical and political boundaries via OSM. In addition, proprietary data were obtained on request for both cities.
Data source location	• Bergen, Norway: Latitude: 60.339371 – 60.426075 Longitude: 5.266552 – 5.381914 • Zürich, Switzerland: Latitude: 47.351269 – 47.402858 Longitude: 8.489675 – 8.578846
Data accessibility	The data is hosted at GitHub. Repository name: HVL_PhD, HVL_PCS953 Spatial data: https://github.com/redekoning/HVL_PhD Geo-processing toolkit: https://github.com/redekoning/HVL_PCS953
Related research article	de Koning, R. E., Tan, W. G. Z. & van Nes, A., Assessing Spatial Configurations and Transport Energy Usage for Planning Sustainable Communities. Sustainability, Vol. 12:19 (2020), 8146. 10.3390/su12198146

Value of the Data

- Comparable data on densification patterns and transport energy from cities in different countries are not readily available. Data on urban form, building density and road centre lines are found at varying units and levels of scales (i.e., neighbourhood and citywide). However, the comparison is essential for drawing insights on spatial relationships to achieve sustainable development.
- The dataset contains spatial data such as building, plots and street networks attached with non-spatial data of building functions and simulated transport energy usage. These georeferenced shapefiles are usable across multiple GIS platforms and allow other researchers to compare with their own cities.
- The primary data of hand-drawn axial maps of Bergen and Zürich are georeferenced and validated. Furthermore, this unique empirical data is confirmed with local authorities and experts involved in the research project available to other researchers.
- The data for urban structure carries the metrics of 'betweenness' and 'closeness' calculated based on Space Syntax theories and methods [2,3] via depthmapX. These metrics improve current geographical and transport planning approaches of proximity or access through speed and distance to improve planning decisions for sustainable mobility.
- The data for urban form (dimensions, age and functions) and building density (function, floor space and plot sizes) are calculated with the Mixed-Use Index (MXI) calculator designed for this workflow. Decision-makers of local, regional and national authorities for spatial planning, transport and infrastructure planning, and resource planning can use this to consider how space is distributed, if the distribution is efficient, and if the content of the distribution can facilitate liveability and sustainability.
- The unique data on workflow automation allows for repetition of data input by other researchers using other cities while allowing for generalisability across different cases. The knowledge and insights can be helpful for strategic spatial and transport planners, spatial development policymakers and road engineers to make well-informed decisions on how to develop urban areas more sustainably and offer methods for analysing cities.

1. Data Description

This article provides data on urban structures and forms from Bergen, Norway and Zürich, Switzerland, for a partially automated spatial analysis to understand densification patterns and transport energy usage for sustainable development. Densification patterns [4] are derived from data on the distribution of building densities and land uses. Transport energy was derived from data on traffic volume and speeds. Resulting insights are pertinent to achieving more sustainable cities because housing, public and commercial services and transport account for more than half of all energy usage in cities [5]. Furthermore, the data allows for questions on (i) what conditions are required for sustainable development understood through densification patterns or transport energy usage, (ii) which direct or indirect relationships can be observed when comparing spatial configurations across different cases, and (iii) what is the best way to collect, prepare and automate similar data for comparison across context and case.

Most of the data prepared are from publicly available open-source databases wherever possible. The exceptions to this rule are the unique, validated hand-drawn axial maps from which urban structure is calculated and the proprietary data on transport flow. Data proxies or alternatives to proprietary or unobtainable data required to understand urban structure and form are provided. For example, the building density data for Zürich was approximated through open-source data as it was not available to the public. There is no significant observable difference in the provided proprietary data from Bergen versus that proxy data built by the authors on Zürich.

Each city studied requires a data package, combining primary (i.e. self-drawn axial maps) and secondary data (i.e. building plot outlines, property characteristics) obtained from public authorities and open-source data. The spatial data consists of the object (a point, line or polygon with x-y coordinates) and an attached attribute table consisting of relevant information to the spatial object (i.e., shape, size, ownership information etc.). The unique data for urban structure are axial lines drawn by the researcher as an overlay on existing maps and transformed into first-hand empirical data in the form of a georeferenced shapefile for each data input for both cities. The shapefile format (*shp) is commonly used on GIS platforms. There are five types of data used for each case.

1. **Urban structure** represented as line segments (from axial drawing) including attribute data such as network values of closeness and betweenness (see Fig. 1a and d); and
2. **Urban form** is represented as polygons (see Fig. 1b and e) with building attribute data such as dimensions, age and functions.

These data are the key independent variables for both cases. Extra information that permits us to identify densification patterns is represented by:

3. **Building density** is calculated via the dimensions and spatial location of the land use plots (see Fig. 1c). This is only available for Bergen due to a lack of proprietary data.;

Relating urban structure and form to transport energy usage are represented by:

4. **Road centre lines** containing dimensions and spatial location of the network of roads, streets, paths and alleyways; and
5. **Transport use**, the amounts of traffic and maximum speeds on the roads and streets to calculate transport energy usage.

The five data types are explained here in detail.

- **Urban structure**, showing the space between buildings, is partially represented as line segments for Bergen [200707_BERGEN_SS.shp] and Zürich [191014_ZÜRICH_SS.shp]. The data is stored in georeferenced vector maps. The files contain single, straight lines between two geo-coordinates that intersect or overlap each other and cover all convex urban spaces using the fewest, longest lines determined by the line of sight (see Fig. 1a and d). The sample total for Bergen is 35,304 segment lines created from 8534 axial lines and 43,443 segment lines derived from 9398 axial lines for the study area Zürich. The relevant (tabular) attribute fields attached to the shapefile objects are the metrics of betweenness and closeness calculated using the open-source software program depthmapX (https://spacegroupucl.github.io/depthmapX/). The metric betweenness shows the likelihood of a street segment to be part of a route and is found with Angular Choice calculations. This takes into account cognition and wayfinding and explains the potential of movement through a network of streets. For example, most trips taken within a street network in a given radius will go through the street segment with the highest choice value. The metric closeness demonstrates the likelihood of a street segment as a destination and is calculated via Angular Integration. This expands on current approaches to understanding networks through the hierarchy (speed and volumes of streets) and accounts for the occurrence of movement as destination potential of a street segment within a given network. For example, a street segment on which the shortest path between most pairs of segments within a given radius falls on will have a high value [6]. Both metrics are calculated at the neighbourhood (500m radius) and citywide (5000m) scale. The choice for 500 or 5000 meters as the radius is related to the logic of space assumption [2,3], which suggests that these dimensions are where pedestrians or car users would make a cognitive choice that determines their routes.

