Modeling future population's vulnerability to heat waves in Greater Hamburg

Dissertation with the aim of achieving a doctoral degree
at the Faculty of Mathematics, Informatics and Natural Sciences
Department of Earth Sciences
Institute of Geography
University of Hamburg
Germany

Submitted by
Giedrius Kaveckis
Hamburg, 2017

Day of oral defense: 22 of June, 2017

The following evaluators recommend the admission of the dissertation:

Prof. Dr. Jürgen Oßenbrügge
Dr. Benjamin Bechtel

Declaration of Oath

I hereby declare, on oath, that I have written the present dissertation by my own hand and have not used any other than the acknowledged resources and aids.

Place and date	Signature
Hamburg, 2017	Giedrius Kaveckis

Abstract

Heat waves are responsible for most of the human losses, inflicted by natural disasters, in post-industrial countries. Due to rising temperatures, aging population and increasing urbanization, the heat-related mortality in the future might be even higher. In order to lower future population's vulnerability to heat waves, the decision makers need to know where the highest heat impact will occur and the heat-vulnerable people will live. Unfortunately, current future vulnerability to climate change assessments does not fully address the future population and urban landscape. This study takes an innovative approach to model future conditions (2050) in Greater Hamburg, Germany, via the proxy parameter, the Urban Vulnerability Climate Zones (UVCZ).

UVCZ is a spatial classification of the urban areas by landscape, climate and, based on verified hypothesis – population. The hypothesis has been verified through statistical analysis which showed uneven distribution of population groups with different age, income and density among the potential housing UVCZ classes. This enabled to model future conditions, through four future UVCZ spatial allocations, simulated by cellular automata-based future land use modeling software under one climate (MPI RCP 4.5), one socio-economic and four urban development (business as usual, concentration, de-central concentration and uncontrolled urban sprawl) scenarios. Future conditions were composed into relative and absolute vulnerability indices. Although the low projected population increase would cause limited effect on extreme urban development scenarios, the concentration scenario would be the most favorable in case of lowest average relative vulnerability while the lowest absolute vulnerability would be typical for the business as usual scenario.

In most of the cases, the eastern areas of Hamburg City would experience the highest relative vulnerability, mainly due to higher concentration of older population and welfare recipients. Along the outskirts of Greater Hamburg, the eastern and southern areas would also be vulnerable, because of higher monthly average minimum, maximum temperatures and the long distance to the closest healthcare facility. The sensitivity analysis has shown that climate data from other global climate model would cause 225% higher average vulnerability, meanwhile the increase of older population by 0,5 of standard deviation would cause higher average vulnerability by only 18%. Although the modeling of future vulnerability has high uncertainty, this new approach to model future conditions, operated by cellular automata, opens new doors for decision makers to pilot multiple scenarios at the building block scale. The provided framework can be used in other urban areas around the world.

Zusammenfassung

Hitzewellen sind für die meisten durch Naturkatastrophen hervorgerufenen Personenschäden in den westlichen (Post-)Industriegesellschaften verantwortlich. Infolge der zu erwartenden Klimaerwärmung, aber auch aufgrund der alternden Gesellschaft sowie der zunehmenden Urbanisierung, ist davon auszugehen dass die auf Hitzestress zurückzuführende Mortalität in Zukunft noch weiter ansteigen wird. Um die zukünftige Vulnerabilität der Bevölkerung gegenüber Hitzewellen zu senken, sind für Entscheidungsträger in Planung und Politik Erkenntnisse über die räumliche Verteilung von Hitzeeinwirkung und die besonders hitzeanfällige Bevölkerung von hoher Bedeutung. Bedauerlicher Weise wird die zukünftige Bevölkerungsverteilung und die Stadtlandschaft bei den aktuell verfügbaren Abschätzungen des Klimawandels noch nicht hinreichend berücksichtigt. Mit der vorliegenden Studie wird ein innovativer Ansatz verfolgt, die zukünftige Situation in der Metropolregion Hamburg (2050) auf Grundlage des Proxy-Parameters der „Urban Vulnerability Climate Zones" (UVCZ) zu modellieren.

Beim UVCZ-Ansatz handelt es sich um eine räumliche Klassifikation städtischer Areale auf der Grundlage der Differenzierung von Landschaft, Lokalklima sowie der Prognose zukünftiger Wohnbevölkerung. Die zugrunde liegenden Annahmen über die zukünftige Wohnbevölkerung wurden auf Basis der gegenwärtigen räumlich ungleichen Verteilung von Bevölkerungsgruppen verschiedenen Alters, Einkommen und Wohndichten in den verschiedenen UVCZ-Klassen getroffen und getestet. Hierdurch eröffnet sich die Möglichkeit, die zukünftige Stadtstruktur bzw. urbane Landnutzung auf Grundlage eines auf zellulären Automaten basierenden Verfahrens zu simulieren, wobei von einem zukünftigen Klimaszenario (MPI RCP 4.5), einer stabilen sozio-ökonomischen Weiterentwicklung sowie vier unterschiedlichen räumlichen Entwicklungsszenarien ausgegangen wurde (a) Weiter so wie bisher, b) Konzentration der Stadtentwicklung auf eine starke Innenentwicklung, c) Dezentrale Konzentration auf suburbane Zentren im Umland sowie d) Unkontrollierte Suburbanisierung). Dabei wurden sowohl absolute, als auch relative Vulnerabilitätsprognosen auf Basis eines Indexverfahrens angestellt. Obgleich eine Bevölkerungszunahme auch eine Folgewirkung für die modellierten Stadtentwicklungsszenarien erkennen lässt, ist eine räumliche Konzentration der zukünftigen Stadtentwicklung auf eine starke Innenentwicklung die vorteilhafteste Strategie, wenn die relative Vulnerabilität der Bevölkerung möglichst auf einem niedrigen Niveau bleiben soll. Die moderateste Zunahme an absoluter Vulnerabilität ergibt sich mit dem „Weiter so wie bisher"-Stadtentwicklungsszenario.

Unabhängig vom betrachteten Stadtentwicklungsszenario werden die höchsten Vulnerabilitäts-Werte mit hoher Wahrscheinlichkeit in den östlichen Teile der Kernstadt Hamburg auftreten, vor allem aufgrund des dort höherer Konzentration des Alters der Wohnbevölkerung sowie der dortigen Sozialstruktur der Bewohnerschaft. In den Außenbezirken der Metropolregion Hamburg ist eine Zunahme der Vulnerabilität vor allem in den östlichen und südlichen Arealen zu erwarten – insbesondere aufgrund der höheren durchschnittlichen Temperaturminima, den Maximaltemperaturen sowie der weniger flächendeckend ausgebauten Gesundheitsinfrastruktur. Weitergehende Analysen zeigen, dass basierend auf extremen Annahmen der zukünftigen globalen Klimaentwicklung bis zu 225% erhöhte Vulnerabilitäten erzeugen würden, während die Zunahme der älteren Bevölkerung um eine halbe Standardabweichung eine Zunahme der durchschnittlichen Vulnerabilität um nur 18% bewirkt. Obgleich die Modellierung der zukünftigen Vulnerabilität mit einer hohen Unsicherheit behaftet ist, eröffnet der in dieser Arbeit entwickelte Ansatz zur Modellierung zukünftiger Zustände mithilfe zellulärer Automaten neue Möglichkeiten für Entscheidungsträger, verschiedene Entwicklungsszenarien auf kleinräumiger Ebene zu

simulieren. Das vorgestellte Vorgehen kann auf andere urbane Regionen weltweit übertragen werden.

I dedicate this thesis to

my family: my wife, Kristina, and my daughter, Salomėja,

for their constant support and unconditional love.

I love you dearly.

Acknowledgements

There are a number of people without whom this thesis might not have been written, and to whom I am very thankful.

First of all, thanks to my new family - my wife, Kristina, and our newborn, Salomėja. Although my relationship with this thesis is longer, I love you much more. Thanks for the understanding, that instead of changing the diapers late in the evening, I was reading chapter 4 22^{nd} time in a row. I am very thankful for your support, patience and love.

Many thanks to my professor, Jürgen Ossenbrügge, who guided me through the jungle of PhD, explained not funny German jokes and helped me to discover secrets of Shanghai. Also I am very grateful to my co-supervisor Benjamin Bechtel, who supported me with advanced knowledge of physical geography, insisted against my exaggerated use definite articles, and delivered good critics which helped to improve a quality of the whole study.

Thanks to my colleagues: Thomas Pohl, who makes very delicious cakes; Klaus Carstens, with whom I could talk about everything, Thomas Böge, Malte, Myriam and many others. Also big thanks to my ex-colleague, Christian Daneke. He developed a good foundation of this study and guided me in the early start of my PhD. Thanks to my friends, Jan, Joseph and others, who reminded me good student times. I am very grateful to Berit and Ingo, the chairs of the SICSS School. Also I would like to thank to the chair of my scientific panel – Jörn Behrens.

Many thanks to my friend and English proofreader Grace Colette. Your support will help more people to understand this study.

Also big thanks to my relatives and other friends, in Lithuania and other distant countries. I apologize, that due to this study I could not find enough time for you.

And the last, I want to thank to the Cluster of Excellence (CliSAP, EXC177) which was funded by German Science Foundation (DFG). A financial support is a great help to the young scientists, who are searching for their pathways in this complex scientific world.

Table of contents

List of figures

List of tables

List of abbreviations

AC	Adaptive Capacity
AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
BaU	Business as Usual
CA	Cellular Automata
CBD	Central Business District
CMIP5	Coupled Model Intercomparison Project Phase 5
CORINE	Coordination of Information on the Environment
CRED	Centre for Research on the Epidemiology of Disasters
EEA	European Environmental Agency
ETC/ACC	European Topic Centre on Air and Climate Change
ETC/CCA	European Topic Centre on Climate Change impacts, vulnerability and Adaptation
EU	European Union
GDP	Gross Domestic Product
GH	Greater Hamburg
GIS	Geographical Information Systems
GIZ	Deutsche Gesellschaft für Internationale Zussamenarbeit
GCM	Global Climate Models
IPCC	Intergovernmental Panel for Climate Change
IR	Initial Rules
LCZ	Local Climate Zones
MCK	Map Comparison Kit
MMT	Minimum Mortality Temperature
MOLAND	Monitoring Land Use / Cover Dynamics
MPI-ESM	Max Planck Institute Earth System Model
PET	Physiological Equivalent Temperature
PI	Potential Impact
PVM	Predicted Mean Vote
RCP	Representative Concentration Pathways
RIKS	Research Institute for Knowledge Systems
SD	Standard Deviation
SSP	Shared Socio-economic Pathways
SRES	Special Report on Emissions Scenarios
TAR	Third Assessment report
UBL	Urban Boundary Layer
UCL	Urban Canopy Layer
UHI	Urban Heat Island
UN	United Nations
UNDESA	United Nations Department of Economic and Social Affairs
UVCZ	Urban Vulnerability Climate Zones
WCDR	World Conference on Disaster Reduction
WHO	World Health Organization
WMO	World Meteorology Organization

I. Introduction

22,3 million people have lost their lives because of the natural disasters between 1900 and 2006 (CRED, 2014). Although heat wave is not the most common disaster in the world, it inflicts about 95% of all human losses among the natural disasters in post-industrial countries (Poumadère et al., 2005; Smith and Petley, 2009). In order to minimize the population losses, it is important to identify where the impact of heat waves is the highest. That can be done by population's vulnerability to heat waves assessment considering existing conditions. However, the conditions in the future can be quite different - due to a higher degree of urbanization degree and a high probability of temperature increase in the future, the number of heat waves in the urban areas will probably increase (IPCC, 2007). That is why the population's vulnerability to heat waves has to be modeled using not only existing, but also future conditions. This study introduces a new method to model future conditions via a proxy parameter, the UVCZ. Future UVCZ allocations, based on various scenarios, are assigned by future conditions of urban landscape, climate and population – the indicators of population's vulnerability to heat waves. In the end all the indicators are composed into vulnerability index and assessed. This method was applied for the case of Greater Hamburg, but has great potential for other case studies all around the world as well.

Background

The background information in this thesis is necessary to raise awareness of existing problems, caused by climate change and urbanization, and inform the reader about the motivation of this study. Most of the aspects are roughly covered meanwhile more detailed information can be found within the chapters of this thesis.

Population loss

In 2012 an estimated 56 million people have died worldwide (WHO, 2012) because of various infectious or non-communicable diseases such as cancers, diabetes, chronic lung diseases. The cardiovascular diseases are responsible for 30% of all health-related deaths. In the western world the percentage is even higher - 90% of all deaths are due to heart disease, cancers and respiratory ailments (Smith and Petley, 2009). Often these ailments are related to the old and are seen as the cause of "natural death". By contrast, the death, caused by active intervention is called "unnatural death" (Bryant, 2003). Obviously, unnatural deaths including those caused by traffic accidents, terrorism, natural disasters and other such causes which could be avoided, are more painful to members of society.

"Natural disasters" are caused by natural hazards, also known as environmental hazards. Natural disasters account only for 0,01% of the loss of human life in US (Fritzsche, 1992). Italy, second only to Japan, has the second greatest risk of landslides among developed countries. Even with this great risk of landslides, the loss of human life due to landslides is two hundred times lower than the loss due to road accidents (Guzzetti, 2000; Smith and Petley, 2009). Although many more people die of natural causes and daily activities, disasters which could be mitigated are still considered as a major threat. Between 1974 and 2003 more than two million people lost their lives in 6350 natural disaster events which caused additional damages of more than US$ 1.4 trillion (Guha-Sapir et al., 2004). The deadliest disaster ever recorded was the 1931 Yangtze river floods which caused an estimated loss of 3 700 000 humans in China (CRED, 2014). Today, although advanced engineering and science is capable to analyze disasters, their drivers and risks, people are still aware of them but vulnerable to them as well. This high awareness is raised through traditional means and the gaining popularity in social media. An interesting study, conducted by Adams (1986) more than 30 years ago analyzed reports of USA television during 35 global natural disaster events. The results showed that the media's attention was different by geographical location. The assumptions were made by the frequency of the media coverage when the death of one Western European is equal to three Eastern Europeans, nine Latin Americans, eleven Middle Easterners and twelve Asians. Today the differences probably would be even higher, due to the popularity of social networks, such as Youtube, Facebook, Twitter and others. The social media enabled people to report the events instantly from all over the world, in real time. The impact of some natural disasters, such as heat waves, cannot be seen and reported immediately, however.

Heat waves and climate change

Heat waves are periods of abnormally and uncomfortably hot weather (IPCC, 2014a). Because the impacts of heat stress are not seen immediately right after the heat wave, neither is the loss of human life. Figure 1 shows the minimum/maximum temperatures and mortality during the heat wave event in France in 2003. The high temperatures were recorded quite earlier than the actual mortality has been increased. Therefore, the impact, or the consequence, of the heat wave could be identified and reported days or weeks after the actual heat wave actually happened. The other obstacle relating heat waves and human mortality is the effect of the heat stress. The heat stress can be a direct cause of the death in form of dehydration, hyperthermia or heat stroke. However other factors, such as heart diseases, gender, used medication, residence, age, air pollution and others contribute to the heat wave's death toll as well. Hence the loss of apparently healthy elderly and people with diseases during heat waves often are counted as loss due to natural causes, so heat waves usually are not mentioned in their death certificates (Poumadère et al., 2005). It was also the case during the heat wave in France in 2003 as well. That was the hottest summer in 50 years. During the period of August 4-18, about 15 000 people have died in France alone (Assemblee Nationale, 2004) which was in excess of 60% over expected mortality. Most of the victims (82,5%) were over 75 years old. Similar but lower impacts were observed in England, Wales and Portugal (Poumadère et al., 2005).

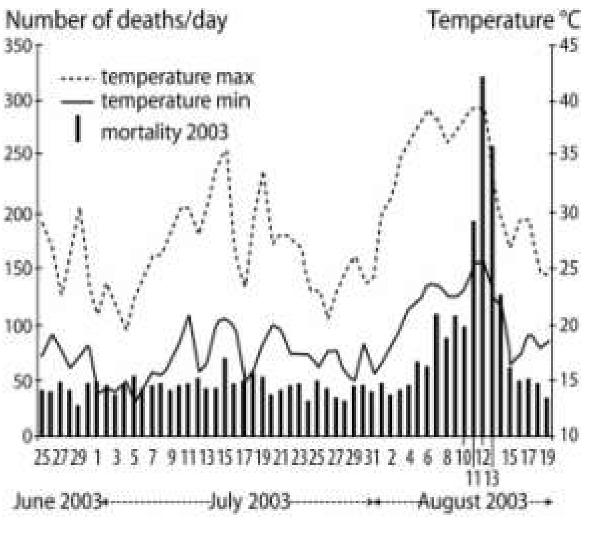


Figure 1: mortality and temperatures during the heat wave in France in 2003 (Dousset et al., 2011).

Another significant heat wave occurred during the summer in 2015 in Pakistan, in which the most affected province was the Sindh, with its capital of Karachi. Between August 17 – 25th the temperatures in Karachi rose to 44,8°C and heat index reached more than 66 °C. In

Karachi alone, more than 1200 people died because of the heat wave which inflicted dehydration and heat stroke. Experts identified that intensive urbanization and removal of vegetation caused the high heat's impact. Additionally, water and power shortages limited population's capacity to cope with the effects of the heat wave. It was concluded that more frequent and more powerful heat waves can be expected in the future and that people should be prepared for those events (Chaudhry et al., 2015).

Heat waves are not a new phenomenon. Although 83 heat wave events occurred between 1900 - 2000 globally, the last 16 years have been marked by 106 such events, with the most devastating in Russia in 2010, with more than 55 000 deaths (CRED, 2014). Figure 2 represents the number of European countries (Turkey included), affected by the heat wave events between 1900 and 2011. The severity and coverage of the heat waves are more clearly indicated than the actual frequency of the heat waves. Only a few countries have experienced heat waves from 1985 to 1997. More countries were affected in 2000 and in 2003, when the major heat wave in Europe occurred, affecting 14 European countries. Officially, the first heat wave thought of as a disaster was recorded in 1985. It's probable that, before 1985, heat waves, as phenomena, were not recorded at all. I think that the probable reason for this is the lack of the methodology to identify heat waves as disasters. A second reason may be the complex and often unseen indirect linkages between heat wave effects and mortality.

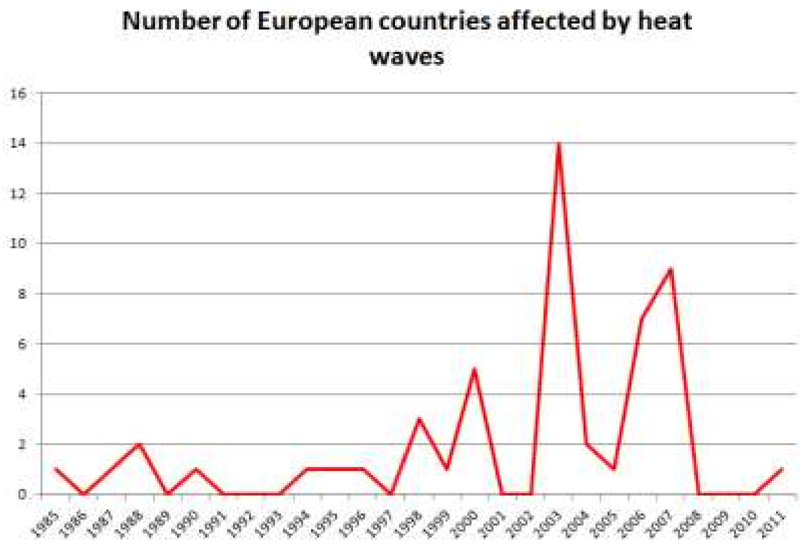


Figure 2: number of European countries (including Turkey) affected by heat waves (data source: CRED, 2014).

The number of heat waves' affected countries can be influenced by many factors: temperature thresholds, increased urbanization, aging society, increased media coverage and many others. Knowing that the past temperature increase in Europe is related to the higher number of heat wave affected countries, it is very likely that heat waves will occur in Europe with a higher frequency and longer duration (IPCC, 2014a).

Figure 3 shows four scenarios of the global average surface temperature change for the 21st century. The change was modeled by multiple global climate models. The IPCC (2013) states that it is likely that for the end of the 21st century the temperature will exceed 1,5 °C relative to the 1850 – 1900 time period under all RCP (Representative Concentration Pathways) scenarios. The exception is the RCP 2.6, the most optimistic scenario, considering lowest possible greenhouse emissions. It means that even in the best case scenario (RCP 2.6), the global temperature likely will increase from 0,4 to 1,6 °C in 2046 – 2065 and from 0,3 to 1,7

°C in 2081 – 2100. The global temperature increase causes higher frequency and higher severity of heat waves (IPCC, 2007).