These fields are named:

- 'NACH500′ categorised as 'C_500′; values for Normalised Angular Choice or NACH (representing 'betweenness') on a 500 m metrical radius for each segment;
- 'NACH5000′ categorised as 'C_5000′; values for NACH at a 5000 m radius for each segment;

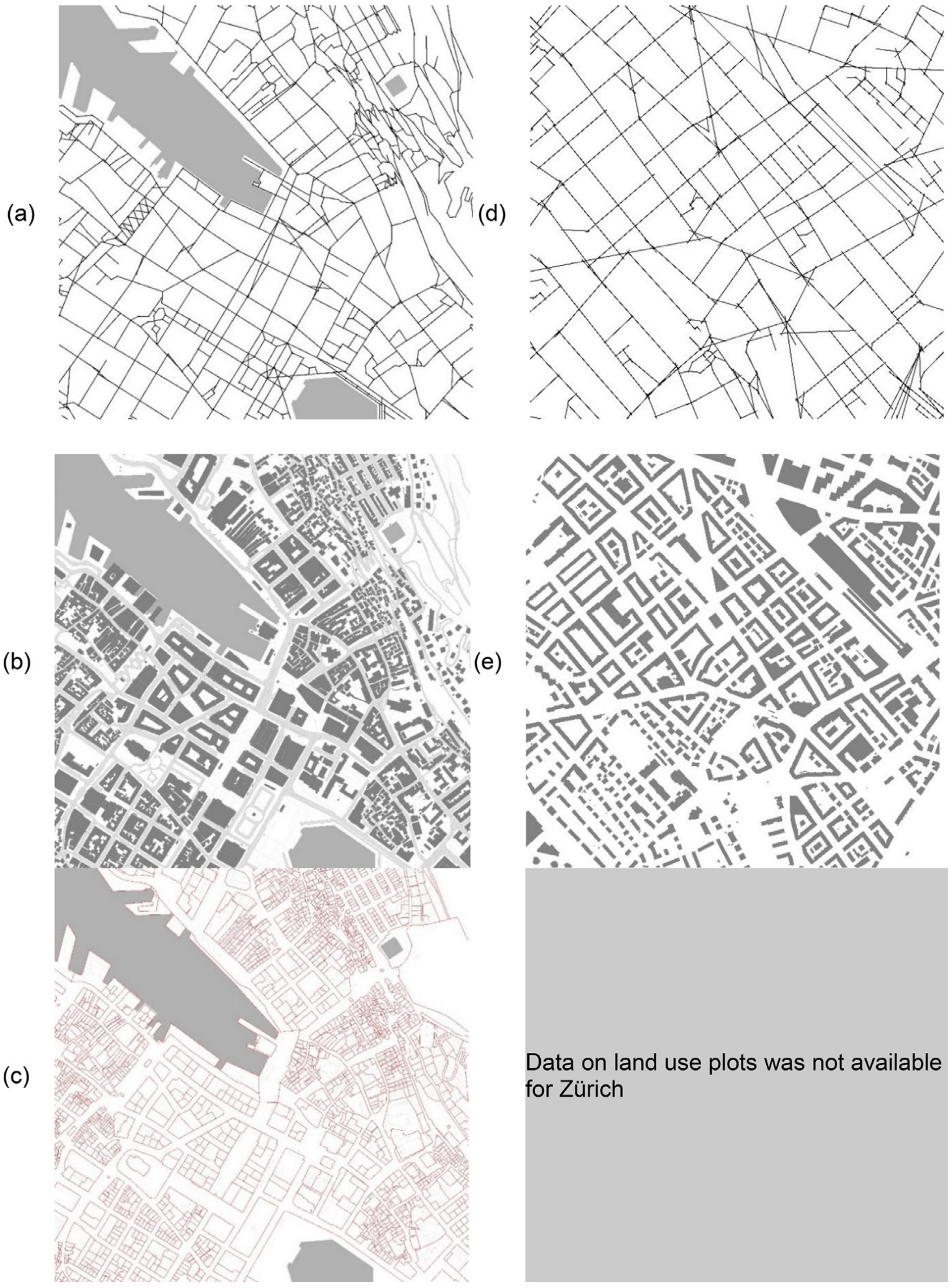

Fig. 1.. 1 × 1 km visual representation of data types for Bergen, Norway (left) and Zürich, Switzerland (right). Fig. 1a, d show axial line maps, 1b and 1e show building maps, and 1c shows a land-use plot map.

Table 1
Attribute codes and functions.

Attribute code	Function	Type of activity
100-199	Residential	Housing
200-249	Industrial	Offices
300-349	Office/business	Offices
400-449	Transport/communication	Amenities
500-549	Hotel/Restaurant	Amenities
600->	Remaining amenities	Amenities

- 'NAIN500′ categorised as 'I_500′; Normalised Angular Integration or NAIN (representing 'closeness') on a 500 m radius for each segment; and
- 'NAIN5000′ categorised as 'I_5000′; values for NAIN at a 5000 m radius for each segment.

The above fields are categorised into three value types (low, medium, and high). The last step of preparing the data on spatial configurations is to aggregate all betweenness (named 'IAGGR') values and all closeness (named 'CAGGR') values to capture how street segments simultaneously perform across two levels of scale. The categorisation and aggregation procedures are described in detail in the next section.

- **Urban form** is represented through polygons that represent the dimensions and spatial location of the buildings and related land use and building density data (when available). The files within the dataset are named [BERGEN_BLD.shp] for Bergen and [191104_ZÜRICH_BLD_NO_HSQ.shp] for Zürich. The sample total for Bergen is 22,548 and for Zürich 22,118 buildings. The relevant secondary data are not equally available for both cases. The information about the land uses for Zürich was incomplete and not open-source. However, the missing information was added manually by checking Google Earth and Google Street View.

These files contain eight fields:

- 'TYPEKODE': shows values of land use. Each land use has a unique three-digit code associated with legal status, stored in this attribute field (see Table 1). A custom script is used to derive the secondary data from this attribute field relevant to this research, namely the ratio between the urban activities performed. In addition, a distinction is made between amenities, offices, and housing for each building. This script is described in the next section.
- 'F_ETASJER': contains the numerical values of the number of building floors;
- 'BRUKSAREAL': values on the area of the building footprint; and
- 'F_BOENHETE': the number of housing units.

In addition, attribute fields for understanding urban form in relation to land use functions for both cases are derived from the above four fields. These attribute values indicate the degree of functional mix or how diverse activities are located or distributed in one particular location. These fields are:

- 'AMENITIES': the percentage of total floor space used for amenities (e.g. transportation, hotels, restaurants, and other amenities);
- 'OFFICES': the percentage of total floor space used for offices and business and industrial functions.
- 'HOUSING': the percentage of total floor space used for residential purposes; and
- 'MXI': the distribution of the above fields AMENITIES, OFFICES, and HOUSING categorised based on the Form Syntax framework [7]. Here, Van den Hoek's [8] terminology was used and corresponded with Dovey and Pavka's 'live' (housing), 'work' (offices) and 'visit' (amenities) classification [9]. The same four attribute fields as for Bergen were added manually for Zürich via open-source online information, rather than calculated via data as was done for the case of Bergen.

- **Building density** helps to understand how urban form is utilised and calculated with the file [200107_BERGEN_PLOTS.shp]. This shapefile is obtained from the municipality of Bergen and contains the geometry of the cadastral pattern, i.e. the plot size and shape on which the buildings stand (see Fig. 1c). The plot sizes are used for calculating building density explained in the next section. However, as open-source data for land for Zürich was not available, this applies to the densification patterns in the case of Bergen only.
- **Road centre lines** are the common feature used for linking transport energy data with outputs of the spatial analysis via depthmapX. The files are named [180906_BERGEN_RCL.shp] for Bergen and [180906_ZÜRICH_RCL.shp] for Zürich. These files contain data contains road centre line data that comes from OSM. It includes the dimensions (length, width and type of roads) and the spatial location of the road and street network in the form of polylines. The key attribute field used is 'maxspeed'. It represents the maximum traffic speed (km/h) on a particular road.
- **Transport use**, which shows the capacity and volume of traffic on the roads analysed, are found in the files [181004_ÅDT_Hordaland.shp] for Bergen and [Macroscopic_Assignment_Model_ZH_link.shp] for Zürich.These files attach attribute data that show traffic volume and flow to road centre lines. These data are proprietary and sourced from the Norwegian Public Road Administration and the Institute for Transport Planning and Systems at ETH Zürich. Relevant attribute fields showing Annual Average Daily Traffic (AADT) for each road segment as the fields' ÅDT_tota' for Bergen and 'VOLVEHPR$\sim$2$'$ for Zürich. Traffic volume from Bergen is measured. From Zürich, this data is simulated [10]. These fields are used to calculate energy usage by cars for each road/street segment. Detailed calculations are described in the next section.

As described, there are some discrepancies in data across both cases, especially for building density and transport use. This is due to differences in data collection systems and legislation in both countries. In addition, access to data is challenging for Zürich. In Bergen, access to data also resulted in more precise building density values and transport use. In Zürich, data had to be supplemented manually for land use or omitted for plot size. Cross-case comparisons for densification patterns were therefore not possible. On the other hand, in Zürich, data could be simulated in the case of transport use. Hence, comparisons for transport energy usage were possible.

2. Experimental Design, Materials and Methods

The data above was processed in an experimental workflow (see Fig. 2) designed to combine GIS with the open-source program depthmapX used to calculate spatial configurations and to facilitate multiple iterations of data processing and analysis with various inputs from both cases. The GIS software used here is ESRI® ArcMap version 10.4.1 for Desktop. The workflow has three stages: data collection, preparation, and comparison. The 19 steps proposed contributes to novel ways to identify and compare spatial configurations through efficiently aggregating and comparing data that are both spatial and non-spatial from different base units (i.e. levels of scales) and different sources. For example, the application of a buffer operation to better compare building level data with street network values is a combination of spatial and non-spatial data. In addition, the authors have shared how to automate the workflow such that internal validity is assured when comparing cases or when updates of data are available.

2.1. Data Collection and Combination

The three steps of combining the data previously described are;

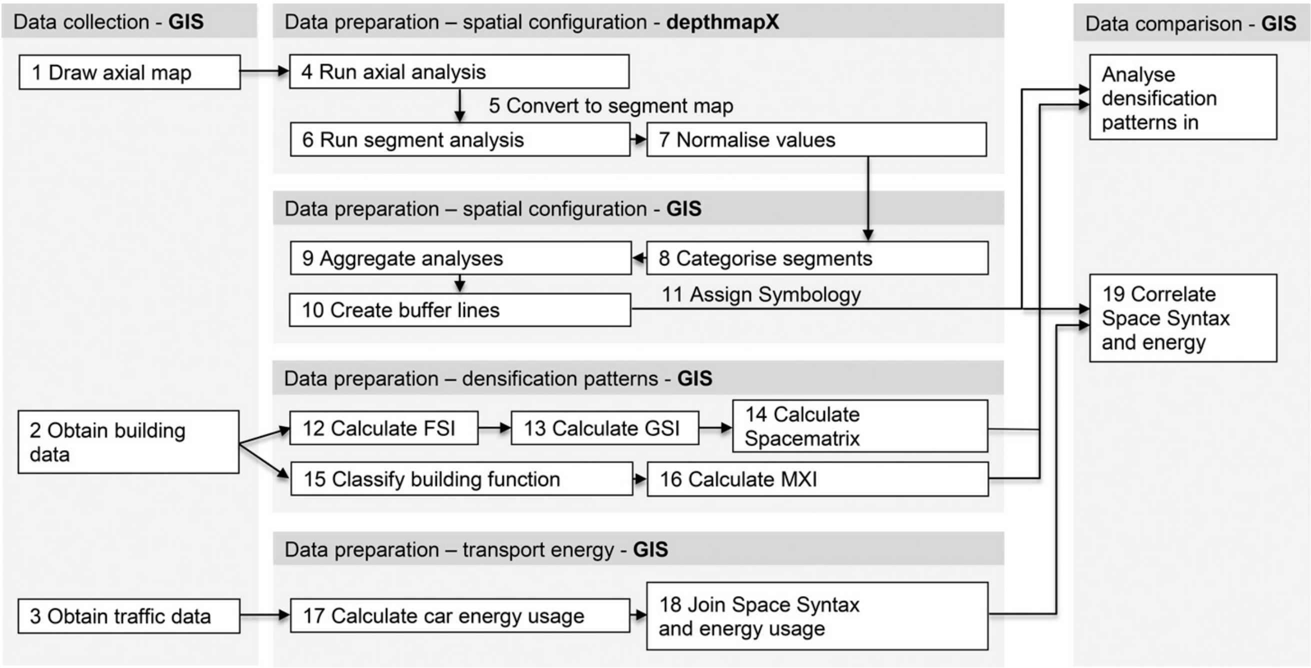

Fig. 2.. Schematic diagram of the workflow.

2.1.1. Steps 1 – 3

1. **Drawing axial maps**; a new shapefile was created in ArcMap and drawing straight lines by hand over an existing georeferenced map. Each line segment follows the Space Syntax [11] rules of thumb. Each line indicates the longest lines of sight, using the fewest lines possible to cover and connect all convex accessible spaces in the urban system between the physical objects making all direct line-to-line connections (i.e. each line must intersect and/or overlap another line). When lines intersect, one line of movement ends, and another continues. There are no continuous corners drawn. In the event of overlapping or 'unlinks' such as a viaduct, underpass or tunnel, a separate shapefile is created to mark points the overlap occurs. Where a viaduct crosses over another road, this is shown as two separate and non-intersecting lines. The amount of lines intersecting on each line affects its relational value to the entire network of lines, and hence the value of the metrics returned with the depthmapX analysis. Both files are exported as DXF file format and analysed with depthmapX before being exported back to ArcMap.
2. **Obtaining building data**; these are georeferenced spatial data as shapefiles from the local authorities (Bergen Kommune) and, in the case of Zürich from OSM. The municipality stores detailed metadata such as functional use, number of floors, number of housing units, and information on the year of construction, heritage status and others for each building. Where information was incomplete, manual checking via Google Maps was done. Plot data for building density is contained in a separate shapefile.
3. **Obtaining traffic data**, the objects in the shapefiles are road centre lines representing the geometry of the streets and roads retrieved from online sources (OSM). For the case of Bergen, measured traffic data and information about the maximum traffic speed was obtained as attribute data from the Norwegian Public Road Administration (SVV). For the case of Zürich, a calibrated traffic model created by the Institute for Transport Planning and Systems at ETH Zürich was used [10].