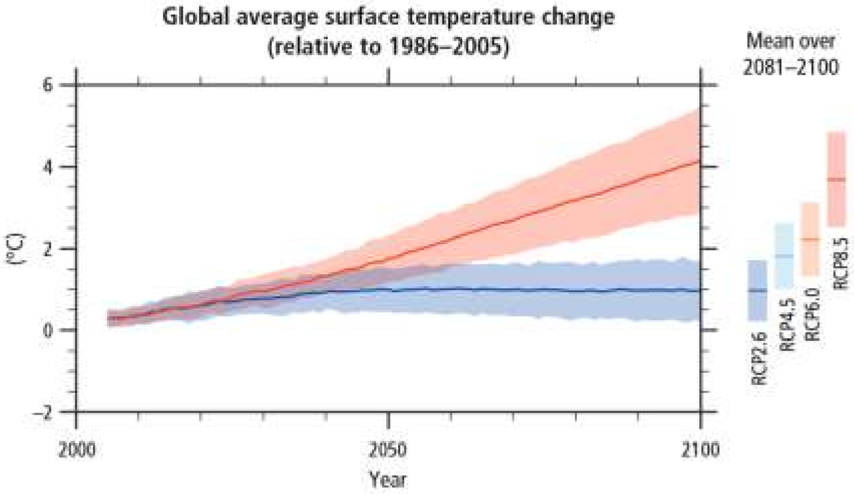


Figure 3: multi-model simulated global average surface temperature change for 4 future RCP scenarios. The colored vertical bars show the range of uncertainty (IPCC, 2014a).

The IPCC presented future temperature changes are average global values. Because the earth has a very complex weather and climate system, the future temperature change is not uniform. Therefore, to identify regional and local changes in surface temperature, models with spatial distribution are required. Figure 4 shows the global distribution of the change in average surface temperature (relative to 1986 – 2005) for two extreme scenarios (RCP 2.6 and RCP 8.5).

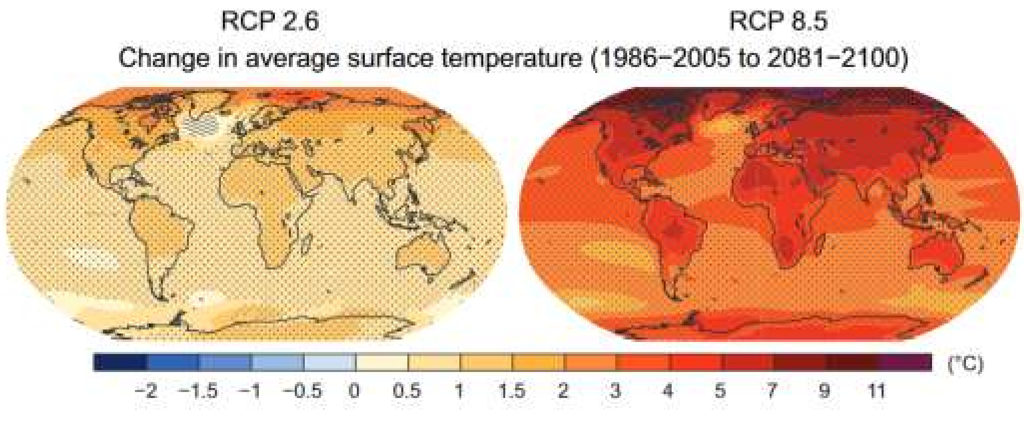


Figure 4: change in average surface temperature for RCP 2.6 and RCP 8.5 scenarios. Results were modeled by CMIP5 multi-model (IPCC, 2013).

Both scenarios show only temperature increase. The highest temperature increase is located in the northern latitudes which will cause an increase in ice melting. In both scenarios the European continent will be affected by the surface temperature increase and very likely that it will experience even more heat waves in the future. In order to know the impact in a more localized area, for instance, a city or a region, regional climate models are required. The previous discussed temperature changes were developed by global climate models (GCM) used for global simulations. Regional climate models are more specific and are modeled addressing past climate data, unique surface and other parameters.

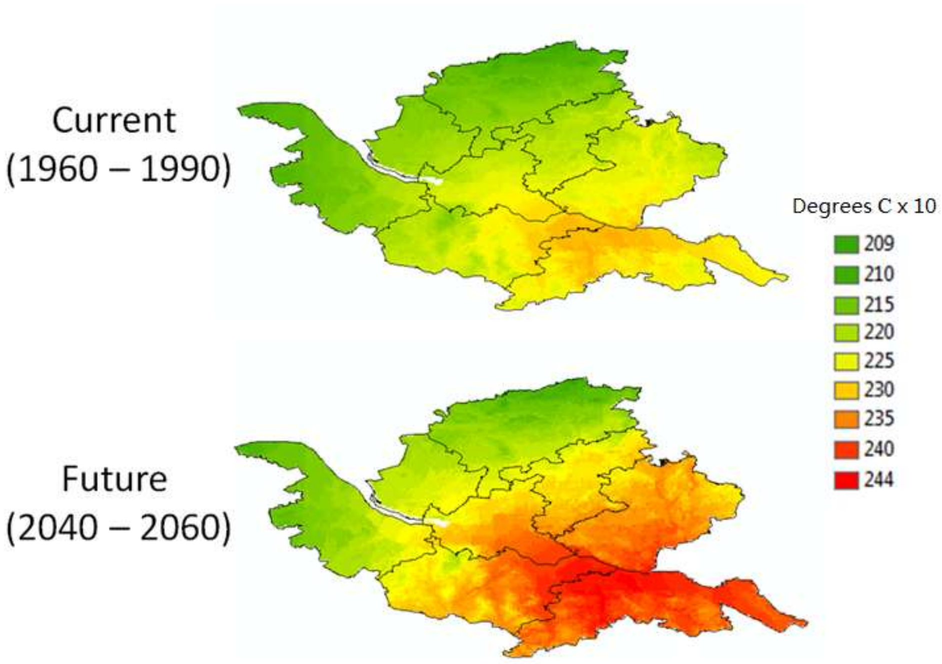


Figure 5: the current and future monthly average maximum temperature in Greater Hamburg (current data are interpolations of observations, the future data is downscaled RCP 4.5 scenario from the MPI-ESM-LR model. Source: WorldClim database).

During the last century the daily mean and maximum temperatures in Hamburg showed an overall increase. From 1891 to 2007 an increase in mean temperature of 0,07 K/decade was identified. From 1948 to 2007 the increase was about 0,19 K/decade. In the last period, from 1978 – 2007, the increase was highest, about 0,6 K/decade. This warming is found throughout the entire year and all seasons are warmer than previously observed (Schlünzen et al., 2010). Figure 5 shows current and future monthly average maximum temperature for Greater Hamburg. The difference between current (past) and future temperatures is more than 1 degree and reaches 1,3 degree in the southeastern areas. The rise of one degree does not seem much, but it can have devastating effects caused by the increased frequency and severity of heat waves (IPCC, 2007). The rising future temperature, however, is not the only factor affecting an increase in heat-related human mortality.

Urbanization and population

Another very important factor contributing to the heat-related mortality is the higher urbanization degree (Smoyer et al., 2000; Souch and Grimmond, 2004) caused by population increase. Moreover, the increasing urbanization can increase the effect of urban heat island (UHI). The UHI refers to the warm temperature difference between the urban and rural areas in the screen height of 1 – 2 meters above the ground (Stewart and Oke, 2012) (more about UHI and heat wave effect can be found in chapter 2.2). One of the reasons for the warmth difference is the presence of impervious surfaces, such as parking lots, buildings, and the absence of vegetation and water sources. Impervious surfaces emit absorbed heat and causes high heat stress to the people (Oke, 1982; Smith, 2004).

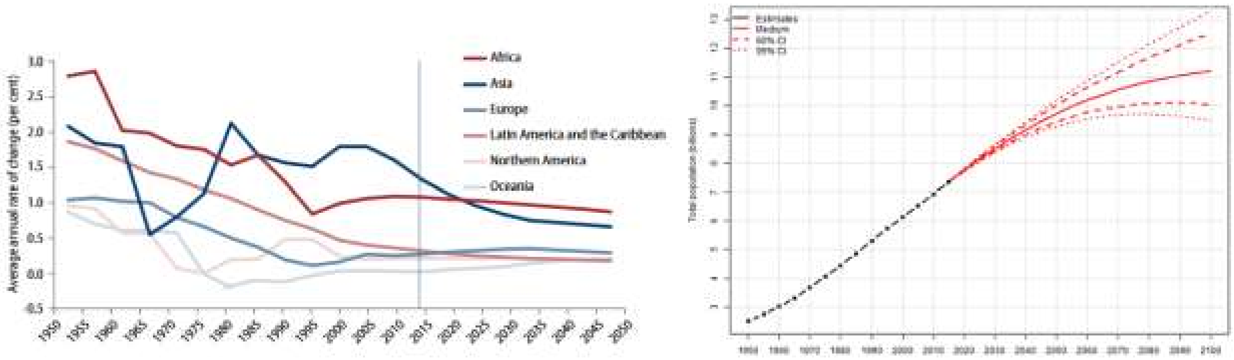


Figure 6: projected average annual urbanization rate's change by regions (left) and projected global population by billions (right) (sources: UNDESA, 2015, 2014).

According to the United Nations (UNDESA, 2014) in 1950 about 70% of all population lived in rural settlements and 30% in urban settlements. Today more people live in urban, than in rural areas. In 2050 even 66% are projected to live in urban and 34% in rural areas. One of the reasons for increased urbanization is the population growth. Total world-wide population in 1950 was only 2,53 billion (UNDESA, 2011), today it is more than 7,3 billion (right image in figure 6). The current population growth is 1,18 % or 86 million people per year. In the last 12 years the population increased by one billion and it will increase by another billion within next 15 years. According to the projections, in 2030 there should be 8,5 billion, in 2050 9,7 billion and by 2100 11,2 billion people (UNDESA, 2015). That is almost four billions more than today. This would cause more people to populate hazard-prone areas. Moreover, about 90% of the growth takes place in developing countries which are particularly vulnerable to natural hazards due to dense population concentration in hazard-prone areas, high poverty, fragile livelihoods, food insecurity and political instability (Smith and Petley, 2009).

Goal of the study - future vulnerability assessment

Considering the future temperature increase, increased frequency and severity of heat waves, growing population and urbanization, the heat-related mortality is very likely to increase as well (Huang et al., 2011). The projections indicate that effects of future heat waves are unavoidable. However, we, the humans, have to try, at all costs, to minimize these losses, adapt to future climate, population and urbanization changes, conserve the natural environment and leave a better and safer world for future generations.

Therefore, in order to reduce the future heat-related mortality, we have to know:

- Where the heat impact will be highest.
- Where the heat-vulnerable people will live.

These answers can be found if the future population's vulnerability to heat waves can be known at the local scale. The higher population's vulnerability will identify the most critical areas which have to be analyzed in detail in order to reduce future heat-related mortality. The focus of critical areas would help local decision makers to implement various adaptation and mitigation measures, develop heat wave plans or shift the policies. The sooner possible consequences can be known, the more time decision makers will have to lower the impact of future climate change.

Problem statement

Based on background information, the future population's vulnerability to heat waves is greatly affected by future climate, future urban landscape (also urbanization degree), and future population. However, the literature analysis of the common vulnerability assessment studies, presented in the later parts of the introduction, shows that the main gap in the existing knowledge of future population's vulnerability assessment is due to a lack of future conditions: the future population and urban landscape data. This raises the problem and the main research question of the study - How future vulnerability can be modeled considering not today's, but future conditions?

The future climate data was produced by global climate models (GCM) and was downscaled to the local scale. The future population and urbanization projections do exist as well, but the problem is that a) most of these projections are global. Because each area has a different trend of population increase and urbanization, the global projections cannot be directly applied at the local scale; b) limited data of future projections (population count and urbanization degree) is not enough to distinguish critical vulnerable areas. The solution to these problems could be the development of a proxy parameter which would be a spatial entity, would be easy to model and would represent areas by different conditions – by urban climate, landscape and population. In order to define a proper name, the proxy parameter was called "urban vulnerability climate zones" (UVCZ). The modeling of future UVCZ allocations would show how future conditions will change and how they could affect future population's vulnerability to climate change.

Hypothesis and assumptions

Because this study addresses the modeling of future conditions, the hypothesis and assumptions cannot be avoided. The hypothesis of this research is that the population groups of different age, income and density are unevenly distributed among different potential housing UVCZ. And the main assumption is that these properties will stay constant for each potential housing UVCZ over time. Moreover, the additional assumption is that each UVCZ zone, affected by certain climates, would have specific heat impact and would not change over time as well. The hypothesis and assumption place high importance and scientific significance on the UVCZ, the proxy parameter which is the key of this research.

The high complexity of this study requires an additional number of assumptions. Most of these assumptions were determined during the study and might be unclear until the reader is familiar with the whole study. I decided to present them in the beginning of this thesis in order to introduce what kind of assumptions this study addresses. The following list presents all assumptions with the reference to certain chapters of this document:

- Although, the people spend days in the forests, work in industrial, commercial and harbor areas, it is much easier to relate people with the areas where they live. Therefore, this study assumes that the people are affected by heat primarily in the potential housing areas where they live and sleep overnight (chapter 6).
- People cannot acclimatize or adapt to the changing climate quickly. My assumption is that for a best case scenario people can adapt to only 30% of the climate change impact (for instance, sometimes even the hospital next door cannot save a person from the heatstroke). Such an assumption is important in order to implement the factor of adaptive capacity into a vulnerability assessment (chapter 8).

- The hospitals and healthcare infrastructure is difficult project, therefore I assume that locations of the healthcare facilities in Greater Hamburg will be the same in the future as they are today (chapter 7).
- It is assumed that the existing environmental restrictions, zoning and transport infrastructure, as well as feature UVCZ classes, such as airports, rail and road infrastructure etc., will not change in the future (chapter 7).
- The future population aging is quite complex, especially at the finer scales. I assume that the population's aging factor in Hamburg city-state is similar to districts of Schleswig Holstein and Lower Saxony (chapter 7).
- The neighborhood effect is limited by eight cells (two kilometers) in the model which gives an assumption that a single area does not affect other areas farther than two kilometers (chapter 3).
- The new or converted potential housing UVCZ cells of the same class would represent homogeneous future conditions (vulnerability indicators) and would form clusters of cells (patches). This assumption is based that new development occurs in greater areas than the building block (250 x 250 m) (chapter 7).
- It is very hard to project future long term specific urban development. My assumption is that the future development patterns of commercial, harbor and urban parks will experience the same trend similar to 1990 – 2000 (chapter 7).
- A similar situation is with the population distribution among the potential housing UVCZ classes. I assume that in different urban development scenarios, the population fractions for each potential housing UVCZ class will not change over time (chapter 7).
- I assume that minimum daily average temperature which causes increased heat-related mortality in Greater Hamburg is 20°C, the same as it is in cities with similar climates in Great Britain and Netherlands (chapter 6).
- Because of the lack of Soil Sealing 2000 data, I assume that the degree of soil sealing did not change much in 2000 - 2006 for potential housing UVCZ in Greater Hamburg (chapter 6).

Each of above stated assumption forms a condition. The change in any of these conditions cause change in the outcome of this study.

Additional research questions and objectives

The defined hypothesis can be verified or falsified by research which should be based on research questions. The main research question, as the main problem, was identified previously. In order to answer the main question, the additional specific research questions must be answered. Most of these additional research questions have been raised, not in the initial stage, but during the research process. The following research questions (Q) have to be answered and research objectives (O) have to be achieved in order to solve the main problem, answer the main question and reach the goal of the study:

Q1: What are the definitions of vulnerability?

O1: Collect existing definitions of vulnerability and perform their qualitative and quantitative analysis.

In order to assess vulnerability, it has to be defined. Therefore, one of the primary steps is to determine the meaning of vulnerability? The objective is to collect and analyze a number of vulnerability definitions, used in different contexts. The qualitative and quantitative analysis would help to understand the meanings of definitions among the different contexts and how it changes over time.

Q2: What are the main aspects of vulnerability?

O2: Collect, overview and analyze all details about vulnerability to climate change.

The detailed analysis of vulnerability would help to understand how other disciplines perceive it conceptually, and how it can be measured and assessed. This would help to frame how a population's vulnerability is interpreted in the case of Greater Hamburg.

Q3: What factors affect a future population's vulnerability to heat waves in Greater Hamburg?

O3: Name the factors which have the highest impact on population's vulnerability to heat waves in Greater Hamburg.

Identified factors affecting vulnerability would help to narrow the conceptual setting and operational methods.

Q4: How can the properties of urban landscape, climate and population be combined into a proxy parameter?

O4: Develop a spatial classification system which would be based on urban landscape, climate and population properties.

The idea of future vulnerability modeling is to model a spatial proxy which would contain the conditions of urban landscape, climate and population. Therefore the big question is how to combine these properties and differentiate their variation through the classification system.

Q5: What is the conceptual setting and operational options required to model vulnerability?

O5: Develop conceptual setting and operational options.

Conceptual setting and operational options could help to understand the concept of proxy parameter, the effects of future conditions and would provide a list of operational options, required to model vulnerability and process the data.

Q6: How can future proxy parameter (UVCZ) be modeled?

O6: Search and employ existing future land modeling tools.

The modeling itself is not possible without a modeling software. The search and usability of a tool, capable to model the proxy parameter (UVCZ), is another important step. The more detailed steps include the model's calibration using historical proxy values and model's validation.

Q7: How have UVCZ changed in the past in Greater Hamburg?

O7: Identify the past UVCZ trends in Greater Hamburg.

In order to model the future, the model has to be calibrated using the historical data. Additionally, historical UVCZ changes will help to identify the urban development trends which will be used for a "business as usual" scenario.

Q8: What indicators could measure future population's vulnerability in Greater Hamburg?

O8: Conduct an analysis of literature and list the most comprehensive and easy to model indicators, capable to indicate the population's vulnerability to heat waves in Greater Hamburg.

The selection of indicators should be based not only on ability to indicate population's vulnerability to heat waves, but also on the availability and plausibility to apply to the case of Greater Hamburg.

Q9: What is the minimum mortality temperature in Greater Hamburg and how can it be related to future monthly average minimum and maximum temperatures?

O9: Identify the minimum mortality temperature in Greater Hamburg and perform a statistical analysis of the historical monthly average and maximum temperatures in order to find a correlation.

The minimum mortality temperature which is the average daily temperature, is required in order to identify what temperature causes greater heat-related mortality. However, the only available future climate data in Greater Hamburg is the monthly average minimum and maximum temperatures. The statistical analysis of historical temperature data would show what thresholds of monthly average minimum and maximum temperatures correlate with minimum mortality temperature.

Q10: What future scenarios could shift future conditions affecting the population's vulnerability to heat waves in Greater Hamburg?

O10: Collect or develop, analyze and list climate, socio-economic and urban landscape or other scenarios, affecting future population's vulnerability to heat waves in Greater Hamburg.

The scenarios help to frame future modeling and overview the scope of decisions which can shift future conditions. The list of such scenarios is essential in order to explain why certain decisions could lead to certain consequences.

Q11: If extreme urban development scenarios had been applied in 1960, how would Greater Hamburg look today?

O11: Apply future extreme urban development scenarios to the past UVCZ and develop an alternate history UVCZ.

Due to limited population growth in the future, the impact of extreme urban development scenarios cannot be properly identified. Alternate history scenarios with greater historical population growth would help to verify if extreme urban development scenarios represent certain urban development patterns properly.

O12: How can future conditions be modeled using future UVCZ?

Q12: Develop a framework, capable to model future conditions via future UVCZ.

The detailed step-by-step framework would show UVCZ's role and procedure how the indicators of future population's vulnerability to heat waves would be modeled.

Q13: How can the future population's vulnerability to heat waves in Greater Hamburg be assessed?

O13: Develop a clear, comprehensive and simple vulnerability assessment approach.

The clear and transparent vulnerability assessment approach is vital in order to show how the final result has been developed. The simple aggregation methods and weights, promoted by local experts, would give fair judgment of final results.

Q14: What are the common adaptation options and measures to reduce population's vulnerability to heat waves?

O14: Develop a list of adaptation options and measures to lower the impact of the future heat waves in urban areas.

The key identified vulnerable areas are the potential targets for adaptation. Therefore, in order to lower the future vulnerability and impact of heat waves, the certain adaptation measures and options should be known.

The above listed research questions and objectives are not the only ones. Many smaller unknowns were found and clarified during the research, but not included in this section. The ways to answer them form an appropriate study approach.

Study approach

The study approach presents the developed step-by-step summarized procedure of how the population's vulnerability to heat waves in Greater Hamburg is modeled and assessed:

I. First, it is important to define what the vulnerability means within the context of the Greater Hamburg case study. A good way to define vulnerability is to search for existing definitions.

II. The easiest way to understand and to define vulnerability is to identify a vulnerable situation, using certain criteria. This method helps not only to identify vulnerability, but also to determine the goals, objectives, values, domain, properties of the vulnerable system, and its scale. Such information is great support to find an appropriate vulnerability concept.