2.2. Data Preparation

Due to the different platforms for analysis and the different expected outcomes (densification patterns or transport energy usage), a series of data preparation steps are required that differ in calculations or aggregation. Step 4–11 performed in depthmapX prepare axial maps for analysis to obtain spatial configurations. Building data is prepared in Steps 12–16 to understand densification patterns. In Steps 17,18, transport energy usage is calculated, and the values to be compared are joined. Steps 8–18 are done in ESRI® ArcMap. Steps 15, 16 and 18 have been automated. See the next section for details.

2.2.1. Steps 4 – 7: Depthmapx Operations for Spatial Configuration

Within the depthmapX interface, after importing the axial map in DXF format created in ArcMap, the graph analysis menu is used to run axial analysis. Input for the menu includes a radius of n to obtain results for global integration analysis (from all lines to all others, see [11], p. 48,49 for an explanation of the calculation of global integration) and a radius of value 3 to get the local integration analysis. These analyses must be done before converting the map to a segment map.

Segment maps are generated using the function of 'convert active map'. depthmapX will split up all axial lines into separate segments where they cross each other. Next, the function of 'Run angular segment analysis' opens a dialog window where 'Metric' is chosen as radius type. For the neighbourhood and citywide scales, 500 and 5000 metres radii are entered, respectively. The base unit of the georeferenced map on ArcMap is in meters. Hence, the values are entered without unit conversion. Next, values from the previous steps are normalised to obtain NACH500 and NACH5000 (for Normalised Angular CHoice) and NAIN500 and NAIN5000 (for Normalised Angular INtegration) with the following formulae. These values are joined to the segment map file as four new attributes. The normalised values are obtained by populating these attribute columns with a normalisation formula. The calculated values for Angular Choice were normalised using the following formula for each radius [12]:

$$\mathrm{NACH} = \frac{\log(\mathrm{Choice}\ (\mathrm{r}) + 1)}{\log(\mathrm{Total\ depth}\ (\mathrm{r}) + 3)}$$

The non-normalised values are auto-generated in depthmapX under the following fields' T1024 Total Depth', 'T1024 Node Count' and 'T1024 Choice'.

Following this, the following formula is entered into the “Replace values” interface for both radii:

```
log(value("T1024 Choice R500/R5000 metric")+1)/log(value("T1024 Total Depth R500/R5000 metric")+3)
```

The values for NACH500 range from 1.079171 to 5.59329 for Bergen and from 1.0413927 to 5.5103316 for Zürich. For NACH5000, values range from 1.079171 and 8.116694 for Bergen and from 1.0413927 to 8.3752794 for Zürich.

For integration, normalisation values are obtained from [11]:

$$\mathrm{NAIN} = \frac{\sqrt[1.2]{\mathrm{Node\ count}\ (\mathrm{r})}}{\mathrm{Total\ depth}\ (\mathrm{r}){+}2}$$

The following formula is entered into the “Replace values” interface for both radii:

```
(value("T1024 Node Count R500/R5000 metric)^(1.2)/(value("T1024 Total Depth R500/R5000 metric")+2)
```

The values for NACH500 range from 0.754693 to 2.848512 for Bergen and from 1.0430746 to 2.8643966 for Zürich. For NACH5000, values range from 2.474288 and 3.672265 for Bergen and from 3.0674546 to 3.9541197 for Zürich.

To export the values above to a GIS-compatible format, it is saved as a MIF file which maintains its georeferencing. The axial and segment maps are exported as separate MIF files and then converted to the ESRI® Shapefile format (SHP) using QGIS or ArcGIS.

2.2.2. Steps 8 – 11: ArcMap Operations for Spatial Configurations

Resulting values from steps 4 – 7 are categorised into low (value of 1), medium (value of 2) and high (value of 3) values for each attribute following the 'natural break' method [13,14] via