III. The vulnerability concept presents how vulnerability is perceived on the conceptual level, to which common concepts it is more familiar, what the features of it are, how the inner components of vulnerability interact and what the external factors are.

IV. The vulnerability framework is the implementation of the vulnerability concept. It is straight forward and introduces the factors affecting vulnerability, how they interact with each other, the sequence of interaction etc.

V. Because the general aim of this study is to deliver quantitative data on a very fine local scale, the entire approach is based on the indicators at the local scale. After it is known what factors affect vulnerability, the search of available future indicators representing these factors, can be initiated. It is important to consider that the spatial and temporal resolution of the indicators have to match or at least be very close to each other.

VI. All applications, more or less, dealing with the future, experience a lack of future data. A way to overcome this issue is to model the data. This method has been chosen for Greater Hamburg as well, because more than half of the future indicators are not available.

VII. The future population's vulnerability to heat waves in Greater Hamburg is represented by future conditions. The idea was to model future conditions via the proxy parameter, the UVCZ. UVCZ is a spatial classification of areas by urban landscape, climate and population. In total there are 24 UVCZ classes, with 19 of them being typical for Greater Hamburg. The future UVCZ allocations would allow to model future conditions.

VIII. The next step is to model a future baseline UVCZ. For this purpose, the commercial future land use modeling tool, called Metronamica, was chosen. Metronamica is cellular automata-based software which uses historical baseline (the historical UVCZ) data, neighborhood and transport attractiveness rules to calibrate the model. All the data was collected, analyzed and reviewed. The historical data change is identified as a pattern which helps to understand past processes in UVCZ change during the years. The same pattern can be applied afterwards by modeling future UVCZ in business as usual scenario. If there is no population growth, however, the same urban development pattern can have a different impact In order to predict the future UVCZ more accurately, therefore, future projections have to be obtained. The additional required information is the special zoning and urban development plans which are known today and certainly will take place in the future and will affect UVCZ allocation. These plans, together with zoning and population projections are applied in Metronamica. This enabled to model the baseline scenario of UVCZ until 2050 using historical UVCZ patterns.

IX. Although the future baseline UVCZ is considered as Business as Usual (BaU) scenario, it was decided to see how extreme urban development would shape vulnerability. Each scenario has different population allocation (based on population growth) among the potential housing UVCZ classes, neighborhood, transportation infrastructure and city center/sub-centers attractiveness and specific conversion rules. Using these inputs allowed the creation of a total of four different future UVCZ scenarios which can be used to model future vulnerability indicators.

X. The urban development scenarios, however, were not the only ones applied in this study. In total there are three types of scenarios: urban development (UVCZ), socioeconomic and climate. The socio-economic scenario, which considered official population projection and baseline commercial growth, was chosen because of limited availability. Additionally, from three available climate scenarios, but only one, the RCP 4.5, was selected. This decision was made to keep the model simple as possible. In the end there are four different scenarios, mainly shifted by different urban development trends.

XI. Assuming that future conditions (population's vulnerability indicators) for each potential housing UVCZ class will not change in the future (except the effect of aging population), the indicators can be assigned to newly modeled UVCZ scenarios. However, the new values would be assigned only to the patches of the new or converted cells, assuming that the UVCZ which were not affected in the scenarios, maintain the same properties. In order to find these properties for each potential housing UVCZ class, the baseline UVCZ year 2000 data and various datasets, representing exposure, sensitivity and adaptive capacity indicators, have to be transferred to UVCZ by aggregation and disaggregation operations. The outcome is that each potential housing UVCZ cell for the year 2000 has a certain value of each vulnerability indicator.

XII. The patches of new or converted cells are assigned by average historical values of the vulnerability indicator. However, because of the heterogeneity, it was decided to assign random values of vulnerability indicators within the range +/- 0,5 of standard deviation from the mean of the historical (2000) data. This solution gives more realistic representation of the vulnerability indicators' distribution within the Greater Hamburg case study area. The result in the end contains four UVCZ allocations (results of four urban development scenarios), with modeled future vulnerability indicators.

XIII. The last step is the actual vulnerability assessment. First of all, all the vulnerability indicators have to be composed into an index. But composing various data types, with different scale, can be difficult. This step is done by the normalization operations. Additionally, each indicator carries its own importance, which can be defined by weight. The weights have to be assigned by experts or should be based on scientific literature. In the end the vulnerability index is composed by transformed, rescaled, weighted and normalized indicators and presented as a map. Each scenario is analyzed in details and compared to other scenarios.

The steps of the study approach for this certain case study are flexible and can be changed, if other case studies require that. However, a future vulnerability assessment is not possible without the future data (future vulnerability indicators, which show future conditions). The novelty and strength of this study is that it models missing future vulnerability indicators through a proxy parameter – UVCZ. The future UVCZ allocations are modeled by four different urban development scenarios. Therefore, the future population's vulnerability in Greater Hamburg is presented in four different pathways. Each pathway serves as great spatial decision support information in order to find the best solution as to how the city should develop and which areas would experience the highest vulnerability to heat waves.

Audience

The typical audience interested in this study is the researchers working with climate change impacts. Because this study is quite complex, practitioners might experience some difficulties in implementing it. It could serve quite well, however, as a guideline for teams consisting of researchers and practitioners. The researchers could provide the missing data and develop new methods, while the practitioners could model and assess vulnerability.

This book also should be interesting to urban planners, social scientists, environmental, emergency and healthcare experts, although the implementation of the entire procedure might be complicated to them as well. However, using support from the research and GIS fields, this would be an insurmountable problem. A successful outcome could even be applied at the political level afterwards. This would not only raise the awareness of the probability of future heat waves, an increase in the elderly population and social inequality, but it would also encourage the planning of adaptation measures and the shifting of urban development patterns to greatly reduce future population's vulnerability.

Structure of the thesis

This study is very complex, spatially oriented and aims to answer many research questions. Therefore, this thesis contains many figures. Instead of placing them in the annex, it was decided to add them parallel to the text. In this way the figures might help to understand the complexity of the thesis. This decision increases the size of the thesis dramatically, but brings much more clarity and better understanding of research problems, used methods and generated results.

In total this thesis consists of more than 300 pages with about 130 000 words and includes more than 200 figures. There are five parts and contains a total of thirteen chapters, eleven are numbered in Arabic (figure 7). The first part is the introduction, including literature analysis. The second part covers conceptual setting and operational methods which are the key understanding the concept of future vulnerability modeling in Greater Hamburg. The applied methods, data and results can be found in third part. The last part of the thesis covers discussion and conclusion which identifies existing problems and summarizes the whole study. It was decided to number both as final chapters because of the strong linkage to previous chapters.

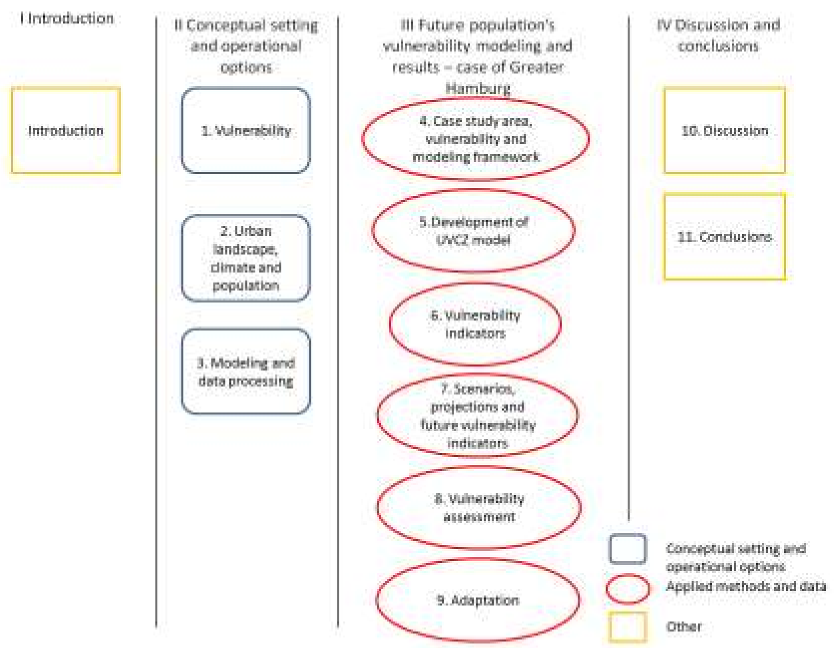


Figure 7: structure of the thesis by parts and chapters.

Considering chapter-by-chapter contents, the first, the vulnerability chapter starts with the analysis of existing vulnerability definitions. After goes the vulnerable situation which is essential to define vulnerability. The vulnerability concepts, frameworks and interpretations present how vulnerability is seen by different scientific communities and from different perspectives. The next two sub-chapters highlight the measuring and quantification problem of vulnerability and how it can be solved using the indicator based approach. Later on the future vulnerability as a challenge is then presented. Concluding the entire chapter of vulnerability, the IPCC vulnerability approach which is selected as the most suitable for this study, is explained in details. In the end, the vulnerability assessment is explained and the step-by-step guidelines are presented.

The second chapter explains the relations between the urban landscape, climate and population. It introduces landscape properties, urban climate, the social and economical diversity and what the effects of climate change on cities are. Additionally it presents the negative effects, the ways of urban management and common urban development patterns.

The last chapter of part II, contributes to the technical part of this study. It describes the operational options used to model future urban development and prepare data for vulnerability assessment.

The third part of the thesis starts with the fourth chapter which introduces the study area of Greater Hamburg. It analyzes and defines the future population's vulnerability to heat waves within Greater Hamburg, based on fundamentals of vulnerability presented in the first chapter. Later whole framework of vulnerability modeling is explained.

Once the modeling framework is clear, the fifth chapter presents the development of the UVCZ model. The development includes the analysis of the historical UVCZ changes and very detailed steps and results of model's calibration.

The sixth chapter covers modeled and auxiliary vulnerability indicators. It judges the selection of indicators, describes how the population and heat exposure indicators were modeled, and how the temperature and one of the adaptive capacity indicators were acquired and processed.

The seventh chapter gives detailed information about future scenarios and projections. The climate change, population, urban zoning, urban development and alternate urban development scenarios are analyzed in details. The outputs of these scenarios are used to develop future vulnerability indicators.

The eighth chapter of Greater Hamburg case study presents the results of the vulnerability assessment. This chapter finalizes the indicators' composition into vulnerability index and presents plentiful results, in form of maps.

The last chapter of the third part overviews a list of adaptation options and measures which can be used to reduce vulnerability to heat waves.

The fourth part is composed from the discussion and the conclusions chapters of this study.

In addition to the structure of the thesis, I would like to mention that when I was writing this thesis I experienced a language-related challenge. Because this study has a high empirical focus and is mainly data-driven, some of the specific aspects were difficult to express in common and understandable language. It is my hope that this issue will not be a great obstacle understanding the concept, methods and approaches of modeling future population's vulnerability to heat waves.

Literature analysis of common vulnerability assessments

This sub-chapter presents a deep literature analysis of common vulnerability assessment approaches and methods, applied in various case studies. Results of literature analysis were used to identify research gaps and develop new ideas which would enable the modeling and assessment of future population's vulnerability to heat waves at the local scale. In order to find appropriate literature, the analysis was based on four criteria, relevant for this study:

Qualitative indicator-based vulnerability assessment. The goal of this research is to assess how certain areas within the case study are more vulnerable to heat waves than others. The common way to assess the differences is to use the indicators. Many vulnerability assessment studies exist today and I wanted to find and review the more standardized studies which were developed by larger research teams and scientific cooperations and could be applied in multiple countries.

Future vulnerability modeling/assessment. Most of the vulnerability assessment studies consider historical or today's (current), but not future conditions. Knowing that the future is very uncertain, one of the ways to "project" the future is to develop future scenarios. So I reviewed some studies which addressed future scenarios and used their outcomes to assess vulnerability.

Socio-economic projections. There is a high awareness of impacts of future climate change, such as temperature increase, sea level rise etc. This awareness was raised after future climate impacts were widely discussed in IPCC reports and draw attention of the mass media. Because global, regional and local downscaled future climate data is readily available, it should be included into climate change vulnerability assessments. However, future vulnerability to climate change should consider not only the change of future climate, but also the change of future urban landscape and future population. Most studies assume that population will not grow, the cities will not expand, people will not get older, income of the people will not change. Because one of the values of this research is population, I searched for studies, considering future population's properties, such as future growth, process of aging, densification/expansion of the cities etc.

Heat hazard-related vulnerability assessment. Due to higher potential of applicability, many of the vulnerability assessment approaches are multi-hazard. However, multi-hazard studies do not address the hazard-related properties in details. Because the focus of this study is the heat hazard, the priority for the literature analysis has to be the heat-related vulnerability assessments. Obviously, the heat hazard vulnerability in Vancouver (Canada) should be assessed differently, than in Cairo (Egypt), due to different data, availability of future projections, different population's acclimatization and other factors. Therefore, it is preferable to overview assessments, done in multiple case studies of different climate.

The following projects and studies met one or more (but, unfortunately, not all) criteria, mentioned above. There is always the possibility to argue and discuss which studies are the best and should be analyzed in details. While it's possible that some better quality studies have been done, they may have stayed unpublished or have limited accessibility for other reasons. The studies below are diverse and not all of them address vulnerability to heat waves, but they are more known for their comprehensive methodology and standardized approaches which can be used as guidance to assess vulnerability.

Methods for the Improvement of Vulnerability Assessment in Europe (MOVE)

The project “MOVE” was an EU Commission financed project from the Seventh Framework Programme. The project results were published as a handbook of vulnerability assessments in Europe (DG Environment, European Commission, 2011). The authors of this project were from multiple European countries, such as Italy, Hungary, France, Austria, Spain, UK, Norway, Germany and Portugal. Their task was to develop the knowledge, methods and frameworks for the quantitative indicator-based assessment of vulnerability to heat waves, floods and earthquakes in Europe. Afterward the methods and frameworks had to be tested in one of the case studies at sub-national and local scale. The number of case studies was high, because it was necessary to test the developed methodology and assess vulnerability to different hazards in different areas.

On the conceptual level, the vulnerability in the MOVE project is coupled with exposure and resilience which are the parts of the society (or a system) (figure 8). It affects and is affected by external stressors, such as environmental hazards and socio-natural events. The extreme stressors and society are influenced by adaptation which the project authors call “hazard and vulnerability intervention”. Meanwhile the adaptation is organized, planned and implemented by the risk governance. Through the interaction between the society and the hazards, the risk, as potential social, economical and environmental impact, is assessed and evaluated (figure 8).

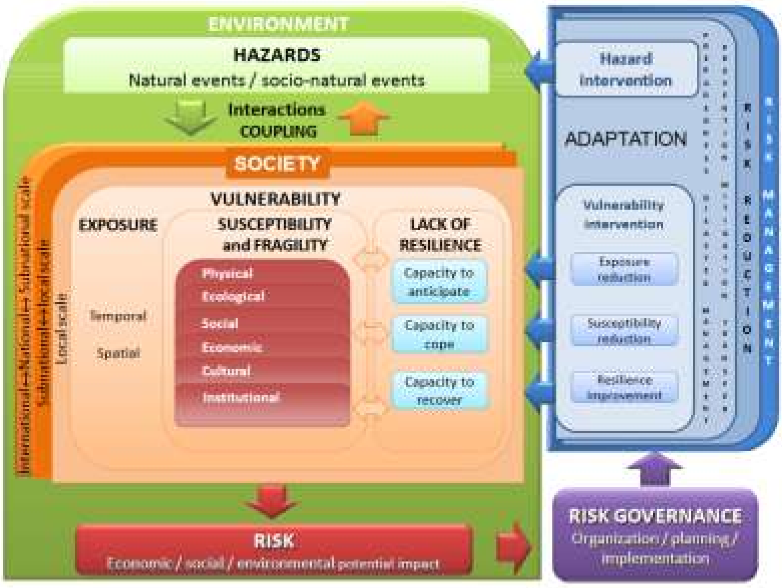


Figure 8: conceptual framework of vulnerability assessment in MOVE project (DG Environment, European Commission, 2011).

Vulnerability as an element of society (system) contains temporal and spatial exposure, physical ecological, social, economic, cultural and institutional susceptibility and fragility all of which are affected by the capacities of the resilient society, capable to anticipate, cope and recover in an emergency or disaster. Additionally, the qualitative composition of vulnerability can be expressed as exposure's multiplication by sum of susceptibility and lack of resilience divided by two (figure 9). The role of exposure is clear - if there is no temporal or spatial exposure (no parts of system is exposed), the exposure is 0 and there is no vulnerability. While the susceptibility and lack of resilience are equal components, representing sensitivity and adaptive capacity of the system. The mean of the sum is multiplied by exposure and is composed into vulnerability. At that point, the exposure has the highest impact on vulnerability, meanwhile the susceptibility has the same influence as lack of resilience.

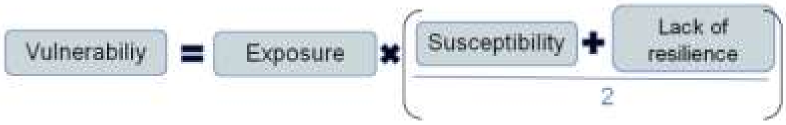


Figure 9: components of vulnerability within MOVE project (DG Environment, European Commission, 2011).

The scale of vulnerability assessment was based on city districts. The case study area of Cologne, Germany, contains 370 city districts in total. Various indicators for the vulnerability to heat wave assessment were chosen. The indicator of exposure was selected as a number of people (acquired from the statistical census data) exposed to heat waves and multiplied by normalized mean surface temperature (delivered from thermal infrared satellite imagery). The four susceptibility indicators were selected based on literature review and experts' workshops: the relative number of people with very young (0-5 years) and old (>65) age, weighted by 0,6, the rate of unemployment weighted by 0,1, the relative number of foreigners weighted by 0,1 and the relative number of elderly households weighted by 0,2. The weights which were defined by local experts, show importance of the indicators. For instance, in this case, the age groups are six times more important than unemployment rates and only two times more important than the number of elderly households. The lack of resilience indicators was a greater challenge. They were not available on the district level, therefore the authors made an assumption to use the household size as a proxy and calculated the coping capacities. Additionally, the study considered the ecological dimension of vulnerability which contributed to the resilience component and was coupled with social-ecological vulnerability. The ecological dimension of vulnerability to heat waves was represented by a percentage of green and water areas per district and multiplication by the coefficient of air quality regulation. In the end the lack of resilience was aggregated by adding susceptibility with the weight of 0,6 and ecological indicators with the weight of 0,4. The institutional dimension was developed from 15 mostly qualitative indicators, such as trust, representation, access to information and many others. All the exposure, susceptibility and lack of resilience indicators were normalized, weighted and aggregated into one vulnerability index. The following figure illustrates the vulnerability to heat waves index. The vulnerability index shows the highest and lowest vulnerability between all 370 districts of Cologne city.

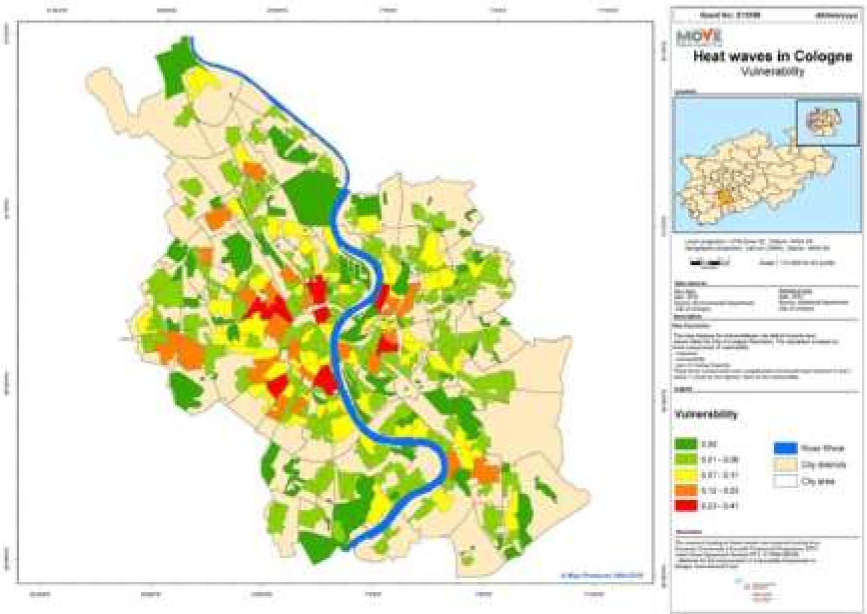


Figure 10: population's vulnerability to heat waves in Cologne at the city district scale (DG Environment, European Commission, 2011).

The loss of the values of numerous indicators is a typical consequence of the aggregation process and is often identified as popular discussion topic. However, the one value (or index) indicators assist in communication with stakeholders and decision makers. The data availability and uncertainty was another significant addressed issue in the study. In general the project was successfully evaluated with the hope to strengthen the resilience of Cologne against natural hazards.

The MOVE research study is aware of future climatic events and rising challenges, but there is no actual future vulnerability assessment - neither the future data from other models nor projections or assumptions were applied in presented vulnerability framework. The authors concluded that although their approach is comprehensive enough to perform vulnerability assessment using "up to date" data, the future data can be used as well (DG Environment, European Commission, 2011). It is not, however, defined how the future data can be acquired or modeled.

Urban regions: vulnerability assessments by indicators

The comprehensive scoping study with the full name of "Urban Regions: Vulnerabilities, Vulnerability Assessments by Indicators and Adaptation Options for Climate Change" (Schauser et al., 2010) has been done by European Topic Centre on Air and Climate Change (ETC/ACC). ETC/ACC was a Consortium of European Organizations contracted by the European Environment Agency (EEA). ETC/ACC it is the predecessor of European Topic Centre on Climate Change impacts, vulnerability and Adaptation (ETC/CCA) which carries out the annual ETC/ACC action plans with EEA five year strategy and multiannual work programme in the area of climate change impacts and vulnerability. Today ETC/CCA supports the development and implementation of the 2013 EU Strategy on Climate change adaptation, the main EU environmental policies in the sectors of biodiversity and water, contributes to many other European initiatives related to climate change vulnerability (ETC-CCA 2016).

The aim of the study was to understand and to fill the knowledge gap of the vulnerability to climate change impacts across Europe. The authors wanted to assess the feasibility of developing climate change-related vulnerability indicators for urban areas in order to support EU spatial development policy by reviewing available literature and research activities. The study collected and analyzed existing information of climate-related vulnerabilities of urban areas in Europe, overviewed vulnerability assessment methods, evaluated existing vulnerability indicators and identified their data needs, reported a summary of existing adaptation options and listed recommendations for the developments of vulnerability indicators and adaptation measures (Schauser et al., 2010). Additionally, authors provided case studies as the best practices of the vulnerability assessment and recommendations for adaptation measures.

The definition of vulnerability in ETC/ACC study was taken from the IPCC the Fourth Assessment Report (IPCC, 2007) where vulnerability is defined as a product of exposure, sensitivity and adaptive capacity. The study takes the IPCC vulnerability concept as a starting point, but diverts it into exposure as climate and sensitivity as spatial information (figure 11) which shows which areas ("WHERE") are the most likely to be affected by climate change. The affected areas are divided into two sectors – biophysical sensitivity ("WHAT" - land use or infrastructure) and social sensitivity ("WHO" - population). Additionally, the effects of climate change can be reduced in both sectors by the adaptive capacity.

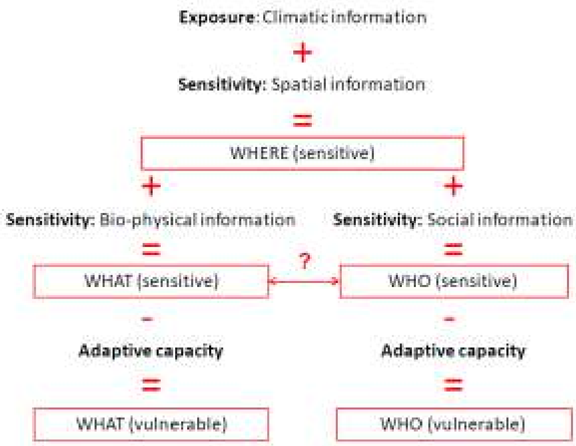


Figure 11: ETC/ACC concept of vulnerability (Schauser et al., 2010).

The boxes of "WHERE", "WHAT" and "WHO" are represented by indicators, defining exposure, sensitivity and adaptive capacity. ETC/ACC provided some examples of the indicator components of a vulnerability to heat waves. Among the climatic indicators are the maximum summer temperature, number of heat days and number of tropical nights. Meanwhile the spatial indicators are the urban and impervious areas. Together the climatic and spatial indicators specify where the heat wave causes an impact. The bio-physical sensitivity is described by land use (particularly the residential areas), location of hot spots (hospitals, retirement homes etc.), and residential housing condition. The social information is represented by the population density, population above 65 years old and single households, population with renal sickness and population working outdoors. The bio-physical adaptive capacity indicators are the blue (water) and green (vegetation) areas, meanwhile the soft adaptive capacity indicators are GDP, access to information via internet, household income, access to air conditioning and installation of cooling centers. Authors also analyzed a list of studies and reviewed numerous of indicators by the climatic threat. For the heat wave hazard, they analyzed six studies and evaluated used exposure, sensitivity and adaptive capacity indicators. Most of these indicators are based on literature review, but not on the statistical analysis (Schauser et al., 2010).

For the specific vulnerability to heat wave assessment case study, the ETC/ACC selected the cities of Birmingham (Great Britain) and Bozen/Bolzano (Italy) where they applied a method developed by Kropp et al. (2009). This method aggregates IPCC defined exposure and sensitivity elements into regional vulnerability index (figure 12). As the exposure indicator, the number of heat days for the years 2020, 2050 and 2080 was selected. The sensitivity was indicated by proportion of impervious area, population density and population over 65 years old. These datasets contained different resolution data. The number of heat days was produced from 120 x 120 meters resolution land surface temperature data received from LANDSAT TM satellite, past climate data and future regional climate model with spatial resolution 25 km x 25 km which was disaggregated in the end and composed into the number of days indicator (figure 12).

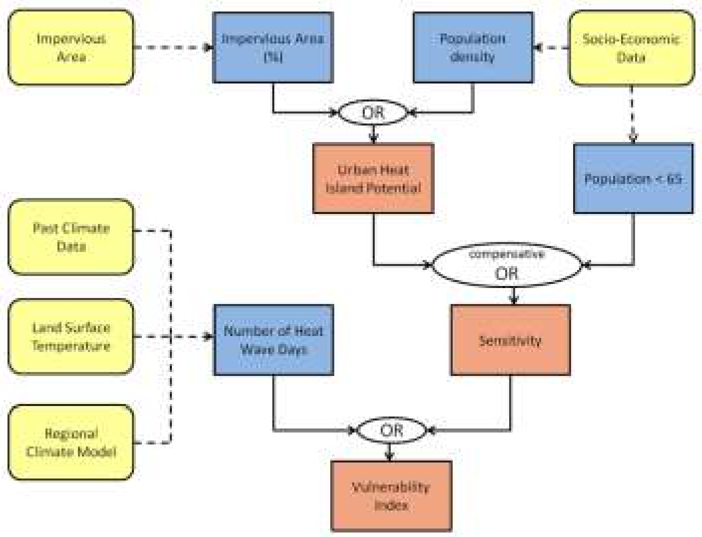


Figure 12: regional vulnerability to heat waves flow chart (after Schauser et al., 2010).

Unfortunately, the resolution, sources and processing information regarding physical and social data was missing. But by reviewing the results (figure 13) of the study, the resolution differences between the datasets can be identified. The layer of impervious surfaces had a high resolution, probably delivered by EEA as a soil sealing layer and available for entire Europe. The population density of Bolzano and population over 65 years old probably was available at the census tract level, most likely was received from a national or local statistical office. In order to combine all these datasets, they were normalized to the range 0 – 1. The UHI potential was aggregated by indicators of impervious area and population density. The sensitivity indicator was aggregated by UHI potential and the population older than 65 years old. In the end sensitivity was aggregated together with number of heat wave days for three future time steps (in the middle of figure 13) into final a vulnerability index.

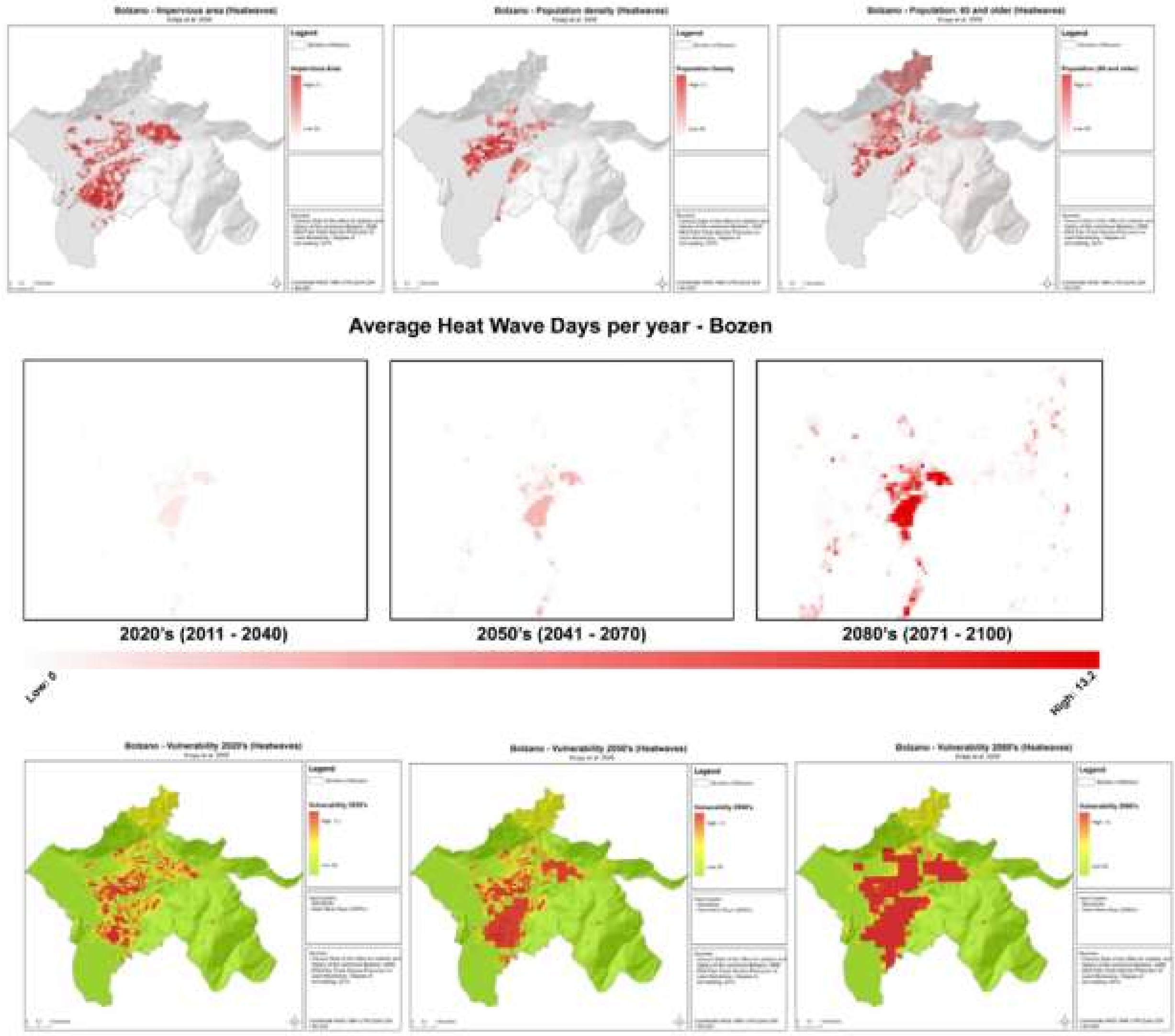


Figure 13: regional vulnerability index for city of Bozen/Bolzano (Schauser et al., 2010).

The three bottom images show the combination of sensitivity with different number of heat wave days in 2020, 2050 and 2080. In accordance with the future climatic model projections, the number of heat wave days and vulnerability increases over years. However, due to uncertainty and lack of future data, the resolution of the results decreases. According to the 2080 projection, most of today's populated areas will have relatively high vulnerability, compared with Northern and unpopulated zones.

Concerning the future data, it was modeled by the 3rd party future regional climate model "HadCM3Q0". The data was statistically processed and provided by the Met Office Hadley Center for the time periods 2010 – 2040 (for the year 2020), 2040 – 2070 (for the year 2050) and 2070 – 2100 (for the year 2080). It was the only future data in this study. Because not only the climate, but also the society and the landscape are changing, the comprehensive future vulnerability assessment would require additional social and physical data. Authors identified that one of the major gaps for future vulnerability to heat waves is the lack of information about future sensitivity and adaptive capacity changes which are very hard to project (Schauser et al., 2010) and still exists as a major challenge today.

Although the ETC/ACC study presented an indicators-based vulnerability assessment, some aspects are unknown. For instance, the Kropp's methodology, combining the data layers with

“OR” operator, and social/physical data’s sources, are questionable. No details were provided concerning the vulnerability’s aggregation/composition. The most likely reason for this is the limitations of intellectual property rights (Schauser et al., 2010).

The Kropp’s methodology was better explained in another study done by Lissner et al. (2012) which used the same approach. The aim of this study was to introduce a standardized methodology to assess vulnerability to climate change using the quantitative approach. (Schauser et al., 2010), and was applied in North Rhine – Westphalia, as the previous Kropp’s study (Kropp et al., 2009). This time the fuzzy logic which was used in all cases, was more clearly explained. According to Kropp et al.(2009), the fuzzy logic algorithm considers data uncertainties and allows the gradual allocation of the values instead the binary ones. It normalizes values from 0 to 1 using the customized minimum and maximum thresholds. Additionally, the approach applies the mathematical boolean operator “AND” which is used for the data aggregation. The final impact data is aggregated by two layers – sensitivity and number of heat wave days (figure 14). The impact is high if both the sensitivity and number of heat wave days, are high. However, the study does not say anything if one layer has low, meanwhile another layer has high value. From figure 14 it appears that if the low and high values are aggregated, it receives a low value which is the result of an “OR”, but not “AND” operator.

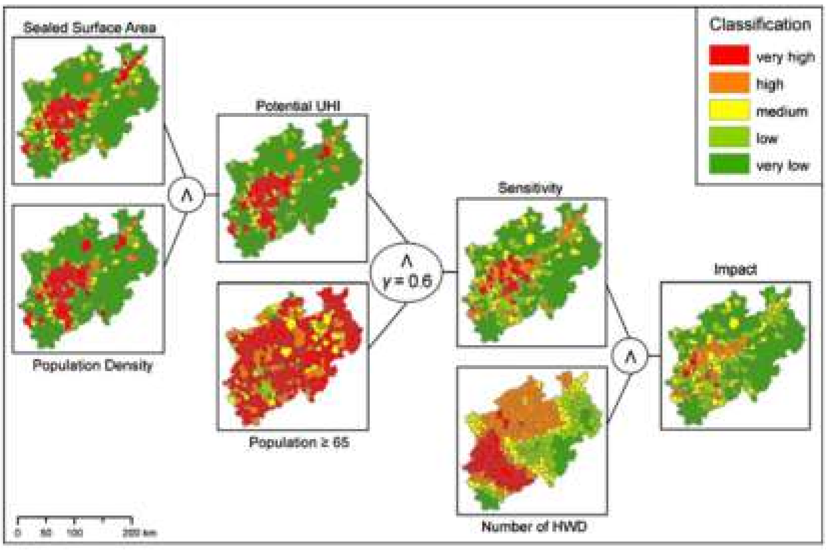


Figure 14: vulnerability assessment using the “AND” operations for data aggregation (Lissner et al., 2012).

The data used to compose vulnerability index is the same used in ETC/ACC study although the sources are different. The exposure data, the number of heat wave days was developed by two regional climate models - CCLM and STAR, using the A1B emission scenario. The re-sampled data from empirical measures from 1951 to 2003 was extrapolated as the 2060 scenario. The social and physical data was received from the local governmental spatial information agency. This time it was clearly noted that there were no future projections for sealed surfaces, future city development, future population densities and elderly proportion. The study has used the 2008 data as a baseline, assuming that it will not change over time (Lissner et al., 2012). Unfortunately, this study, as well as the previous one, considered only future number of heat wave days as future climate data, developed by regional climatic models. Instead of future population and physical data, the baseline 2008 year data was used.

The Vulnerability sourcebook – concept and guidelines for standardized vulnerability assessments

The vulnerability sourcebook is a successor of the "Vulnerability Network" project in Germany where the same approach was used to assess vulnerability across a number of different sectors and various administrative levels in Germany. The framework was enhanced, well documented and applied in Bolivia, Pakistan, Mozambique and Burundi. The aim of the sourcebook is to contribute to vulnerability assessments and to support effective adaptation planning. Along with the authors, comparing with other vulnerability guidance books, their publication offers a standardized vulnerability assessment approach covering a broad range of sectors and topics, various spatial levels and temporal resolution. The document was published by the German Society of International Cooperation (GIZ, "Deutsche Gesellschaft für Internationale Zussamenarbeit" in German), together with aDelphi and EURAC research, supported by the German Federal Ministry for Economic Cooperation and Development in 2014 (GIZ, 2014). The sourcebook is well structured and consists of eight modules: preparation of vulnerability assessment, development of the impact chains, selecting indicators, data acquisition, normalization, weighing and aggregation, and presenting. Although this sourcebook did not cover any examples of the vulnerability to heat waves assessment, its applied IPCC approach is a good standardized example of how vulnerability to climate change can be assessed.

The definition and concept of vulnerability, the study used was based on the IPCC Fourth Assessment Report (IPCC, 2007). Similar to the ETC/ACC (Schauser et al., 2010) study, this research uses four elements of vulnerability: exposure, sensitivity, potential impact and adaptive capacity (figure 15). The exposure is the external stressors of climate change and variability which affects the system from outside. The system's sensitivity is represented by natural, physical and societal environment and shows how sensitive is the system to the external stressors. The adaptive capacity is influenced by the environment and can increase or limit the system's adaptation. In the end, the vulnerability depends on system's ability to adapt to potential impact, caused by external stressor. Each element of vulnerability has a certain role - is a part of the system or affects the system. The conceptual framework is broad, but easily can be applied to any sector (for instance, fishery, human health, transport etc.)

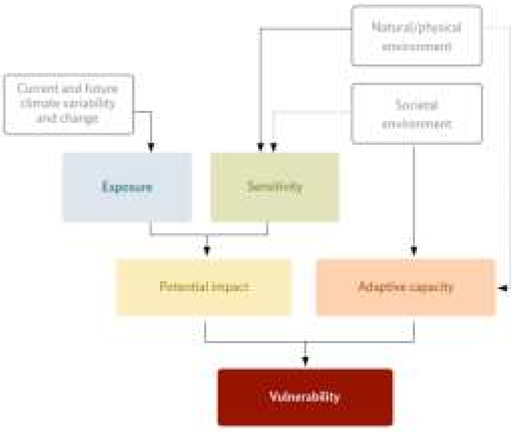


Figure 15: GIZ adopted vulnerability assessment conceptual framework from IPCC (GIZ, 2014; after IPCC, 2007 and after Isoard, 2010).

Each vulnerability element contains a number of factors and corresponding indicators. If no indicators are available, they should be modeled, projected or supplied from other models. When all required indicators are available, in order to compose them into the vulnerability index, they have to be normalized and weighted. Although GIZ (2014) gives very informative examples of how to normalize data using min-max method, the other normalization methods are not presented. The weighting defines importance of each indicator. In most of the cases the local experts from the case study area are required to assign weights on each indicator. In the end the processed indicators can be aggregated into the vulnerability index. Another option is to group indicators into the intermediate indices - the vulnerability components (exposure, sensitivity, potential impact and adaptive capacity).

In summary, the vulnerability sourcebook highlights the importance of future climate change impacts and risks and introduces a standardized vulnerability approach for most of the sectors, but does not provide any guidelines as to how to acquire or model future data.

Review of projected future heat-related mortality studies

The last study was not directly related to future vulnerability to heat waves, but more to future heat-related mortality. The study (Huang et al. 2011) was conducted as a systematic review of projected future heat-related mortality studies. In this study authors conducted a literature research and analyzed a number of peer-reviewed English language articles, published from January 1980 to July 2010. Huang et al. (2011) found in total fourteen studies which were related to future heat-related mortality. The common approach used in these studies was a scenario-based projections approach. The scenarios were used not to predict, but to understand uncertainties and find out possibilities of future decisions (Moss et al., 2010). The future uncertainties and complexity were identified as the greatest challenge in projecting future heat-related mortality in these studies. The authors of the review stated that, currently, there are no guidelines for scenario-based approach to assess future heat-related mortality. Their article aims to fill the knowledge gap and systematically reviews past literature in order to suggest new ideas for future research.