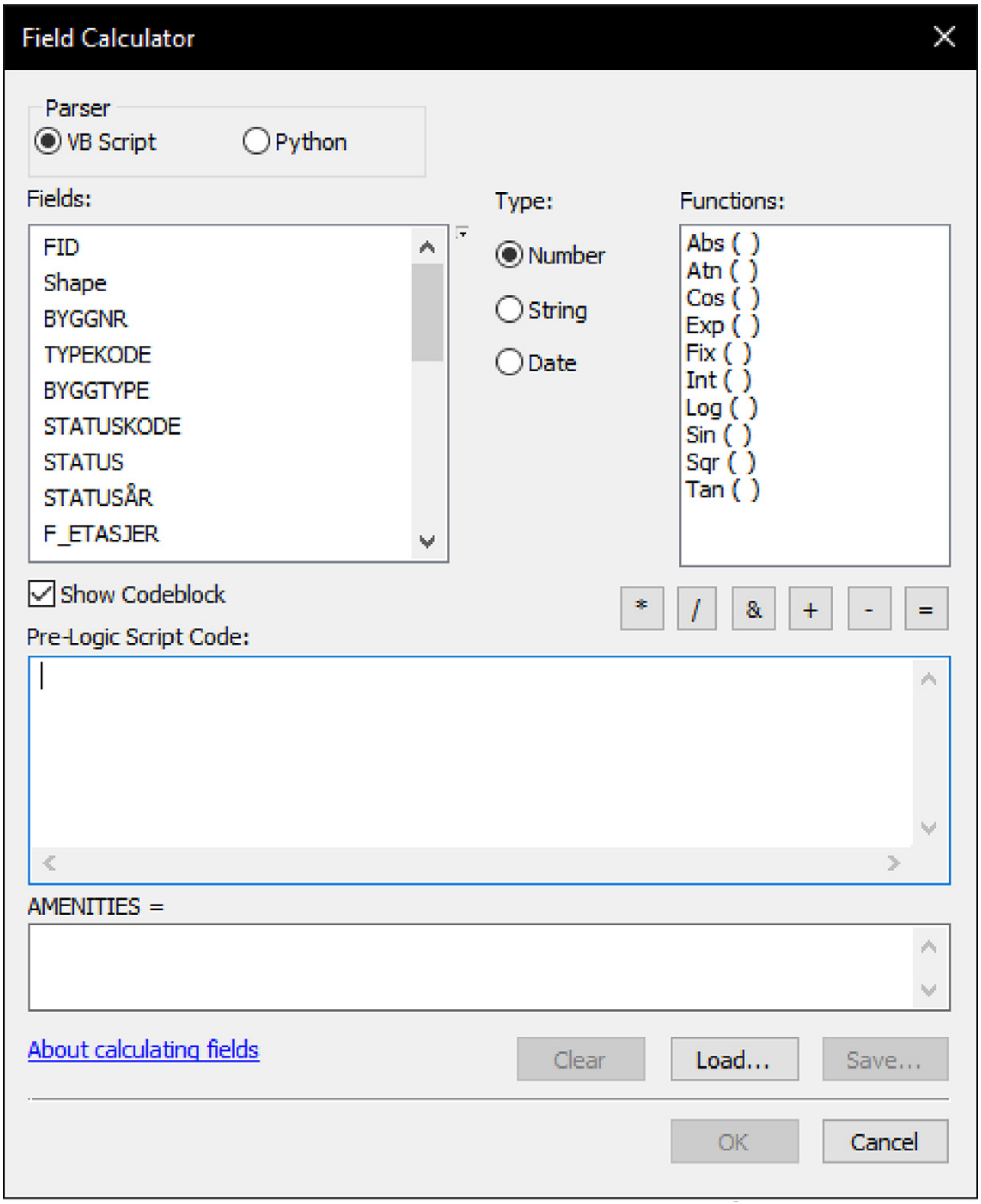

Fig. 3.. Field Calculator GUI in ESRI® ArcMap.

the Symbology menu. These values are contained in the attribute tables of the relevant shapefiles.

The values are categorised using the Visual Basic script in Field Calculator in ArcMap. This tool calculates the values of a field for a feature class [15] (see Fig. 3). This can be an arithmetic formula or more advanced Visual Basic or Python scripts, which can be entered in the "Codeblock". VB Script is used for consistency and in relation to the relatively simple operations required. The attribute field(s) to be queried can be selected on the left. The data type is assigned in the middle, and on the right, different mathematical functions can be added. Field Calculator uses (conditional) if-statements in the Codeblock input field under the Pre-logic script code window.

The calculations are assigned to a new categorised attribute (randomly named 'a' in this article). The script used is:

Table 2
Aggregating low radius and high radius.

		Angular choice with low radius (R = 500 m)		
		Low	Medium	High
Angular choice with high radius (R = 5 000 m)	Low	LL	LM	LH
	Medium	ML	MM	MH
	High	HL	HM	HH

```
[CATEGORISED_ATTRIBUTE_NAME] = a
dim a
if [UNCATEGORISED_ATTRIBUTE_NAME] <
"(threshold low-medium)" then
a = "1"
elseif [UNCATEGORISED_ATTRIBUTE_NAME] >
"(threshold medium-high)" then
a = "3"
else a = "2"
end if
```

Here, 'UNCATEGORISED_ATTRIBUTE_NAME' is the name of the attribute containing the uncategorised normalised choice and integration values: 'NACH500′, 'NACH5000′, 'NAIN500′, and 'NAIN5000′. 'CATEGORISED_ATTRIBUTE_NAME' is the new attribute fields containing the resultant categorised values' C_500′, 'C_5000′, 'I_500′, and 'I_5000′. The threshold low-medium and medium-high are the numerical thresholds between low and medium and medium and high values for each of the four Space Syntax measures, calculated based on the statistical distribution of natural breaks. The threshold values will be different for each study case since it depends on the relational values of each segment to the street network under investigation.

To better analyse normalised values related to other variables, a matrix combining high and low choice values needs to be produced. This is done by aggregating the categorised low scale and the high scale values with another Visual Basic script to populate an attribute field 'CAGGR' with values based on 'NACH500′ and 'NACH5000′.

For angular choice, the categorised low scale attribute is named 'C_500′, and the categorised high scale attribute is named 'C_5000′. The script returns a two-letter string indicating a low (L), medium (M) or high (H) value for citywide scale and neighbourhood scale, respectively (see Table 2).

The script for Aggregated Angular Choice is:

```
[CAGGR] = a
Pre-logic script code:
  dim a
  if [C_5000] = 3 and [C_500] = 3 then
  a = "HH"
  elseif [C_5000] = 3 and [C_500] = 2 then
  a = "HM"
  elseif [C_5000] = 3 and [C_500] = 1 then
  a = "HL"
  elseif [C_5000] = 2 and [C_500] = 3 then
  a = "MH"
  elseif [C_5000] = 2 and [C_500] = 2 then
  a = "MM"
  elseif [C_5000] = 2 and [C_500] = 1 then
  a = "ML"
  elseif [C_5000] = 1 and [C_500] = 3 then
  a = "LH"
  elseif [C_5000] = 1 and [C_500] = 2 then
  a = "LM"
  elseif [C_5000] = 1 and [C_500] = 1 then
  a = "LL"
  end if
```

Next, each segment line receives a buffer. This is done through the Buffer Tool in ArcMap to a radius of 35m and with a round bevel. Each buffer is merged with identical categorised aggregated choice values from the previous step. The Clip Tool is then used to remove the overlap of the buffers of various categories. To visualise the outputs, an optional step is introduced to create a map in the workflow (see Fig. 2, Step 11). The Symbology menu determines the choice of colour, line density, and iconography to customise which attributes are visualised and how. Desired settings can be saved to a separate file (called layer file, in LYR format) for repeating across cases.

2.2.3. Steps 12 – 16: Densification Patterns at the Building Level

These steps result in values of floor space index (FSI) and ground space index (GSI), which provides insights into building density values using the Spacematrix method [16]. First, the plot data (specifically the attribute column containing area size) is joined to the building data through the Spatial Join tool. This adds an attribute field in the building shapefile that contains the plot area size. Next, a new attribute column 'FSI' is added and populated using the following formula:

$$\text{Floor Space Index (FSI)} = \frac{\text{floor space area}}{\text{area of the plot}}$$

where floor space area is the total building's floor space (all floors) is divided by the total area of the plot. This is achieved in the Field Calculator by entering the formula above.

Next, GSI can be derived from the geometry of the plot and the building by the following formula:

$$\text{Ground Space Index (GSI)} = \frac{\text{ground space area}}{\text{area of the plot}}$$

Where ground space area is the attribute column containing the building footprint. This yields values ranging between 0 (unbuilt) and 1 (fully built).

A basic script is made in the Field calculator to classify buildings from (A) to (I) in a new attribute field called 'SPACEMATR'. The classification is based on GSI values where 0.15 and 0.25 [7] were taken as thresholds and the number of floors:

```
[SPACEMATR] = a
Pre-logic script code:
  dim a
if [GSI] < 0.15 and [F_ETASJER] < 3 then
a = "A"
elseif [GSI] < 0.15 and 3 <= [F_ETASJER] < 7 then
a = "D"
elseif [GSI] < 0.15 and [F_ETASJER] >= 7 then
a = "G"
elseif [GSI] >= 0.25 and [F_ETASJER] < 3 then
a = "C"
elseif [GSI] >= 0.25 and 3 <= [F_ETASJER] < 7 then
a = "F"
elseif [GSI] >= 0.25 and [F_ETASJER] >= 7 then
a = "I"
elseif 0.15 <= [GSI] < 0.25 and [F_ETASJER] < 3 then
a = "B"
elseif 0.15 <= [GSI] < 0.25 and 3 <= [F_ETASJER] < 7 then
a = "E"
elseif 0.15 <= [GSI] < 0.25 and [F_ETASJER] >= 7 then
a = "H"
else a = "X"
end if
```

Building functions are related to densification patterns. This is classified in Table 1 as the attributes amenities, offices and housing. Here, three Field Calculator scripts are executed for each attribute to convert the values to their corresponding MXI categorisation. Unfortunately, each

Table 3
Letter codes for Mixed-Use Index categorisation.

Letter code	Functionality
A	Mono-functional, amenities
O	Mono-functional, offices
H	Mono-functional, housing
HA	Bi-functional, housing and amenities
HO	Bi-functional, housing and offices
AO	Bi-functional, amenities and offices
TH	Triple-functional, predominantly housing
TA	Triple-functional, predominantly amenities
TO	Triple-functional, predominantly offices

building may contain only one function code. For example, in a high rise building with multiple units, the code attached may indicate offices, but if the polygon feature has values in the other attributes of 'F_BOENHETE', which lists the number of housing units in each building, then that object will be listed as a bi-functional building. The following scripts will be determined using the attribute 'F_ETASJER', the number of floors, the ratio of 'Amenities' vs 'Housing' vs 'Office'.

For 'AMENITIES', the script is:

```
[AMENITIES] = a
Pre-logic script code:
  dim a
if ((([TYPEKODE] > "200") and ([TYPEKODE] < "300") and ([F_BOENHETE] = "0")) or
(([TYPEKODE] > "320") and ([F_BOENHETE] = "0"))) then
a = [F_ETASJER]
elseif ((([TYPEKODE] > "200") and ([TYPEKODE] < "300") and ([F_BOENHETE] > "0")) or
(([TYPEKODE] > "320") and ([F_BOENHETE] > "0"))) then
a = "1"
else a = "0"
end if
```

For [OFFICES], the script is:

```
  [OFFICES] = o
Pre-logic script code:
  dim o
if ((([TYPEKODE] < "320") and ([TYPEKODE] > "300" and ([F_BOENHETE] = "0"))) then
o = [F_ETASJER]
elseif (([TYPEKODE] < "320") and ([TYPEKODE] > "300") and ([F_BOENHETE] > "0")) then
o = "1"
else o = "0"
end if
```

For [HOUSING], the script is:

```
[HOUSING] = h
Pre-logic script code:
  dim h
if [TYPEKODE] < "200" and [F_BOENHETE] > "0" then
h = [F_ETASJER]
elseif [TYPEKODE] > "200" and [F_BOENHETE] > "0" then
h = ([F_ETASJER] - ([AMENITIES] + [OFFICES]))
else h = "0"
end if
```

The mix and diversity of building functions are calculated by looking at the ratio between 'AMENITIES', 'OFFICES', and 'HOUSING', resulting in the Mixed-Used Index' MXI' based on the method, see [8,9]. Each value MXI is categorised with a combination of letter codes (see Table 3) according to thresholds established in previous research [7], p. 78.

[MXI] is calculated by the following script:

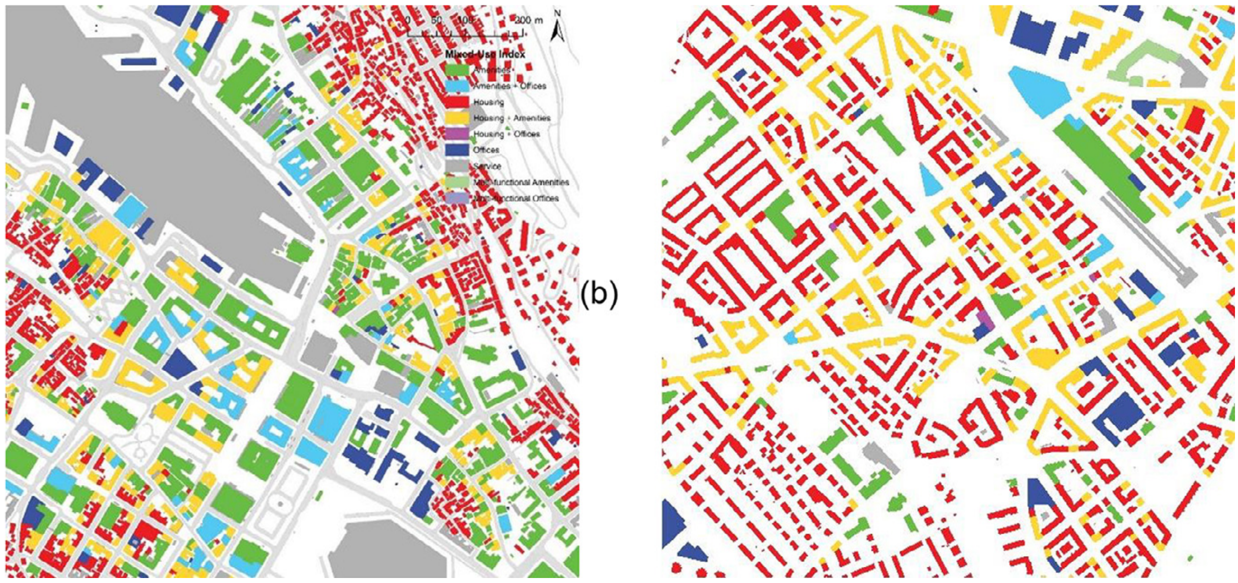

Fig. 4.. 1 × 1 km excerpts of the Mixed-Use Index (MXI) map for Bergen (left) and Zürich (right).

```
[MXI] = m
Pre-logic script code:
  dim m
if [HOUSING] < 0.2 and [HOUSING] > 0.05 and [AMENITIES] > 0.05 and [OFFICES] > 0.05
then
m = "TH"
elseif [AMENITIES] < 0.2 and [AMENITIES] > 0.05 and [HOUSING] > 0.05 and [OFFICES] >
0.05 then
m = "TA"
elseif [OFFICES] < 0.2 and [OFFICES] > 0.05 and [HOUSING] > 0.05 and [AMENITIES] > 0.05
then
m = "TO"
elseif [HOUSING] > 0.05 and [AMENITIES] > 0.05 and [OFFICES] < 0.05 then
m = "HA"
elseif [HOUSING] > 0.05 and [OFFICES] > 0.05 and [AMENITIES] < 0.05 then
m = "HO"
elseif [AMENITIES] > 0.05 and [OFFICES] > 0.05 and [HOUSING] < 0.05 then
m = "AO"
elseif [HOUSING] > 0.95 and [AMENITIES] < 0.05 and [OFFICES] < 0.05 then
m = "H"
elseif [AMENITIES] > 0.95 and [OFFICES] < 0.05 and [HOUSING] < 0.05 then
m = "A"
elseif [AMENITIES] < 0.05 and [OFFICES] > 0.95 and [HOUSING] < 0.05 then
m = "O"
else m = "S"
end if
```

Fig. 4 below shows an example of the MXI results for Bergen and Zürich.