The fourteen studies, reviewed by Huang et al. (2011), cover future heat-related mortality estimation in cities of Canada, US, Australia, Italy, Spain, France and Hungary. The mortality projections were based on historical exposure-mortality functions. The common exposure indicator was maximum and mean temperatures. The other studies used composite indices, taking into account the temperature, humidity, wind speed, cloud cover, pressure and other parameters. Barnett et al. (2010) studied which temperature is most efficient to predict mortality. They analyzed daily humidity index, minimum, mean, maximum temperature and apparent temperatures in 107 US cities from 1987 to 2000. The results have shown that there is no “best” temperature measure and each parameter had similar predictive ability. Therefore, Huang et al. (2011) suggest to choose the temperature indicator based on availability. The future temperatures, used for these studies, were based on emission scenarios, developed by IPCC. Different studies used different climate models and emission scenarios, therefore it was difficult to compare their results.

One of the greatest challenges of the analyzed studies Huang et al. (2011) identified the uncertainty of future demographic changes which affects future population's sensitivity to heat waves. Studies have stated that the elderly are most susceptible to heat waves, mainly because of the limitation of physical abilities to cope with heat stress, the greater probability to live alone, their limited social contacts and their poor health (Hajat and Kosatky, 2010). However most of the studies did not consider the demographic changes and assumed that over time the population size and age groups will remain constant. Only a few studies used projected population or adjusted data: a) the heat stress and mortality study by Dessai (2003) developed population scenarios for Lisbon from the international IPCC Special Report on Emission Scenarios (SRES). For each scenario on the city scale, the Organisation for

Economic Co-Operation and Development (OECD) population growth's projections to Lisbon 1990 baseline population were applied. The national, regional and local projections were not available for the distant future or were not available at all; b) predicted future heat mortality impacts in five Australian cities by Guest et al., (1999) used city scale population projections for the year 2030. The projections were not modeled, but obtained from the Australian Bureau of Statistics; c) population projections for counties of Washington State (Jackson et al., 2010) for the years 2005 – 2030 were acquired from the Washington Office of Financial Management which developed them using the demographic forecast model, addressing births, deaths, net migration and fertility rate.

In addition to the population projections, Huang et al. (2011) analyzed whether or not the population acclimatization factor was considered in the fourteen studies. A few studies (Gosling et al., 2009; Kinney et al., 2008; O'Neill et al., 2005) noted that acclimatization can be done through increased use of air conditioning, improved building designs and urban planning which are typical adaptation measures, but not the population's acclimatization over time. Knowlton et al. (2007) approximated acclimatization for New York City by using the exposure-response curves from analogue cities (Washington DC and Atlanta). Meanwhile Cheng et al. (2008) and Hayhoe et al. (2004) used the mortality difference between historically hottest and coldest summers as a range for possible acclimatization. Dessai (2003) and Gosling et al. (2009) used the acclimatization scenarios. For instance, Dessai (2003) assumed that acclimatization of 1° C temperature is achieved in 30 years. Although the other studies did not consider the factor of acclimatization, Huang et al. (2011) strongly recommended to use it in order to assess future heat-related mortality.

Summary of literature analysis

The literature analysis review analyzed few comprehensive vulnerability assessment studies. Such analysis is essential in order to evaluate the possibility to assess future population's vulnerability to heat waves at the local scale considering future climate, landscape and population. Because no such research has been done yet, the successful vulnerability assessment studies were searched by four criteria: qualitative indicator-based approach, future data, social population's projections and heat hazard focus. Unfortunately, there was no such study which would satisfy all criteria.

The MOVE project (DG Environment, European Commission, 2011) has done a comprehensive vulnerability assessment to heat waves at the city district level using their own vulnerability concept. However it was focused on current, but not on future data. The ETC/ACC by Schauser et al. (2010) study used similar approach, but they included future climate projections which were downscaled to the local scale. In addition they developed impact chains and followed the IPCC vulnerability framework. Nearly the same approach was used by Lissner et al. (2012), to assess future heat wave impact at the city district level. They used the downscaled climate projections as well, but no future city development or future population projections were addressed. The other comprehensive and detailed vulnerability to climate change study was done by GIZ (2014). The documented step-by-step vulnerability assessment framework lacks case study examples of heat waves and no future, including climate, projections were considered in their conducted vulnerability assessment. The last research (Huang et al., 2011) reviewed fourteen studies of future heat-related mortality. Only three of them addressed future population's projections. One was using the global projections and adjusted baseline population, and the other two studies received projections from the local statistical departments for the city level analysis.

In the end it is clear that none of the reviewed studies are capable of assessing future population's vulnerability to heat waves at the local scale, because of the missing future socio-economic and physical data. This issue requires additional research and development of modeling techniques. But even before that, the vulnerability and relations between climate, landscape and population, have to be overviewed in details. These aspects are covered within conceptual setting and operational options of this thesis.

II. Conceptual setting and operational options

Because the modeling of future population's vulnerability is a complex study, it is important to identify operational options and to set the conceptual setting. The conceptual setting covers vulnerability, basics of urban landscape, climate and population. The level of detail of these topics in conceptual setting is rather low, but for the readers who lack knowledge in vulnerability, urban and climate sciences, this information is necessary in order to understand how vulnerability is modeled. Meanwhile the operational options help to understand data processing and modeling techniques used in this study.

Whereas vulnerability in this study is multidisciplinary and covers multiple topics, it has to be presented in greater detail. The first chapter in conceptual setting gives detailed overview about vulnerability, how it is defined, its concepts and frameworks. Additionally, it introduces the common vulnerability approaches and assessment methods used. This information is necessary to explain why the certain vulnerability assessment method or concept has been chosen for the Greater Hamburg case study. The second chapter introduces additional topics, supplementing vulnerability. It explains the properties of landscape and introduces urban climate and its classification with a major focus on heat. Additionally, this chapter covers the social and economic diversity in the city and how it affects population's vulnerability. It also looks at the effects of climate change on human settlements, gives an overview of the consequences of multiple disaster types on cities and reviews how urbanization negatively affects the population's vulnerability. Furthermore, the chapter explains available options to shift, manage and plan urbanization via urban planning, policies and zoning. In the end the common urban development patterns present three urban development scenarios which have been used for the case study of Greater Hamburg. These topics are relevant to understand the relations between urban landscape, climate and population which compose the proxy parameter, and are used to model population's vulnerability. The third chapter of operational options addresses the technical side of population's modeling and presents the basic principles of selected mathematical model, chosen landscape modeling software and its factors, the spatial data transfer and data normalization methods.

1 Vulnerability

Vulnerability in this study is a multidisciplinary topic, combining different aspects of urban landscape, climate and population. Thus, prior to the modeling of the population's vulnerability, various aspects about vulnerability have to be known. Meanwhile the specific population's vulnerability of Greater Hamburg case study, based on vulnerability aspects, presented in this chapter, can be found in chapter 4.2.

Vulnerability is a common term in the literature of environmental risks, hazards and disasters. But today it can be seen in many articles discussing climate change as well. Despite all scientific efforts to explain and understand vulnerability, it still means different things to different groups of people. Origins of the term "vulnerability" started in the early 17th century. It has Indo-European roots and emerged from the Latin word "vulnus" (wound) and "vulnerare" (to wound) (Oxford University Press, 2015; Thesaurus, 2014). Today, a word "vulnerable" in common English serves as an adjective meaning of "*exposed to the possibility of being attacked or harmed, either physically or emotionally*". And a vulnerable person is described as individual "*in need of special care, support, or protection because of age, disability, or risk of abuse or neglect*" (Oxford University Press, 2015). But this definition is too broad and does not bring the clarity or common agreement of what, exactly, vulnerability means. Because this thesis analyzes local impacts of climate change, the use of the term will be dedicated existing definitions of vulnerability in this domain.

In accordance with Eaking & Luers (2006), the definitions of vulnerability emerged from three main areas:

- Resilience in ecology;
- Risk/hazard (or biophysical) approach;
- Political-ecological/economic frameworks.

These areas partly correlate with main concepts of vulnerability (chapter 1.3). However, today in practice, these approaches often are mixed between each other.

Similarly to Eaking and Luers, Brooks (2003) also identified three focus areas of vulnerability: risk/hazard, economy/sociology and instead of the resilience in ecology, author referred one category as climate change (Klein and Nicholls, 1999; Pelling and Allen, 2003). Brooks (2003) sees vulnerability in climate change as "*the likelihood of occurrence and impacts of weather climate related events*". That statement would be correct if the vulnerability would be directed to biophysical domain only, however it is not. The likelihood and probability are parts of the climate change concept, but they cannot be considered as main factors (the details of vulnerability concepts can be found in chapter 1.3).

Füssel (2005) states that some authors use the term "vulnerability" to strongly relate to "exposure". One of the examples by Smith (2004) which names vulnerability as a human vulnerability to severe storms which rise because of the progressive occupation of the hazardous areas, and "*an estimated 75 million people are vulnerable to arsenic poisoning*". This statement agrees with the above mentioned risk/hazard or biophysical approach in which exposure is a critical part. In this case vulnerability is not directly connected with a climate change phenomena (storms), but more with the people's physical exposure. These limited examples show that the definition of vulnerability can be confusing.

1.1 Qualitative and quantitative analysis of vulnerability definitions

In order to understand the definition of "vulnerability", I updated a research done by WeADAPT project (WeAdapt, 2013), (Musser (2006), Green (2004) and Cutter (2006), which collected and analyzed 49 definitions of vulnerability, dating from 1974 to 2004. I assigned these definitions to the following domains: hazard, disaster, risk, climate change, resilience and mitigation. These domains can be also be interpreted as concepts. The domains of hazard, disaster, risk and mitigation are commonly used by disaster and engineering/physical scientists. Meanwhile, the domains of resilience and climate change are more common among social and natural scientists.

The analyzed definitions of vulnerability are short and simple, mainly referring to one domain. However, some of them are long, complex, broad and can be related more or less to all domains. The most common domains are the hazard, risk and resilience (figure 16). The hazard and risk domains show strong focus on the biophysical (risk and hazard) concept, while the resilience reflects a social concept. These three domains point out the most frequently used vulnerability concepts. The domain of climate change was not popular in last few decades, but the situation today is changing dramatically. And the last domain where the term vulnerability is used the least, is the mitigation. The following analysis of some significant definitions highlights the changing understanding of vulnerability in various domains through the years.

Figure 16: frequency of vulnerability definitions in scientific literature (1974 – 2004) by domain.

The distribution of meaning between different domains (figure 16) shows high diversity. The following analysis of some significant definitions highlights a changing understanding of vulnerability through the years.

The timeline of vulnerability definitions starts with the famous natural hazard researcher White (1974), who identified vulnerability as a "*degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor*". White uses the risk/hazard (the dominant at that time) concept, to describe vulnerability. However, today vulnerability is beyond exposure to hazard and this definition might be not sufficient for this study.

Gabor and Griffith (1980) follows the same concept and defines vulnerability not as a degree, but as a "*threat (to hazardous materials) to which people are exposed (including chemical agents and the ecological situation of the communities and their level of emergency preparedness)*" – with this definition, Gabor and Griffith named vulnerability as a threat to hazardous materials. In my opinion, this definition is too specific, even for a risk/hazard approach, because the threat is considered only as biophysical hazards. Moreover, this definition names the people which are exposed, as a subject. The other subjects, such as environment, buildings or special groups of people are not mentioned.

In 1981 Timmerman (1981) defined vulnerability in the similar way, but without specifying the hazard and the subject which is named as a system: "*Vulnerability is the degree to which a system acts adversely to the occurrence of a hazardous event. Human vulnerability is a degree of resistance offered by social system to the impact of a hazardous event*". This definition is similar to White's vulnerability description, but in this case system receives some functionality – not only the possibility to suffer/experience the hazard, but also act and maybe mitigate effects. And in the second part of definition, Timmerman specifies human vulnerability as sensitivity with some elements of adaptive capacity. In addition, contrary to Gabor and Griffith, Timmerman does not specify a subject or a stressor, giving them a broader meaning and some uncertainty.

Just a year later, in 1982, the United Nations Disaster Relief Organization (UNDRO) (known today as Department of Humanitarian Affairs in UN), defined vulnerability as a "*degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude*". This definition holds the similar level of abstraction as Timmerman's and highlights the risk/loss, by not specifying the cause (specific hazard) and subject (given element). In this definition the biophysical approach is emphasized, and contrary to Timmerman, no ability to react or resist is mentioned. In other words – only the external stressors are named.

Contrary, to previous definitions, Kates (1985) defined vulnerability as "*the capacity to suffer harm and react adversely*". This definition represents resilience and mitigation domains, but does not mention any specific hazard or the subject. It promotes the subject's capacity to suffer and react, and focuses mainly on the inner properties of the subject, without naming external stressors.

The UN/ISDR (2004) definition which Birkmann (2006) identified as the best known vulnerability definition, states that vulnerability is a set of "*conditions determined physical, social, economic and environmental factors or processes which increase the susceptibility of a community to the impact of hazards*". However, Birkmann did not mention the reason he considers it as the best known definition. This definition is quite broad and informative. It can be used in all domains, but it focuses on the community and its impact from hazards. Therefore, it is more related to the biophysical vulnerability.

Green (2004) provides a good example of how the definition of vulnerability can be neutral: "*vulnerability is the relationship between a purposive system and its environment where that environment varies over time*". He defines vulnerability as relation or junction between the system and environment, without specifying any additional context. In this case, the environment and the system are quite unclear and undefined, and gives to this definition quite broad meaning as well.

In 1997 the Inter-governmental Panel for Climate Change (Watson et al., 1997) identified climate change as a serious cause and included it into the vulnerability definition: "*Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability is a function of the sensitivity of a system to changes in climate and the ability to adapt to system to changes in climate. Under this framework, a highly vulnerable system is highly sensitive to modest changes in climate*". This definition is more complex and identifies the existence of a system which is suffering damage from climate change, and at the same time the sensitivity (the property of the state, ability to adapt) is defined as a part of vulnerability. Moreover, in 2001, IPCC published (McCarthy, 2001a) a slightly modified definition: "*The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*" – vulnerability is defined not as an extent anymore, but as a degree (similar to definitions by White, Timmerman and UN). The system, as a subject, stays unchanged. And the "damages" are now "adverse effects" (again referred to Timmerman) which are broader, but more comprehensive in the context of climate change. Also the consequence as an inability to cope is mentioned and the domain (function) of vulnerability has expanded. Vulnerability is described not only as a function of sensitivity, but also as character, magnitude and rate of climate variation (exposure), sensitivity and adaptive capacity. In summary, vulnerability is the function of three elements: exposure, sensitivity and adaptive capacity. While this latest IPCC definition is complex, it appropriately represents the complexity of climate change and its impacts. Therefore it is most suitable for this research, in order to assess future population's vulnerability to climate change. Some authors, however, have different and critical opinions about the IPCC vulnerability definition.

Brooks (2003) interprets IPCC definition as biophysical vulnerability which has much in common with risk concept. But the "risk" and the "probability" are not mentioned in the definition by IPCC at all. Moreover, Brooks sees most of the definitions of vulnerability as probabilistic or related to the probability of occurrence of the hazard. I agree that some of the definitions mention "probability", some indicate it indirectly, but not all of them. Brooks also says that many definitions relate to probability of outcome of the disaster. I would say definitions relate not to the probability, but to the fact of an outcome of disaster. For instance, none of the definitions say that the system or assets are vulnerable every certain period of time to specific hazards. They are vulnerable only when the disaster/hazards occur, when the discrete events are taken into account. If the continuous hazard is considered, the system or assets are vulnerable after the certain threshold. Therefore I disagree with Brooks' statement and endorse Füssel's (2005) position. He maintained that it is essential to understand the risk of global climate change. Originally, the hazard-risk concept considers discrete and rare events, like disasters. And the probability serves very well to describe their risk. But a climatic change is a long, continuous and not discrete process. However, consequences of climate change are its impacts, or "adverse effects", as mentioned in the definition. These effects can be determined by the magnitude and the probability (property of risk) of the specific climatic scenario. Therefore, I agree that the risk and the probability take a part in the IPCC definition and affect vulnerability indirectly, but still, the IPCC definition does not represent a pure biophysical vulnerability concept, because it also includes sensitivity, adaptive capacity which originally are not the parts of biophysical (risk/hazard) vulnerability.

Another question, raised by Füssel (2005) is whether or not the IPCC definition describes future and/or long term vulnerability. It is obvious that the effects of climate change are global and long term. The statement that the IPCC's vulnerability definition describes only future vulnerability is too subjective and maybe false. The question must be asked: What about the historical climate change and past vulnerability, even if it was a long term climate change? Füssel may have kept in mind future vulnerability due to today's awareness of future climate change, without looking into the past. But in this case, I would agree that IPCC focuses on a long term, but especially on future vulnerability.

Other scientists from the European Topic Centre on Air and Climate Change (Schauser et al., 2010) identify the IPCC definition as limited and complicated to operationalise. The main limitations they see are the use of unclear terms, the form of the function, and the overlapping concept between adaptive capacity and sensitivity. The highest challenge they identified is the absence of the adaptive capacity concept and how it is affected by political, social, economical and technological factors. Since the numerous factors are influencing adaptive capacity, a short definition of vulnerability necessarily fails to give a clear explanation of this term requiring additional definitions. In comparison with the other definitions, the terms in IPCC definition are quite clear and are also explained in detail in the glossary of the IPCC report (Watson et al., 1997). Additionally, the concepts of sensitivity and adaptive capacity unavoidably overlap, because they have many common properties and both belong to the same, the socio-constructivist concept of vulnerability.

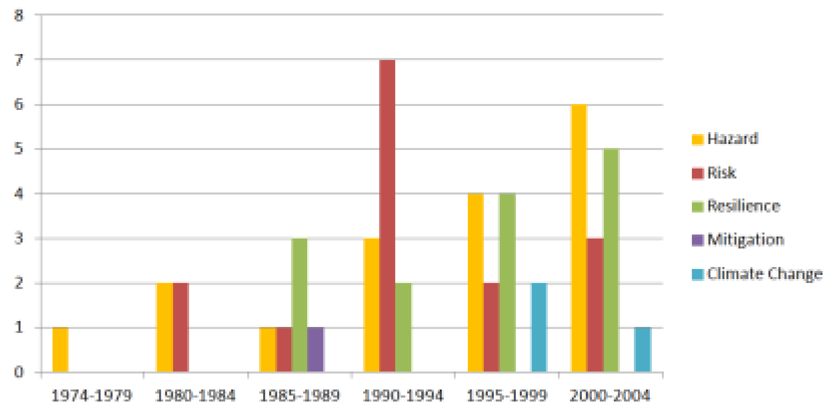


Figure 17: frequency of vulnerability definitions by domain and time period, they were published in the literature.

Figure 17 represents the timeline of definitions' domains from the investigated literature. Following the graph, the increase of the new definitions in hazard and resilience domains can be observed. This is not surprising, because many definitions are developed for case studies where only one specific hazard is considered. Meanwhile the climate change, as the domain, emerges only in the second part of '90, when the awareness of climate change became more present in the scientific literature and public debates. A peak of the vulnerability definitions emerges in the early '90. The reason could be the number of disasters, that occurred between 1980-1990 (Earthquake in San Francisco in 1989, numerous hurricanes over Atlantic, El Nino in 1982´and 1983, Armenian earthquake in 1988 and others) (CRED, 2014). It is worth to mentioning that the development of new vulnerability definitions does not reflect an actual use of these definitions.

According to Smith & Petley (2009) (table 1) the risk (behavioral) paradigm was common in 1950 – 1970, when it was observed that hard engineering works did not always mitigate the hazard. Scientists began to focus on behavior, risk assessment and measures to minimize the risk. Later on (1970 – 1990), because of the inefficient disaster loss' reduction, the paradigms have changed from behavioral to development and encouraged people to focus on state and sensitivity which increases their capabilities to cope with hazard instead of searching for physical causes of hazards. High emphasis was placed on socio-economical and political differences between developing and developed countries. It was interpreted that economic dependency increases the frequency and impact of natural hazards. However, this paradigm did not go along with the peak of emerged vulnerability definitions of risk domain from 1989 till 1995 (figure 17).

Table 1: evolution of environmental hazards paradigms (after Smith and Petley, 2009).

Period	Paradigm name	Main Issues	Main Responses
Pre-1950	Engineering	What are the physical causes for the magnitude and frequency of natural hazards at certain sites and how can protection be provided against the most damaging consequences?	Scientific weather forecasting and large structures designed and built to defent against natural hazards, especially those of hydro-meteorological origin
1950-1970	Behavioural	Why do natural hazards create deaths and economic damage in the developed countries and how can changes in human behaviour minimize the risk?	Improved short-term warning and better long-term land planning so that humans can avoid the sites most prone to natural hazards
1970-1990	Development	Why do people in developing countries suffer so severely in natural disasters and what are the historical and current socio-economic causes of this situation?	Greater awareness of human vulnerability to disaster and an understanding of how low economic development and political dependency contribute to vulnerability
1990-	Complexity	How can disaster impacts be reduced in a sustainable way in the future, especially for the poorest people in a rapidly changing world ?	More emphasis on the complicated interactions between nature and society leading to the improved long-term managemend of hazards according to local needs

The last, complexity paradigm which emerged in 1990 and is still used today, addresses global climate change effects and involves much more complex relations between nature and human environment than hazards. The people have become aware that sea level rise or temperature increase in the future can have global impacts and they have started to search for approaches to sustainable development, to reduce greenhouse gas emissions. The view of disasters has changed from the discrete events to the long term and more frequent impacts of climate change.