The above steps are sufficient to generate insights into densification patterns concerning urban structures and forms. Preliminary results from the data show that energy usage in cities correlates with its spatial configuration. The denser and more compact the city, the more concentrated and efficient the expected energy usage. Compact cities, where highly integrated transportation networks connect local centres with high building and function densities, are more energy-efficient and sustainable [1,4].

2.3.4. Steps 17 – 18: Transport Energy Usage

Transport energy usage is calculated from traffic speed, traffic volume and average energy consumption from cars. This step uses the Road Centre Line (RCL) as the object combining road geometry and traffic data. The total energy usage of car traffic on each road segment is represented as kWh per day. The calculation is based on the attribute fields containing the maximum allowed traffic speed and the total number of cars travelling daily across a segment expressed as the Annual Average Daily Traffic (AADT).

The calculation is derived from [5]:

$$\text{Etot} = (\text{number of cars per day}) \cdot (2.08 \cdot (\text{traffic speed})3 + 400 \cdot (\text{traffic speed}))$$

A new attribute field [KWH] is populated using the following expression in Field Calculator:

```
[KWH] = (2.08 * [freespeed] * [freespeed] * [freespeed] + 400 * [freespeed]) * [carvolume])
```

Next, the processed Space Syntax data (Steps 4 – 7) are joined to the energy usage results contained on the RCL features (Step 17) through a one-to-one Spatial Join. This is based on proximity, whereby the nearest/closest line segment will inherit the normalised values. This step is required to run a correlation analysis for data comparison. The RCL feature class inherits all data joined in its attribute table when the Spatial Join tool is executed. This attribute is then exported as a table (e.g. CSV or DBF format) for statistical correlation.

One of the goals of the workflow described is to verify whether the urban structure and form influence transport energy usage. For example, historic city centres tend to have highly integrated spatial structures (this can be quantified by betweenness and closeness) and are highly suitable for walking and cycling [1,7]. This relationship is verified via correlating spatial configuration data (from depthmapX) using the Space Syntax methods [2,3,17]. The data is compared statistically with the values generated in Step 17 using a bivariate correlation, Pearson correlation coefficients and two-tailed test significance in SPSS (see for results [1], Table 4).

2.4. Workflow Automation

The above steps for data collection and data preparation are then automated. This ensures an efficient repetition of the necessary input processes, cross-platform data translation, data aggregation, and combination calculations for analysis. This partial automation is done by designing data operations specified through a Visual Programming Language (VPL) [18] via the ModelBuilder™ in ESRI® ArcGIS. The workflow shared can support fellow researchers and planning professionals in adopting the proposed method for analysing urban form and structure. Making the steps of the workflow explicit can also support the decision-making processes of policymakers. This can increase understanding of how cities function and develop them more sustainably.

The models designed and tested are provided as an ArcGIS Toolbox file, which is a container for the various tools and steps of operations within ArcGIS (see Data preparation section, Steps 8 – 19). The Toolbox file allows for the automation (or parts of) the scientific workflow that requires a repetition of tasks and/or standardisation of analytical procedures. Users do not need to specify additional steps or perform any geocomputational tasks manually. The end-user is presented with a Graphical User Interface (GUI) (see Fig. 5). Relevant input parameters and variables can be selected from a drop-down menu in this interface. When exported and made usable for other researchers who might have limited resources or computing capacities, it reduces potential complications or human error when inputting multiple datasets and increases the internal validity of the research.

The file [REK_Urban_Analysis_Toolbox.tbx] consists of standard, pre-programmed operations combined by the authors into complex models. Within the ModelBuilder environment, a model is comprised of four elements, (i) geoprocessing tools and (ii) variables linked by (iii) connectors to indicate the direction of processing and can be combined as (iv) groups as required. For the data presented, these elements are used (see Figs. 6 and 7);

- Tools to run specific tasks include adding a buffer or calculating values shown as rounded rectangles. Special tools, including Iterators, are used here to repeat or loop the operations within a model and are shown as a hexagonal node.

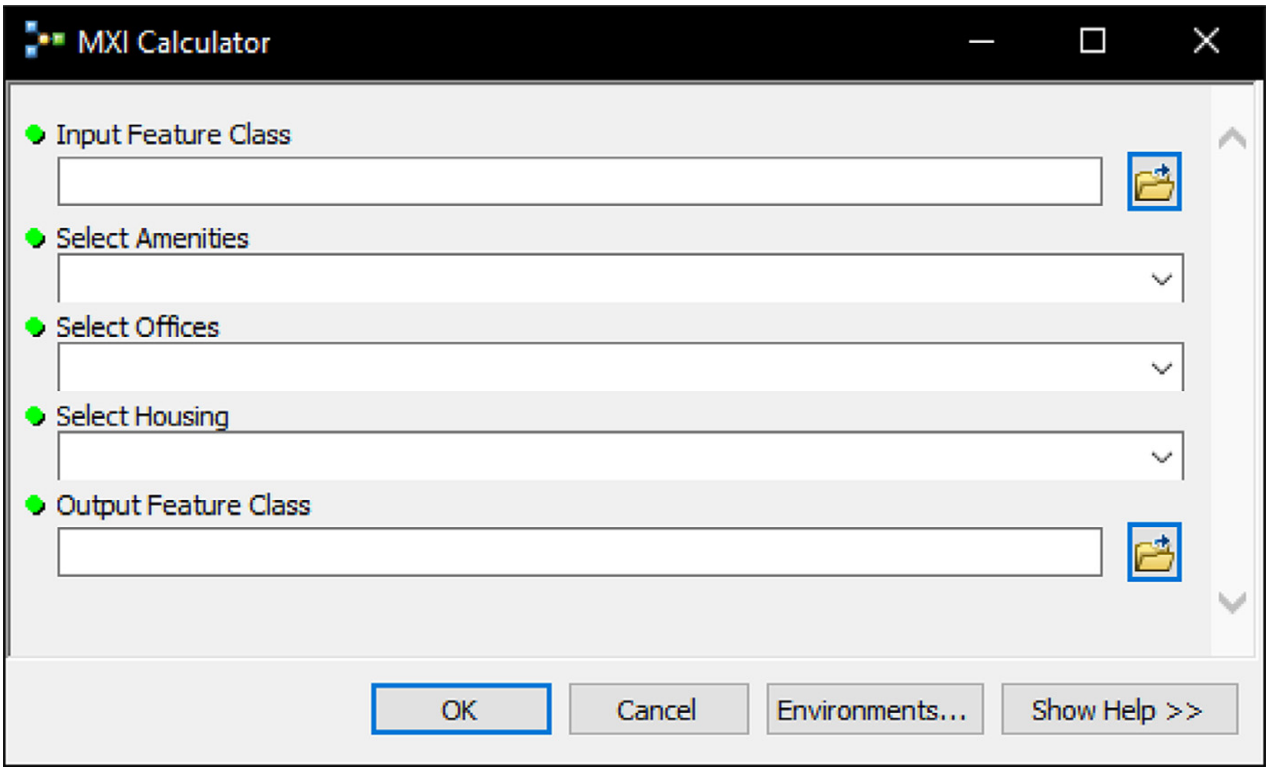

Fig. 5.. Graphical User interface of the Mixed-Use Index Calculator.