But to go back to the vulnerability terminology, as Timmerman posited in 1981 (Timmerman, 1981), "vulnerability" is such a broad term which is almost useless for careful description.

Füssel (2005) and Green (2004) joined Timmerman and stated that there is no single 'best' and 'correct' vulnerability. The neutral/coarse definition of vulnerability is not always sufficient. The question of "how much vulnerable is Hamburg and Cape Town?" does not have any sense without more details provided – some would say Hamburg has higher vulnerability due to the storm surge from the Elbe river and possible public transport disruption, while others would say that Cape Town is more vulnerable, because of the high crime, poverty rates and sea level rise. Vulnerability is very context specific. Each situation is unique and has its own properties, values and representations. Therefore, each definition of vulnerability is suitable for a specific purpose and it is important to know the vulnerable situation.

1.2 Vulnerable situation

The vulnerable situation (i.e. assessment context) was emphasized by number authors (Brooks, 2003; Downing et al., 2003; Füssel, 2005; Green, 2004; Luers et al., 2003), because the term "vulnerability" should be used only when the situation is known. The meaning of vulnerability is more context specific than a universal concept and the vulnerability depends upon decisions which should be taken (Green, 2004).Therefore, there is a need to analyze what kind of vulnerable situation exists for each unique case.

What affects vulnerability and what are the factors? The United Nations (2004) identified following vulnerable situation factors through the disaster reduction initiatives:

- Physical (exposure of vulnerable elements);
- Environmental, and
- Social factors.

These factors are internal and based on domain. They describe a state of the system and must be known in order to reduce an impact of disaster. Meanwhile, the external factors are not specified by UN. They are defined as characteristics of stressor (negative) and external assistance (positive) (Füssel, 2005).

The "Mediation" project (Carter, T.R. and Mäkinen, K, 2011) which deals with climate change policy in Europe, takes into account such properties of vulnerable situation:

- The type of exposure (people, natural resources and region);
- Nature of climate change hazard (i.e. heat-wave, flood etc.);
- Nature of vulnerability (i.e. damage to property, loss of fauna etc.).

Nature of vulnerability represents a risk/hazard (biophysical) approach but at the same time cover some aspects of sensitivity (social properties of affected people). In comparison to UN (United Nations, 2004) factors, they do not specify a domain (social, natural or artificial), but split into the groups of the external stressor (the cause), subject and consequence. However, these factors still have to be more specific in order to identify a vulnerable situation.

Green (2004) uses another set of indicators. He implies vulnerability by four following steps:

- A system;
- Specific objectives of the system;
- A dynamic environment which supports or interrupts to achieve these objectives;

- Processes/relations between the system and the environment of the adaptive strategies for the system.

According Green (2004), the first step is to identify and describe the system – it is important to know an environment. The following step is to define a desired state of the system which should be achieved and maintained. Ideally, the system has to function, but there are always are stressors, inner or outer. In our case of vulnerability, the hazards or climate events are the challenges or so called "perturbations". These perturbations can vary in magnitude and nature. They can adversely affect the state which reacts to these changes and tries to minimize effects. The effects prevent the system from reaching desired state of the system in order to function again. The system seeks to achieve objectives with the highest efficiency and at the same time minimize the extents and duration of perturbations. This causes a trade-off between the level of attainment of the desired objectives, the system's susceptibility to perturbations and a rate at which the system recovers. After a shock of perturbation the ideal situation is to recover to a desired state of the system in the shortest possible time. It is not necessary, however, to return to a previous state of the system, a state before the perturbation (Green, 2004). The Green's approach focuses on the system itself and relies on the desired objectives of the system. However, it is still difficult to identify the vulnerable situation and quantify the factors when the emphasis on the system and its properties is not so explicit.

The comprehensive framework to identify a vulnerable situation is developed by Brooks (2003), Downing et al. (2003), Füssel (2005) and Luers et al. (2003). Their framework defines dimensions and context of a vulnerable situation which is represented by:

- System: a system of a region and/or population group and/or sector;
- Hazard: an external stressor (or set of stressors like floods and heat waves which also can be named as perturbations);
- Valued attribute: a valued attribute (or variables) of the vulnerable system that are threatened by hazard. Effects of complex hazards can vary on a particular system or community (i.e. heat stress to population, flood damage to crops);
- Temporal reference: a time period of interest (Füssel suggests to use such terms as 'current', 'future' or 'long term').

Füssel (2005) proposes an even more detailed analysis of vulnerable situation by identifying additional vulnerability factors (also known as risk factors). Many authors distinguish these factors as external (system is exposed to) and internal (the properties of the system). The following groups of factors also can be used to identify the most appropriate vulnerability concept for specific vulnerable situation.

Scale group: internal vs. external

Factors which are controlled by the community or the vulnerable system itself and indicate their properties are considered as internal factors (i.e. land use, local law regulations etc.). Such factors as national policy on the local level or external financial aid are identified as external factors. However, on the national level, the national policy would be internal, but financial aid from another country would be an external factor.

Disciplinary domain group: socioeconomic vs. biophysical

Socioeconomic factors are related to the distribution of power, economic resources, social institutions, cultural practices and all other characteristics of social groups, typically investigated by the social and economic sciences. Brooks (2003) suggests that the social internal factors may be further distinguished between generic and specific hazard factors. Examples of socioeconomic factors are poverty, risk awareness, income, age etc. Meanwhile the biophysical vulnerability's factors refer to the system properties, investigated by physical sciences. Useful and specific examples of such factors are the topography, weather phenomena, flash flooding etc. Socioeconomic and biophysical factors may overlap sometimes, for instance in the case of built infrastructure or land use.

Table 2: examples of domain factors by scale (after Füssel, 2005).

Domain / Scale	Socioeconomic	Biophysical
Internal	**Response capacity** (unemployment, income, social networks etc.)	**Sensitivity** (topography, land cover, typical climate etc.)
External	**External social factors** (international policies, external aid, global economy)	**Exposure** (precipitation, heat wave earthquakes etc.)

All four groups (socioeconomic, biophysical, internal and external) of vulnerability factors complement to create a profile of a vulnerable system or community to a specific hazard at a given point of time. Vulnerability can be reduced or increased by targeting any group of vulnerability factors and vulnerability can be identified differently, dependant on which factors are taken into account.

However, there exist factors which can be assigned to multiple groups: as internal and external, socioeconomic and biophysical or even to all four groups. The list by Füssel (2005) gives following naming:

- Defined by one group of factor (scale and domain);
- Cross-scale (internal and external factors);
- Integrated (socioeconomic and biophysical domains);
- Cross-scale integrated (all four groups);

By summarizing all the factors and dimensions, the following properties of each vulnerable situation should be considered:

- Temporal reference: the time period of interest (current, future, long-term);
- Scale: internal, external, cross-scale;
- Disciplinary domain: socioeconomic, biophysical, integrated;
- Vulnerable system: the system of a region and/or population group and/or sector of concern;
- Values' attribute: the valued attribute (or variables of concern) of the vulnerable system that are threatened by its exposure to hazard (for instance, urban population). Complex hazards may have a wide range of effects on a particular system or community (heat stress and flood susceptibility);
- Hazard: the external stressor (or set of stressors of concern) (floods and heat waves);

Giving names to the temporal reference, Füssel (2005) suggests to use terms 'current', 'future' and 'long-term' due to the possible conflicts with other terminology. The 'coping capacity' is described as the ability to cope with short-term weather variations, while 'adaptive capacity' as an ability to adapt to long term changes, like climate change. Both can be determined by different factors. I would say that the coping and adaptive capacities are quite similar concepts and the statement, that one suits long term, the other short term applications, is too categorical.

An above described conceptual framework of vulnerable situation helps to understand and interpret vulnerability, to identify a vulnerability concept and suggests how it should be framed and applied. It also improves the communications between scientists when talking about specific vulnerability assessment. Additionally, it promotes discussions of how and why different vulnerability concepts differ from each other. And last, but not least, it provides a framework to review existing terminologies of vulnerability (Füssel, 2005).

1.3 Vulnerability concepts

As we discussed previously, there is no one vulnerability, as well as one definition. Different research fields have different perspectives of vulnerability, different values, assessment methods, approaches and different concepts of vulnerability. The word "concept" emerged from Latin word "conceptus" which means to conceive. Today "concept" means an abstract idea, plan or theme, understanding of something ("Dictionary, Encyclopedia and Thesaurus - The Free Dictionary"). Different concepts of the same thing mean different understanding and perceptions. Therefore, it is very important to analyze and evaluate existing concepts, to know their strengths and weaknesses, and their values. Only then, depending on goals, methods and approaches, can the most suitable concept be chosen and employed.

There are a few ways of vulnerability concepts' analysis. Birkman (2006) discuss the spheres of vulnerability by widening the concept and increasing dimensions and the number of factors. However, my way is domain-orientated and may be a better solution in distinguishing and applying the vulnerability concepts.

The general concept of vulnerability evolved from the social sciences in 1970s and focused mainly on disaster risk (Schneiderbauer and Ehrlich, 2004). Since then, the dominance of hazard-focused paradigms got altered by vulnerability as a starting point for risk reduction studies (Birkmann, 2006; Brooks, 2003; Füssel, 2005). Preston et al. (2008) highlights two main concepts of vulnerability: biophysical and social vulnerability. These concepts are popular among the scientists, working with environmental impacts. Each concept has different vulnerability meaning and can be easily misunderstood. Some of the authors (Brooks, 2003; Füssel, 2005; Preston and Smith, 2008) are not talking about the third vulnerability concept directly, but they mention it as a climate change vulnerability concept which is a mixture of both, biophysical and social vulnerability. I think this concept is important for the climate change research community in order to have its own concept with specific values, understanding of vulnerability, risk, exposure and sensitivity. This concept received more attention after rising awareness and exposure of the IPCC assessment reports in the media of future climate impacts. However, the scientists from different disciplines should be cautious of conceptualizing vulnerability. It is important to know key aspects of each vulnerability concept and choose the most suitable one. The following sections informatively describe three main concepts of vulnerability.

Biophysical vulnerability

The term "biophysical" emphasizes a physical component of the nature of the hazard and its impacts to bio or socio elements. The biophysical vulnerability concept is the oldest concept, coming from the natural hazards and risk discipline. It is also referred as "the former concept of risk approach" (Brooks, 2003) as well as "vulnerability of the pre-existing condition". Often biophysical vulnerability is referred to the exposure or susceptibility, but not to the risk, as some authors (Cutter, 2006) state. Biophysical vulnerability is an element of a risk, together with the element of hazards and exposure (Birkmann, 2006; Smith, 1992).

The definitions of biophysical vulnerability vary between the authors as well. Brooks (2003) names biophysical vulnerability as (I) "*an element, caused amount of damage to a system by a particular climate event or hazard*" (definition by Jones R and Boer R, 2003) and (II) "*as a state that exists within a system before it encounters a hazard event*" (Pelling and Allen, 2003). The first (I) definition is similar to the risk definition and includes negative consequences of hazards without mentioning the probability. I agree with Füssel (2005), that this definition is more suitable to risk, than to biophysical vulnerability, because the vulnerability itself cannot cause the damage. Rather it expresses the biophysical susceptibility and exposure. Meanwhile, the second (II) definition is more similar to the social vulnerability (or vulnerability in risk approach) in that it is defined as a state of a system. A better and simpler definition of biophysical vulnerability was suggested by Burton et al. (1993). He names biophysical vulnerability as exposure of human systems to natural extreme events and, as a consequence to hazard. Hazard at this point is a stressor, but neither a function nor a determinant of biophysical vulnerability (differentiated from the risk concept). It is referred to physical manifestations of climatic variability and its occurrence. According to Brooks (2003), the hazard could be defined as long term climate changes and shifts in climatic regimes. I disagree - biophysical vulnerability covers (or should cover) discrete, but not continuous long term climatic change events and their impacts which have different properties, scale, and require different perspective, assessment methods and frameworks. Therefore, the long term climate change events and their impacts should not be mixed with biophysical vulnerability.

As it was mentioned before, the biophysical vulnerability focuses on exposure and susceptibility. According to Cutter (2006), the biophysical vulnerability analyzes hazardous conditions, potential hazards, their frequency and locational impacts, as well as the human occupancy within the hazardous zone. The exposed units often are measured as number of people, buildings, hectares of farmland etc. Biophysical vulnerability focuses on human exposure to hazard, rather than on people's ability to cope with a hazard (Brooks, 2003) whereas coping is reflecting more the inner property of a system. Coping, therefore, belongs to the social vulnerability concept. The biophysical vulnerability can be identified in terms of amount of damage inflicted to a system and is assessed by indicators, such as monetary costs, lives lost, people affected etc. (Brooks 2003). The following three examples of the case studies of biophysical vulnerability assessment introduce the applicability and common practice:

(I) The Rocky Ripple community in Indianapolis, IN, USA is at risk to be inundated by the White River. One of the mitigation options is to build a dike and protect the community from flooding. However, the construction of the dike is expensive and engineers have been asked to calculate whether the losses of past floods on buildings would be higher, if the flood happened today, than the costs of the construction of the dike.

(II) A major hailstorm devastated crops of the local farmers of the Schleswig Holstein, Germany last May. Luckily, the crop insurance mechanism is in place and local authorities were asked to evaluate the percentage of the lost crops by municipalities which would assist in a more efficient distribution of funding.

(III) Curonian Spit, a famous Lithuanian resort, got hit by an early summer storm. More than 3000 inhabitants and about 5000 tourists did not have a power supply, due to failure of the power grid. The engineering company reported power grid disruptions at more than twelve locations.

Social vulnerability

Social vulnerability "*evolves from activities and circumstances of everyday life or its transformations*" (Cutter, 2006; Hewitt, 1997) and often it is seen as sensitivity or adaptive capacity (Preston and Smith, 2008) of an affected system. Cutter (2006) names social vulnerability as a tempered response. Such terms have risen from social studies in which human societies are identified as susceptible to damage from external hazards (Pelling and Allen, 2003). Contrary to biophysical vulnerability, the hazards in social vulnerability are external factors. They are outside the system and cause negative impacts. Along with Adger and Kelly (1999), the social vulnerability is an "*inherent property of a system arising from its internal characteristics*". The interaction of social vulnerability with the hazards produces damages and losses expressed as human mortality and morbidity (Brooks and Adger, 2003). Although the social vulnerability and hazards are closely connected, social vulnerability is not a function of hazard severity or probability of occurrence. Therefore, the social vulnerability may be seen as the determinant of the biophysical vulnerability (Brooks, 2003). However, Füssel (2005) disagrees with such statement. He prefers to see the social and biophysical vulnerability distinguished and independent. But Brooks used the word "may", therefore the social vulnerability can, but does not have to be an element of biophysical vulnerability.

Cutter (2006) sees the social vulnerability as an outcome of social (susceptibility and ability to respond) and place (physical environment) inequalities. I would disagree, saying that it depends on the target. If a study analyses the environmental vulnerability, then the place inequality could count as an inherent property. Otherwise, the place inequality represents the exposure which is more reflected in biophysical vulnerability. However, if the place inequality means a social environment within the system, then it could be assigned to the social vulnerability.

Social vulnerability is influenced by lack of access to resources, including knowledge and information, limited access to political power and representation, certain beliefs and customs, weak buildings or individuals, and by infrastructure and lifelines (Blaikie, 2004; Cutter et al., 1997; Mileti, 1999; Mustow, 1995). Although many of these indicators hardly can be quantified, often they represent adaptive capacity. Most of the social vulnerability studies focus on demographic and housing properties, such as age, gender, race, ethnicity, income, building quality and building infrastructure (Cutter, 2006). The indicators of poverty, housing quality, food availability, health, marginalization have been identified by Adger and Kelly (1999), Cross (2001) as important factors of social vulnerability as well. All of these indicators have much in common with adaptive capacity, sensitivity and resilience.

Case study examples of social vulnerability assessment:

(I) The Nepal earthquake in 2015 inflicted more than 9000 human losses and more than 21 000 were injured. Many people had no place to live. Till most of them were sheltering in survivor centers, government initiated a reconstruction campaign and allocated huge amount of funding. The local and national construction companies were encouraged to participate in this campaign.

(II) Huge farmlands in East Asia are suffering because of intensive farming. Although the advancing technologies require less and less manpower in agriculture, farms in Asia still employ many people. In order to prevent the upcoming increase in unemployment, the governments initiated an education program and decided to proceed progressively from farming to mining activities in the region. This would help local workers to re-orientate in the market without losing their jobs. The first task, however, is to assess the number of people working in the farming sector and evaluate how many of them would lose those jobs. This would be followed by a study of those people's status, such as age groups, income and education levels in order to know how seriously affected they would be by the loss of their job.

(III) Refugees from Africa, Balkans and Middle East are crossing the Mediterranean Sea and coming to Greece, Italy and other EU countries. Greece and Italy have asked for additional funding to provide better living conditions to incoming refugees the number of which is increasing daily. In order to provide sufficient help to incoming refugees, a certain amount of tents, food and sanitary supplies, doctors etc. is needed. Moreover, some areas in Greece and Italy are lacking space to establish refugee camps. The new need is to find additional spaces which could be used to establish basic utilities and tent sites for refugees.

Climate change vulnerability

The climate change vulnerability defines the effects of the climate change impacts to exposed individuals, communities or assets. It is a quite broad (in various aspects) concept and often considers both biophysical and social vulnerabilities, but in a broader sense. The best definition, probably, covering all aspects of climate change was developed by IPCC Third Assessment Report (TAR) (McCarthy, 2001a) which names vulnerability as a "*the degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity*". However, some authors (Füssel, 2005) defined it as biophysical vulnerability. It is not surprising, by knowing that the impacts of climate change in former times were named as climatic variability or climate events, and went side by side together with hazards and biophysical vulnerability (Brooks, 2003). Today, however, the climate change community has a different understanding and would prefer to separate it from the natural hazard sciences which focus mainly on physical factors. Coming back to the TAR definition, I would disagree with Füssel (2005). Even if the definition puts more weight on the biophysical elements, additionally it adds sensitivity and adaptive capacity as properties of the system which emerges from social vulnerability. In the Fourth Assessment Report (AR4) the IPCC vulnerability concept shifted closer to sensitivity and adaptation, and in the Fifth, the newest Assessment Report (AR5) the principles of the vulnerability concept were, again, similar to the disaster risk concept. Although the terminology and the understanding of vulnerability differ, the main principles and logic behind them is the same (GIZ, 2014).

The main difference between the biophysical and climate change vulnerability is that the latter one does not include any risk or probability factor. Both are analyzing physical threats to systems. However, the main advantages of climate change against biophysical vulnerability are that the adverse climatic events are unavoidable. The benefit of vulnerability reduction is clear, regardless of the future changes in risk. Second, exposed humans have heterogeneous coping capacities and are able to adapt, while biophysical vulnerability does not analyze these properties in details. The third, the reduction of vulnerability lowers the risk of climatic events (hazards), but the inverse process is not necessarily true (Sarewitz et al., 2003). And the fourth, the biophysical assessment often does not consider social factors which makes general assessment less plausible (Preston and Smith, 2008).

Table 3: vulnerability characteristics between natural hazards (biophysical vulnerability) and climate change (climate change vulnerability), (after Füssel, 2005).

	Natural hazards	Climate change
Charachteristics		
Temporal	Discrete events	Long-term and continuous
Dynamics	Stationary	Non-stationary
Spatial cope	Regional	Global but heterogenous
Uncertainty	Low to medium	Medium to very high
Attribution	Natural variability	Natural and anthropogenic
Systems of concern	Social systems and built infrastructure	All systems
System view	Static	Dynamic and adaptive
Consequences	Specific impacts	Broad range of impacts
Targets for risk reduction	Internal vulnerability	Hazard potential and internal vulnerability
Analytical purpose	Normative	Positivist and normative

Füssel (2005) addresses the differences between the vulnerability in risk (natural hazards) and climate change (table 3). His first point is that the climate change is a continuous process which increases or decreases the level of risk. Meanwhile the disaster is considered as a discrete event, causing additional risk to a system. The second point is that the climate change is a long term process. This process requires dynamic assessment frameworks to address the uncertainty of future hazards and changes of vulnerability over time. On the other hand, the hazards are stationary and exogenous, assuming that vulnerability is constant. Additionally Füssel states that the climate change is complex, spatially heterogeneous and uncertain. Mainly due to the larger scale of climate change and the variety between the exposed elements, their properties, the regional climate as well as different impacts of climate change events. I would partly agree. On the other hand, the climate study in most of the cases can be downscaled and focus on a specific climatic phenomena in a certain location for a specific time frame. And the last but not least, the climate change may have multiple effects on a system. Füssel argues that disasters uses a single metric, such as lives lost, percentages of damage etc. in order to define the hazard attributed risk. Whereas the climate change is more complex with multiple effects which are measured differently, and in the end they have to be normalized and aggregated. However, the effects of climate change can also use the single metric and can be analyzed as single hazards with specific impacts and affecting only certain parts of a system.

The factors affecting the climate change vulnerability are similar to the biophysical and social vulnerability. Because the spatial scope usually is broad and heterogeneous, the factors often influence not only social and anthropogenic, but also the environmental structures. Moreover, due to higher uncertainty and consideration of continuous long term events, the climate change concept avoids naming exact numbers. The reason is the complexity of the processes and limited possibilities to deliver accurate results of the long term future. However, the desired outcome of the climate change vulnerability concept is the analysis of the processes and actions which should be taken in order to mitigate climate change effects, decrease system's sensitivity, increase their adaptive capacity and resilience. The next three examples present possible climate change studies and influencing factors:

(I) The heat wave in France in 2003 raised awareness of future heat stress in European cities. Following the scenario that in 2100 the global temperature will increase by 4 °C, it is important to know what heat stress impact could cause to the population in the certain European cities. For this reason it is important to know how the environment will change, its susceptibility to increasing temperature and emitted heat, exposed population and internal abilities to deal with the heat.

(II) The variety and quantity of fish in the North Sea changes not only because of the fishing patterns, but also because of climate change. Following the scenarios of change in salinity, acidity, the water temperature and currents, it is important to find out what kind of species would emerge in the local waters, how fish would migrate and how local fishers and companies should deal with these changes.

(III) Winter tourism is an important industry to European countries, situated around Alps. However, the increasing temperature threatens the ski resorts, but increasing temperatures and sunny weather patterns are causing an increase in the flow of Summer tourists. Instead of going to Southern Europe, where the heat is becoming unbearable, tourists are looking for places in the valleys of the Alps. So, while there is a decrease in Winter tourism in these areas, there is an increase in Summer tourism. To plan future tourism strategy and investments, it is important to assess these changing patterns and forecast possible future needs of incoming tourists.

It may be noticed, that these examples are more complex, uncertain and often immeasurable, in comparison to examples of biophysical and social vulnerabilities. It could seem to be quite confusing and not rewarding, but it is an issue of future climate change – it is always easier to assess past or present than the future.

1.4 Vulnerability frameworks

The vulnerability frameworks systemize concepts and make them operational and applicable. They help to develop methods and define indicators. The frameworks differ in their concept, complexity, structure, attributes and space. As we know, each vulnerability case is unique and has specific goals, values and data available. Therefore, often each approach requires a new framework. Many approaches are based on the same concept and share similar values. Plenty of frameworks are described by Birkman (2006). However, I decided to continue with the domain-orientated approach. The following three frameworks employ the above mentioned concepts and help to understand their operability.

Hazard-risk (biophysical vulnerability)

The first framework, the hazard-risk framework, is the most common hazard-risk framework and represents biophysical vulnerability concept. The risk is defined as a probability multiplied by consequence (International Organization for Standardization, 2002). The hazard-risk (or disaster risk) approach is widely applied in technical studies on disasters. In the hazard-risk community the risk is a function of hazard, its probability and consequence and vulnerability. In other words, the risk depends on the probability of occurrence of the hazard and the systems' vulnerability which is exposed to those hazards (Brooks, 2003).

Crichton (1999) defined risk as a triangulated space and the probability of a loss which depends on hazard, vulnerability and exposure (figure 18). An increase or decrease in any of these elements, respectively increases or decreases risk. In this case, as well as an explanation by Brooks (2003), vulnerability means sensitivity or susceptibility of assets (i.e. humans, buildings etc.).

Füssel (2005) differentiates risk into discrete and continuous climatic events. In a case of a discrete hazard of a given magnitude, the risk can be identified as Risk = Probability * Consequences. In a case of a continuous, the linear event, the risk is a function of hazards and vulnerability (social vulnerability): Risk = Hazards * Vulnerability (Wisner, 2004). If we combine the expressions of the continuous and discrete event, we have the same expression as Brooks (2003).

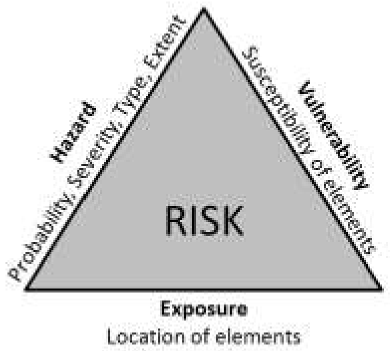


Figure 18: Crichton triangle, frequently used in hazard-risk concept (after Crichton, 1999).

The hazard-risk frameworks slightly differ from case to case. However, the properties of the main factors are similar. The good illustration by Crichton (1999) (figure 18) visualizes these three factors as a triangular space. Each of them is independent, equal, but has a close relationship. The exposure factor works as a bridge between hazard and vulnerability: if the elements (assets or humans) are not in a location where the hazard occurs, there is no risk. If there is no hazard, or the assets are not exposed or they can mitigate/be resilient, there is no risk (edge of the triangle) as well. If the hazard or any other factor increases, while others are not extreme, the larger part of the triangle is covered and causes higher risk.

Social constructivist (social vulnerability)

The social constructivist approach follows social vulnerability concept and analyzes, who is the most vulnerable and why, by identifying the socioeconomic response capacity of individuals and groups to cope with external stressors. It highlights social construction of vulnerability, the economic and social processes which affect individuals and communities and their abilities to cope with disaster. The roots of the social constructivist framework emerged in political economy. The approach is frequently used in social development and poverty analysis literature (Cutter, 2006). The social vulnerability factors address internal properties of individuals, groups or systems and their abilities to cope with external stressors (Füssel 2005). This leads toward the social vulnerability and points out the important elements of adaptive capacity, resilience and coping.

The social constructivist framework is more open and flexible than the hazard-risk framework. Often it involves more qualitative factors as well. Therefore, no common scheme or visualization, of how the social vulnerability concept should be applied, exists. The solution would be to develop an individual framework for a certain case with economic and social factors.

Hazard-of-place (climate change vulnerability)

The roots of hazard-of-place approach is the Hewitt and Burton's studies (Hewitt and Burton, 1971) in regional ecology of damaging events in which they analyzed multi-hazard effects with simultaneously mitigation (Cutter, 2006). The hazard-of-place approach is an integrated framework, which combines biophysical and social vulnerability, but is more spatially focused within the specific geographic domain. The geographic space can be either a location with populated vulnerable people and their assets, or a social space which analyzes the social groups (Cutter, 2006), their vulnerabilities, coping capacities and adaptation. The hazard-of-place framework covers topics from both the engineering and social sciences. It merges social characteristics of people and exposure to external stressors (Cutter, 1996), although according to Füssel (2005), it evolves mainly from the risk-hazard concept. The integrated hazard-of-place approach is widely used in climate change. It is flexible and varies by scale (Cutter, 2006) and time. It addresses various regions, communities and population groups dealing with climate change impacts. Füssel (2005) emphasizes the hazard-of-place framework as a good approach in order to mitigate and adapt to the effects of climate change. When the mitigation of climate effects can be assessed by risk-hazard approach, the adaptation to climate change is done by estimation of the system's internal properties which are addressed in socio constructivist approach. Moreover, Cutter and Solecki (1989) suggest to use the hazard-of-place approach to analyze patterns of hazards and reasons of their occurrence. Although the hazard-of-place framework is commonly used, no standard of its applicability exists. The standardization would decrease its flexibility which is very important and should be maintained considering the impacts of climate change.

The previously presented basic frameworks should guide through the concepts and their implementations. Each vulnerability case is unique and should be carefully addressed. The preferred way would be to identify what the vulnerability means within the scope of the case study, then determine what the vulnerable situation is, only then identify a concept and assign the framework, which would be closer to the needs of the case study.

1.5 Starting and end point interpretations of vulnerability

The vulnerability has to be defined, conceptualized and framed. It is important to know if the only goal is to assess vulnerability, or to develop further outcomes from it. O'Brien et al. (2004) analyzed in detail starting point and end point interpretations of vulnerability. The end point is the most commonly used vulnerability interpretation (Kelly and Adger, 2000) where vulnerability is the final outcome, is static and relies on quantifications of impacts and adaptation. It is usually applied in climate change science, when the goal is to assess and quantify vulnerability using climate projections, development scenarios, impacts and adaptation options. The vulnerability in the end can be expressed qualitatively or quantitatively as damages, human loss, environmental change etc.

The other interpretation refers to vulnerability as the starting point of analysis. It is dynamic and has a continuous state. Instead of being assessed by climate projections and impacts, it considers inner characteristics of a system, its sensitivity, and coping capacity and recovery in the social sciences. The aim of such interpretation is to identify various characteristics and causes of vulnerability, explore policies and measures which reduce vulnerability and increase adaptive capacity (O'Brien et al., 2004). In the biophysical vulnerability concept the aim is to reduce the risk. Because vulnerability is a part of the risk, it has to be reduced as well. Contrary to social and climate sciences, the adaptation and adaptive capacity is not commonly used in the risk and hazard field. Instead of adaptation, the mitigation and risk reduction is used.

In accordance with Füssel (2005), the end-point interpretation looks at the climate change impacts, addressing possible adaptation options. It is essential for developing mitigation policy and prioritization of assistance. The starting-point interpretation considers social vulnerability to current climate variability and makes recommendations to reduce vulnerability to climate change. The end-point interpretation is consistent with climate change vulnerability and hazard-of-place framework, while the starting-point interpretation focuses on adaptation and represents social vulnerability and addresses socio-constructivist approach.

The big difference between starting point and end point interpretations is their vulnerability relation to adaptation and adaptive capacity. The starting point interpretation states that vulnerability affects adaptation and adaptive capacity, while the end point interpretation has the opposite approach – vulnerability depends on adaptation and adaptive capacity. The following table addresses the main differences between the end-point and starting point interpretations of vulnerability.

Table 4: end-point and starting-point interpretations of vulnerability in context of climate change research (after Burton et al., 2002; Füssel, 2005, 2005; O'Brien et al., 2004; Smit et al., 1999).

Vulnerability interpretation	End-point interpretation	Starting-point interpretation	Starting-point interpretation
Main discipline	Climate sciences	Social sciences	Risk and hazard sciences
Vulnerability framework	Hazard-of-place (integrated)	Social constructivist	Hazard-Risk
Main problem	Climate change	Social vulnerability	Risk
Main solutions to problem	Climate change mitigation, technical adaptation, compensation	Social adaptation, sustainable development	Risk reduction, hazard mitigation
Research questions	What are the expected net impacts of climate change in different regions?	Why are some groups more affected by climatic hazards than others?	What are the risk or damages of extreme events?
Purpose	Descriptive	Explanatory	Descriptive
Meaning of 'vulnerability'	Expected net damage for a given level of global climate change	Susceptibility to climate change and variability as determined by socioeconomic factors	Susceptibility to climate change and variability as determined by socioeconomic factors
Vulnerability and adaptive capacity	Adaptive capacity determines vulnerability	Vulnerability determines adaptive capacity	Adaptive capacity is not common factor
Reference for adaptive capacity	Adaptation to future climate change	Adaptation to present climate variability	Adaptation is not comon factor
Starting point of analysis	Scenarios of future climate hazards	Present vulnerability to climatic stimuli	Scenarios of hazards
Policy context	Mitigation policy, compensation policy	Adaptation policy	Mitigation policy, risk reduction policy, compensation policy
Policy question	What are the benefits of climate change mitigation?	How can the vulnerability of societies to climatic hazards be reduced?	How the risk of disasters can be reduced?

Table 4 was modified after Füssel (2005) - additional column of biophysical vulnerability (hazard-risk framework) and its attitude to vulnerability interpretation and climate change research was added. The hazard-risk framework deals with concrete climatic events, has much in common with hazard-of-place (climate change), assesses continuous climatic changes and considers hazards as starting point of analysis. However, both frameworks deal with different problems. Climate change is a problem itself. It can be mitigated or be compensated and adapted. Meanwhile, the hazard-risk community worries mainly about a risk and wants to mitigate effects and reduce the risk. The mitigation or risk reduction is more preferable than adaptation. In this case the hazard-risk approach does not consider adaptation as an option. In the social sciences, meanwhile, the adaptation and sustainable development have much higher weight.

Interpretations of vulnerability vary between concepts and frameworks. It is important to know what the role of vulnerability is in your research – is it an outcome to be assessed or is it to be explored in order to find the causes to be reduced afterwards?

1.6 Measuring vulnerability

Today, there is no common agreement as to how, exactly, the vulnerability has to be quantified. Since, it is a theoretical concept, the vulnerability cannot be measured directly, like temperature or precipitation. The term "measuring vulnerability" does not only include the qualitative or quantitative expression of vulnerability, but also the methods and approaches which bring vulnerability from the conceptual to the applicable level. The international community highlighted the need and urgency to increase the understanding of these methods and approaches in order to measure risk and vulnerability (Birkmann, 2006; UN/ISDR, 2004). The current approaches often lack a systematic and understandable development procedure. The differences between the measuring methods and approaches, and their limitations and applicability are not well explored. And it is difficult to find a systematic, transparent and easy understandable way to measure vulnerability. Again, we have the same problem as we had with a definition, concept and framework of vulnerability – it is pretty hard to or even impossible to shrink multi-domain vulnerability concept using universal measurement approach into a single expression (Birkmann, 2006; Downing, 2004).

But the difficulties are not limited by the lack of systematic and understandable measuring approaches. The common problem is that some types of vulnerabilities are difficult to measure at all. For instance, although the institutional vulnerability is very important in disaster risk reduction, it is hardly measured. Therefore it is important to consider the limits of simplification the complex interactions. Despite the problems and issues, it has to be a way to measure vulnerability. The different practices of measuring vulnerability across the countries help to analyze and understand vulnerability and its contributing factors, and vice versa – the well known factors behind vulnerability makes the measurement of vulnerability easier (Benson, 2004). The most common way to assess or measure vulnerability is to use indicators and criteria (Birkmann, 2006; Schauser et al., 2010).

1.7 Indicator-based vulnerability

The final statements of World Conference on Disaster Reduction (WCDR), held in Kobe, Japan in 2005, highlighted that there is a need to develop systems of indicators of disaster and vulnerability at various scales in order to assess the impacts of disasters and evaluate the results to decision makers, the public and population at risk (ISDR, 2005).

The word "indicator" means a variable which has to indicate, summarize or describe a certain entity, related to the particular phenomenon (Gallopin, 1997). The indicator itself is not important, more important is what it measures or indicates (Birkmann, 2006). It is clear that the temperature is indicated by degrees of Celsius, Kelvin or Fahrenheit. The weather conditions can be described as perfect, good, average, bad etc. All of these indicators are easy to interpret and compare, because they are well known and commonly used. However, the indicator of vulnerability is much harder to interpret. The definitions of vulnerability indicator varies among the authors and often are confusing, therefore the aimless use of indicators should be avoided (Birkmann, 2006).

In order to develop the indicators, their goals, as starting point, should be known. By their goals, it is meant what they have to measure or indicate. For instance, if the general goal is to measure the countries' capacity to deal with the warming climate, the indicator probably will be composite. Meanwhile the more precise goal would be to measure the infestation level of crops due rising average annual temperature in each province. This may be measured by one indicator, depending on the data used.

The goals of the indicators could not be achieved without functions which are activities conducted to reach the goals. The traditional functions of indicators focus on reducing complexity of the composition of indicators, as well as comparison between various indicated entities. Moreover, the experts from vulnerability measuring workshop in Kobe, Japan, stressed out the following main functions of vulnerability indicators: setting priorities, background for action, awareness raising, trend analysis and empowerment (Birkmann, 2005). These functions are practice-based and should serve as guidelines on developing indicators and following standard quality criteria.

The good quality of the indicator is defined by its ability to indicate the characteristic which is relevant to the interest, determined by the goal (Birkmann, 2006) and achieved by the function. By following the standards, the good quality indicator (not focusing on vulnerability, but in general) should be measurable, and should measure not all, but the most important aspects, should be valid, reproducible and appropriate in scope, relevant in policy, theory and practice, understandable and easy to interpret, should have statistical and analytical background, should be cost effective or affordable, accurate or have precise meaning, should be validated, comparable and based on available data (Birkmann and Flacke, 2006; EEA, 2004; Gallopin, 1997; GIZ, 2014; Hardi and ZDAN, 1997; Parris et al., 1999) In practice, the availability of the data should be a primarily limiting factor of vulnerability assessment. Good data accessibility provides up to date data input and transferability of vulnerability assessment. Meanwhile the opposite situation can be a huge obstacle for the whole vulnerability assessment. As we will see further on, the data availability can be one of the most difficult issues to construct a good quality indicator.

When the goals, functions and quality criteria of the indicators are known, the process of indicator development can commence. The detailed step-by-step framework and ideal phases of indicator development is presented in the Birkmann's (2006) book called "Measuring Vulnerability to Natural Hazards". In this book Birkmann gives overview of general and practice oriented cases and issues of measuring vulnerability, provides various concepts and different approaches of indicator based vulnerability.

Additionally to Birkmann, Schauser et al., (2010) recommended following points by developing a set of vulnerability indicators:

- The selection procedure of the indicators has to be structurized and follow the conceptual framework;
- Additionally, it should be based on the scientific knowledge and be discussed with experts;

- The less indicators are used, the easier is to analyze the result;
- The methods of aggregation should be simple as possible;
- The weights of the indicators have to be based on expert opinions or scientific knowledge;
- The interpretation, communication and mapping should be done with caution.

Despite the clear goals and good quality of indicators, many issues concerning vulnerability indicators exist. Schauser et al., (2010) stress out the main gaps of vulnerability indicators on conceptual, methodological, data and application level. As a primary issue on conceptual level is the missing connection between vulnerability indicators and vulnerability concepts and frameworks. Schauser et al. name additional research as a possible solution. The methodological gap is emphasized as the lack of knowledge how the components of vulnerability (for instance, exposure, sensitivity, adaptive capacity) can be composed from various indicators and what indicators these should be. Concerning the application level, the big question is how vulnerability indicators would be used for adaptation, as well as policy support and future decision making. And the last, but not least, the data issue was always important, especially the availability of data which is a common constraint of development of any indicator. One of the solutions could be the development of indicator databases, containing a good quality and well documented data in order to supply vulnerability assessment.

1.8 Future vulnerability

Obviously, that current climate change vulnerability is important, but future climate change vulnerability might be even more important in order to avoid catastrophic consequences. The sooner future vulnerability can be known, the sooner the adaptation measures needed can be planned and implemented.

Füssel and Klein (2006), Preston and Smith (2008) identified that vulnerability assessment needs to understand not only the relationship between complex physical and socioeconomic systems but also how those systems might change in the future. The challenge was that the researchers lacked the expertise and appropriate methods to project future relationships between environmental changes and responses caused by changes in socioeconomic conditions. It has been difficult to justify the cost of an analysis of a long term positive return on any adaptation steps taken, which makes today's vulnerability questionable, and therefore difficult to justify measures to adapt to present challenges (Sarewitz et al., 2003).

A first step it to distinguish the current and future vulnerability. Unfortunately, the IPCC definition does not do that. When we are talking about the current vulnerability, we mean vulnerability today - the current conditions, composed from the latest data. However, Hinkel (2011) states that, by default, vulnerability is the measure of future harm and is based on current and past experiences. Hinkel does affirm the "future" as a "nearly current" or a "close future". It may be that the impacts for which we are preparing are not happening immediately, but may happen soon, and based on current conditions, the potential impact can be estimated. Hinkel (2011) maintains that vulnerability itself already considers future impacts. I disagree with this premise because vulnerability is still based on current and past experiences and does not take into account future projections. This is especially pertinent when trying to apply it to future climate change.

The word "future" means sometime which is yet to come, but it does not say how long it to take to get to the appointed time. In some cases, even the next hour is the "future". If we consider the next hour "future," that what shall we consider the "current" time. There must be a time difference established to understand what is meant by current and future. These are philosophical questions which cannot be answered within the research, but it is necessary to mention it in order to describe future vulnerability more precisely. For this work, to distinguish between current and future conditions, the meaning of future will mean the long term future such as decades from today. The meaning of current will mean in the next five to ten years or so.

The discussion is an endless cycle because current conditions are affected by past conditions, so it's important to know past conditions in order to understand current conditions. Likewise, future conditions strongly depend on current conditions, so it's just as important to understand current conditions. And, pertinent to our immediate discussion, in order to assess future vulnerability, we must understand future conditions. It's clear that in order to prepare for the future we must understand both the past and present in order to project into the future.