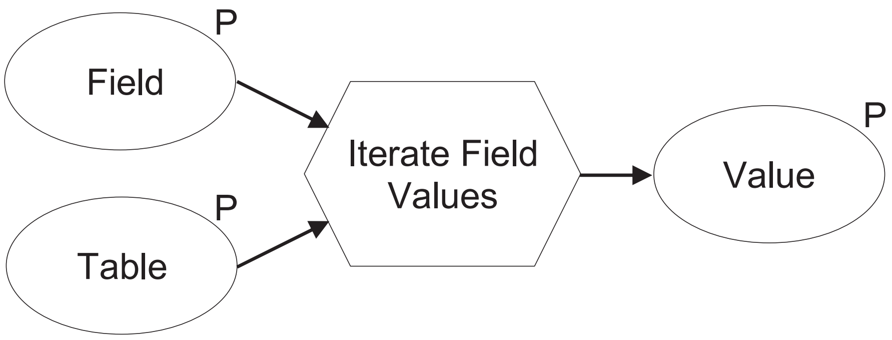

Fig. 6.. Iterator model.

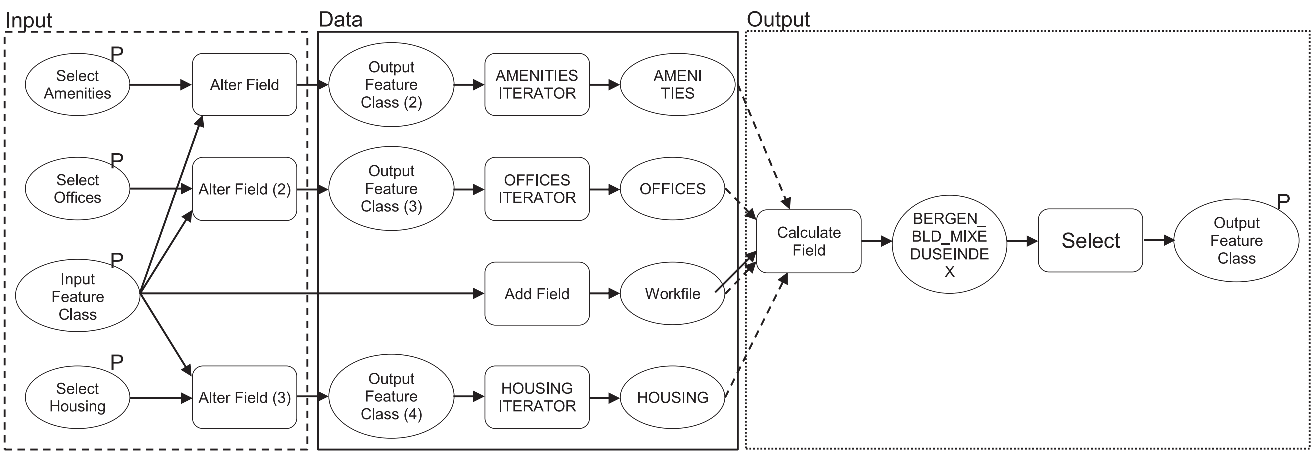

Fig. 7.. Mixed-Use Index Calculator model.

- Variables for inserting input or (derived) output such as shapefiles or data shown as oval nodes and indicated with parameter or P when editable. Output parameters allow users to indicate their desired file name and location for saving. Variables are also shown as dependencies, temporary files after each task before being linked to another operational step.

- Connectors link variables to tools depending on the required process as uni-directional arrows. They indicate how the model should flow. These can be linked and unlinked as required.
- Groups show a combination of the above elements that are collapsible when needed to represent a simplified model.

Next, two custom models, the iterator and the MXI calculator models, are described. The first is a custom model built to facilitate data preparation, and the latter allows for outputs to calculate the distribution of land uses needed for Step 16.

Iterator Model

Each model may contain only one iterator node (see Fig. 6). However, some models require more than one instance of an iterator to perform the desired tasks. For example, the following model can be saved as a custom tool and inserted within a composite model. For the data presented, the iterator model is required to convert data for urban form (i.e., numerical code data for the categories of functions such as amenities, offices and housing) according to building density data (i.e., the ratio of floor space for a specific function to total floor space) to allocate the required letter code categories to indicate the mix of functions via the Mixed-Use Index method (see Table 3).

For example, the input Field would be the calculation of the ratio of floor space for offices, and the input Table would be a selection of codes belonging to buildings with office functions. The iterator tool will be asked to calculate how much of a particular building would belong as offices and cycle it again through all building features in the file until each feature is assigned a corresponding value. Grouping the input, output and iterator together allow it to be saved as a reusable iterator model (rounded rectangle) for building a more complex composite model with only minimal changes to input and output parameters. This is used in the data presented for all three functions within the mixed-use index model (see Fig. 7).

Mixed-Use Index Calculator

A key contribution to data preparation (Steps 12 – 16) requires identifying types of functions within each building and coded based on the ratio of floor space per function to total floor space per building. The calculation is complex and requires a composite model, i.e., the custom Mixed-Use Index (MXI) Calculator model created by the authors (see Fig. 7). The left part (in the dashed rectangle) of the model is where the input parameters are specified. The middle part (in the solid rectangle) prepares the data. Finally, the right part (in the dotted rectangle) calculates MXI and generates the output. The model consists of nine tools, four input variables, eight interim output variables, and a final output variable that indicates the MXI data as strings, i.e. letters or text (see Table 3) assigned to each feature within the urban form dataset. In addition, three custom iterator models (built as stated above) – the amenities, offices and housing iterators – enable the MXI Calculator to generate output for connecting urban form and building density data to understand densification patterns automates four steps (Steps 12 – 16) to be repeated per case in a single step.

Ethics Statements

The above works do not contain information from human subjects, animal experiments or data collected from social media platforms.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

HVL_PhD (Original data) (github).

CRediT Author Statement

Remco Elric de Koning: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Writing – review & editing, Visualization; **Rogardt Heldal:** Writing – review & editing, Supervision; **Wendy Tan:** Writing – review & editing, Supervision.

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