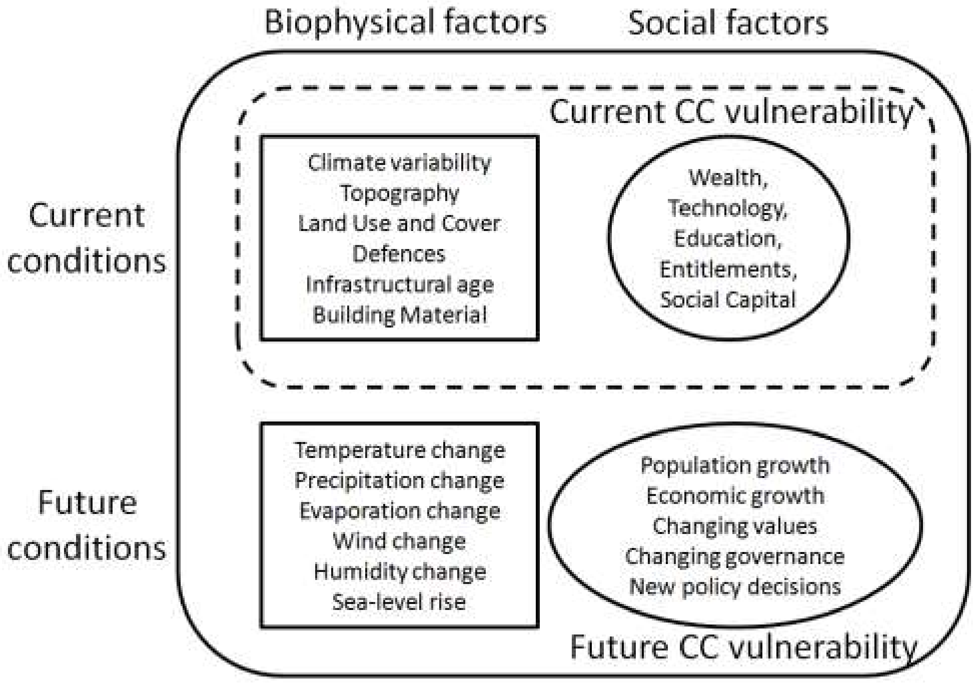


Figure 19: current (dashed frame) and future (unidirectional frame) vulnerability composed from current and future biophysical and social factors (after Preston et al., 2009 and Watkiss, 2011).

Figure 19 presents future climate change vulnerability as composition of current and future social and biophysical factors (after Preston et al., 2009 and Watkiss, 2011). In order to know future vulnerability, we have to know current vulnerability (the current and future conditions) as well. For instance, if we know that in the future the sea level will rise fifty centimeters, without knowing what is the sea level today, this does not make any sense – maybe the sea level today is very low and the increase would have even a positive effect.

Again, figure 19 highlights the two different concepts of biophysical and socioeconomic vulnerabilities and their composition - the climate change concept. The socioeconomic factors account sensitivity, adaptive capacity and adaptation, while the biophysical factors represent climate variability, physical infrastructure and assets. Both type of factors are essential to assess the future climate variability and exposed assets, their sensitivity and adaptive capacity.

Other authors, however, understand future vulnerability differently. Brooks (2003) states that the current vulnerability is determined by past adaptation and current coping capacities, which then provides a baseline to future vulnerability. Meanwhile, future vulnerability is vulnerability at a specific point in time along with its current adaptive capacity. Brooks includes vulnerability and adaptive capacity into his mathematical equation:

Future vulnerability = Current vulnerability – adaptive capacity (1)

The mathematical explanation of Brooks' equation is that the higher adaptive capacity (current adaptive capacity) causes lower future vulnerability. He states that the more adaptive capacity is used, the more adaptation is seen, but it also means that there is less adaptive capacity remaining for the future and there are no new adaptation measures left for the future, resulting in a situation in which there are no new adaptations measures in existence any longer.

It is possible, however, that the adaptive capacity could increase in the future. In an ideal world, there should be no loss in conversion from adaptive capacity to adaptation. In the real world, however, "maladaptation", or unsuccessful adaptation, occurs. Brooks' (2003) equation, ideally, the adaptive capacity = adaption and future vulnerability could be expressed as current vulnerability – adaptation, or adaptive capacity.

Meanwhile Füssel (2005) considers future vulnerability by addressing the vulnerability definition from the Third IPCC Assessment Report (TAR). He describes future vulnerability as a function of future exposure to climatic hazards and future sensitivity to these hazards. Future exposure is determined by future hazards and regional exposure factor, while future sensitivity is determined by current sensitivity and adaptive capacity. Similarly to Brooks' equation, Füssel (2005) sees future vulnerability as a function of future exposure and future sensitivity:

Future vulnerability (future exposure (future hazards, regional exposure factor), future sensitivity (sensitivity, adaptive capacity) (2)

As can be seen, there is no common agreement as to what future vulnerability really means. While there is some common understanding, a standard of the definition of future conditions which is used in real practice does not exist. Most vulnerability assessments use data from past events, mainly because there is limited data available. There are only a few of the many vulnerability assessment studies that actually make use of trends or projections (Schauser et al., 2010).

1.9 IPCC approach

The previous subchapters presented a variety of vulnerability concepts, frameworks and interpretations. It is important to be familiar with them in order to assess vulnerability. The IPCC approach is important enough to not only be mentioned but also analyzed in detail. The acronym IPCC means the Inter-governmental Panel for Climate Change. Its name itself tells us that this institution deals with long term climate change and its effects. The IPCC uses the climate change vulnerability concept and considers biophysical and social vulnerabilities at the global scale. For the same reason, IPCC focuses on list of hazards as climate change impacts. Therefore, the hazard-of-place framework is the most suitable for that role.

The IPCC approach of vulnerability of climate change was highlighted in the Fourth Assessment Report (AR4) in 2007 (IPCC, 2007). Although, it used the same definition of vulnerability from the Third Assessment Report (TAR),(McCarthy, 2001b) in 2001. It states that vulnerability is a function of climate variation to which a system is exposed, its sensitivity and adaptive capacity. So, the vulnerability is a composition of three elements: exposure, sensitivity and adaptive capacity. Figure 20 represents vulnerability as a scheme. Sensitivity defines the system, while the exposure identifies what part of the system is exposed and to what external stressors it is exposed. Together with sensitivity it composites potential impact which does not play any role, just acts as a composite indicator. And in the end the adaptive capacity comes to the play to reduce vulnerability.

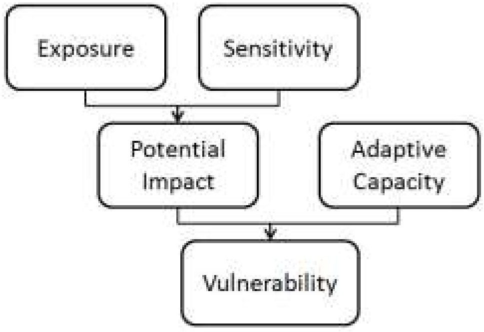


Figure 20: IPCC promoted climate change vulnerability approach (after Füssel and Klein, 2006; IPCC, 2007; Isoard, 2010; Isoard et al., 2008).

This framework is quite simple and can be applied to multiple sectors, hazards (climatic events) and assets. The hazard-risk component is within the “exposure” element which has characteristics of biophysical vulnerability. Meanwhile the sensitivity and adaptive capacity belong to social vulnerability, together with coping and resilience. In order to assess vulnerability, firstly the exposure and sensitivity (social vulnerability) have to be assessed. Exposure means hazard and location where the subject is exposed. Sensitivity identifies inherent properties of the subject, its susceptibility and ability to deal with the external stressors. Sensitivity with exposure form potential impact which can be positive or negative. If the potential impact is negative, the adaptive capacity is added. Adaptive capacity shows capacity of the subject to adapt reacting to the stressors. The previously performed adaptation activities could lower capacity and limit further adaptation and increase vulnerability.

The recent (Fifth Assessment Report, AR5) IPCC report (Field et al., 2014) brings in even more confusion. The vulnerability concept in AR5 has changed dramatically comparing to the last one in AR4. The AR5 concept is closer to hazard-risk/Crichton (figure 18) concept. It sees the risk as a composition of hazards, vulnerability and exposure.

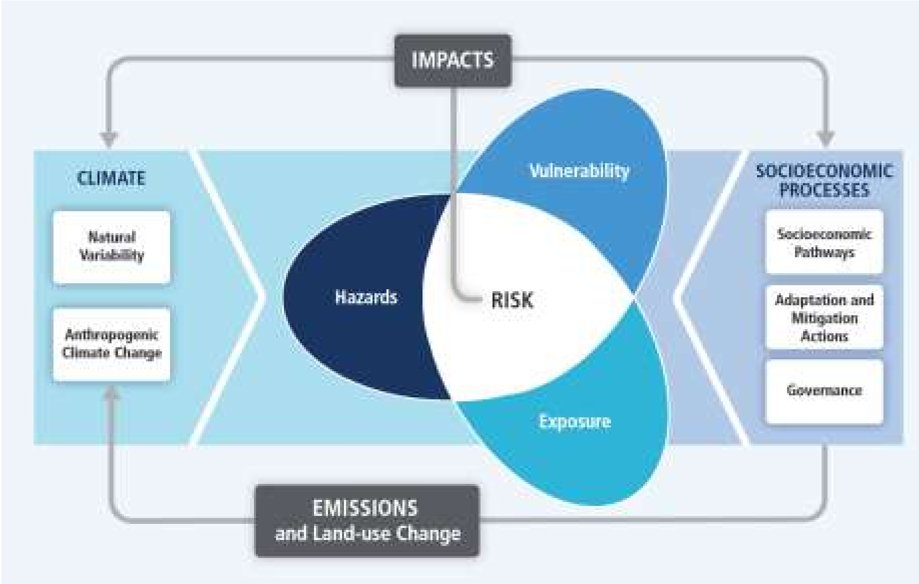


Figure 21: core concept of the IPCC AR5 (Field et al., 2014).

The hazards are natural variability of the climate and anthropogenic climate change, and merge with vulnerability and exposure to come out of the socioeconomic factors. The result is a risk which affects the impacts. The impacts, together with emissions, change the climate, the same hazards and socioeconomic processes which all affect climate through emissions and changes in land use. Such effects create an unending loop in the system in which all factors are closely connected. Looking at this loop, it seems that there are only two ways to decrease the main stressor, or, as we could say, the main "trouble maker", the natural variability and the anthropogenic climate change: 1) reduce the impacts by decreasing vulnerability and exposure and, 2) mitigate emissions and changes in land use.

The main goals of the fifth assessment report differ greatly from the fourth assessment report (AR4, IPCC, 2007) probably due to the stronger focus on the mitigation of the CO_2 emissions and anthropogenic climate change. The definitions, the elements and the entire understanding of vulnerability between AR4 and AR5 also differ as well. "Exposure" is a separate element and means a presence of exposed subject (i.e people, livelihoods, etc.). In the AR5, "sensitivity" is no longer an independent vulnerability element. It appears, instead, as a part of the socioeconomic processes.

Although the concept of vulnerability within IPCC changed dramatically, I ignored the newest IPCC AR5 approach and have chosen to stick to the AR4 definition of vulnerability as a composition of exposure, sensitivity and adaptive capacity. Such a concept and framework, I believe, are more suitable for the complex, multi-sectoral, long term climate change impact assessment of this study.

Exposure

Exposure is also known as exposition and is a common term in a disaster and risk community. Its meaning in the climate change concept is very similar. In the IPCC concept, it is a primary element which is combined with sensitivity and emerges to potential impact. The Third (McCarthy, 2001b) and Fourth (IPCC, 2007) Assessment Reports of the IPCC have similar definitions of exposure. It highlights exposure as the degree to which a system is exposed to climatic phenomena. Meanwhile, the Third Assessment Report (TAR) calls it as the nature and degree to which a system is exposed to significant climatic variation. In our case, I will use the definition from the Fourth Assessment Report (AR4) which describes exposure as a degree which indicates how much the system is exposed to the climate variability or phenomena. However, IPCC does not include any additional explanation of what composes exposure, how the degree can be defined and how it affects the system. First of all, in order to know the exposure, or the degree, it is important to know what kind of climatic phenomenon is being studied. It can be a drought, heat wave, heavy rain or the flood as its consequence, cyclones and other hazards. The exposure includes all extreme climatic events which could cause the danger or risk. Then the next question arises: what, exactly is an extreme climatic event? The + 7 °C in India could cause serious problems (Xinhuanet News, 2015) while similar temperatures in Lithuania would cause citizens to complain that it was not could enough to have a white Christmas. Therefore the disaster in India would be a hazard in Lithuania. The difference between disaster and hazard is that if no one is exposed to the hazard then there is no disaster. For instance, if the cyclone happens somewhere in the Pacific Ocean, no matter how strong it may be, until it creates the negative impact, it is not a disaster. This example shows the importance to know what is exposed or is present. It partly relates exposure to the latest IPCC report's (AR5, Field et al., 2014) definition of exposure. The exposed subject can be people, environment, as well as activities and services. The more they are exposed to the hazard, the greater the risk exists and the more attention is required to prevent a disaster. Another example of the cold wave - years ago, i.e. the area behind Arctic Circle experienced extreme cold weather. There was no human population at that time, although the climate phenomena occurred. But let's assume today, there is a small human settlement and the same severely extreme cold weather, as years ago, occurred again. At this time, it would cause greater risk for people than years ago, because then there were no people. This answers the other question – the higher the number of elements that are exposed, the greater is the exposition. The IPCC and climate change community does not specify or do not get deep into the details about the exposure. Each case study requires additional analysis of properties of the exposition in order to define its degree and how it affects the system.

Exposure indicators

The degree, no matter qualitative or quantitative, has to be measured and assessed. In order to measure and assess exposure, it has to be indicated. In both climate change and risk/disaster community, exposure is defined by many indicators. In general, I recognize three types of exposure indicators: physical, territorial and social.

The physical exposure indicators represent the hazard and its impact. For this study I analyzed main heat hazard-related exposure indicators from 10 climate change indicator based studies (DG Environment, European Commission, 2007, 2011; Hunt and Watkiss, 2013; Kazmierczak, 2012; Kropp et al., 2009; Murphy et al., 2011; Preston and Smith, 2008; Rinner et al., 2010; Schauser et al., 2010). Probably the most common heat hazard indicators are the air and surface temperatures, used to describe the severity of the heat. Not only the average or the maximal temperature, but also the variability of the temperatures are used as well. The historical data, such as warm spell duration index over the certain period, or the days of the last heat wave help to assess historical impacts and observe if the exposure has changed during the years. For the future applications, the projected temperatures, based on specific climate scenarios, are used. The indicator of tropical nights (night time temperature) is a common indicator to assess heat stress on population. The physically-based assessments calculate heat emissions and heat capacities. The wind direction can be used for small scale urban study. All of these indicators are physical and represent the climate phenomena.

The other group of indicators belongs to the territorial exposure. Because the impact of the hazard depends on the environment, environmental indicators play a very important role.

Because the focus of this study is the urban applications, the environment must to represent the urban landscape. The urban landscape often is defined by the land use, land cover (including the fraction of impervious surfaces) and urban morphology. Depending on the land use, the various types of impacts can be considered. For instance, the impact of river flood to unpopulated meadows would not be so high as the impact to the residential area. Or the occurrence of high temperatures in the desert where no population lives, is not considered as disaster at all. The land cover has also very high influence on the hazard impact. The high number of impervious surfaces cause higher heat emissions during the night and have higher heat impact (Stewart and Oke, 2012), while the areas with a lot of vegetation would have much lower impact, due to greater vegetation's cooling effect. The urban morphology also plays an important role in heat impact. Examples would be blocked areas with limited shade, and a lack of winds to ventilate the area and remove hot air. The combination of land use, land cover and urban morphology is used in this study as a proxy parameter and is called "urban vulnerability climate zones" (UVCZ). More about UVCZ will be found in chapter 5.1.

The last, but not least, is the social exposure. Social exposure accounts for the people, exposed to the hazard. In most of the cases the people/population are taken into account as a part of sensitivity. However, the number of exposed people in the hazard-prone area is only a physical representation and does not say anything about the inner properties of the population or how sensitive to the hazards they are. Therefore population, exposed to the heat hazard, is assigned to social exposure.

Sensitivity

Sensitivity is also known as the social vulnerability in the risk and disaster field. In the social sciences it is called "vulnerability". The sensitivity indicates how sensitive the system is. In the context of climate change, sensitivity is the degree as well, but this time, it indicates how the system is affected by climate phenomena. These effects can be direct or indirect, as well as positive and negative (IPCC, 2007). In this study I mostly focus on the negative effects of the heat hazard.

Remembering the exposure which defined the degree to which the system is exposed, the sensitivity indicates the degree to which the system is affected. The system also can be exposed, but not affected at all, if the system is not sensitive. The sensitivity is described by the inner properties of the system. What are these inner properties which make subjects more sensitive? In order to find that out, we have to know the subject. And the subject emerges from social exposure. Therefore, we can state that sensitivity is not so independent, but partly emerges from exposure. Additionally, the sensitivity often can be easily confused with adaptive capacity, because both are based on social characteristics (Schauser et al., 2010). The sensitivity already includes historical and recent adaptation (GIZ, 2014), such as development of heat wave emergency plan or construction of the dam if threatened by flood. But the adaptive capacity is the current additional measures which help the subject to adapt and suffer lower effects of climate phenomena.

Sensitivity indicators

Similar to exposure, the sensitivity can be measured by quantitative and qualitative indicators. The qualitative indicators are common in social sciences and survey-based studies. Meanwhile the quantitative indicators are more commonly used in biophysical vulnerability assessments. In order to review the sensitivity indicators I analyzed a set of studies (Benzie et al., 2011; DG Environment, European Commission, 2007, 2011; GIZ, 2014; Kazmierczak, 2012; Kropp et al., 2009; Preston and Smith, 2008; Rinner et al., 2010; Saffi, 2013; Schauser et al., 2010; Tan, 2008) and collected common heat hazard-related indicators which characterize sensitivity.

If nature is considered a subject, the inner properties would be topography, soil types, land cover, land use, etc. But we are also dealing with population systems that are threatened by heat hazard. The most common use of the sensitivity indicator for heat hazard studies is the elderly, or people aged 65 and over. Also included in the age indicator would be children, especially infants. It is known that young and especially older people are more susceptible to heat than the average adult. Another often used indicator that is used is based on various diseases, uses of medication and/or disability. It is also known that one person households can be very sensitive to any kind of disaster. Foreigners, ethnic minorities, people with language barriers, different religion and even different sexual orientation can be sensitivity indicators for heat hazards. It is not clear how the last one is related, but any misinterpretation of warnings can pace people at risk. Because education can lead to self awareness, precautious and better use of adaptive behaviors, it can be considered as important sensitivity indicator as well. More about the hazard-sensitive population and related indicators, used in Greater Hamburg study, can be found in chapter 6.1.

Adaptive capacity

According to the IPCC, the adaptive capacity is "*the ability of a system to adjust to climate change (including climate variability and extremes) to moderate potential damages, to take advantage of opportunities, or to cope with the consequences*" (IPCC, 2007). The adaptive capacity is an independent element of the IPCC concept (figure 20). Unlike exposure and sensitivity, it reduces potential impact and vulnerability.

As mentioned previously, the adaptive capacity is often confused with sensitivity. This is because, if one follows the IPCC definition, adaptive capacity is the ability of a system. But, it's unclear whether or not this means that the adaptive capacity is the inherent/inner property of the system. Because of this lack of clarity, it's my opinion that the sensitivity and adaptive capacity should be distinguished one from the other. The adaptive capacity should be considered as an additional, often external measure, which may reduce the potential impact.

I find the term "adaptive capacity" to be confusing. According to the Oxford University Press (2015), "capacity" means the maximum space or quantity which can be contained. "Adaptive capacity", then, should mean "the space which can be occupied if adaptive measures are taken". If all measures were taken, there would be no space, and therefore, no adaptive capacity. An example may be helpful here. Assume that an older person is suffering heat. The subject, the person is currently exposed to the heat hazard. Because he is old, some sort of illness might be assumed, meaning the person is sensitive. The heat the person is suffering is defined as potential impact. There are two adaptive measures in this can which are available to the person: drink water and/or go to a building with air conditioning. If both measures are used, and the person is still suffering from heat, there is nothing else to be done. The person's vulnerability is high and there is no additional adaptive capacity. I believe that the term "adaptive capacity" should be not only the ability to adapt/cope, but also the availability of adaptive measures. Unfortunately, in many publications, the adaptive capacity really means "adaptation". More will be said about this in the discussion found in chapter 10.

Therefore I conclude that definition of adaptive capacity can have two meanings: (I) the ability of a system to adjust to climate change and (II) a space, limitations or possibilities of adaptive measures, to moderate potential damages, to take advantage of opportunities, or to cope with the consequences. Theoretically, if there is no space for adaptive measures, the system is not able to adjust anymore.

If exposure and sensitivity would have some clarity and there were a common practice formed to apply all variables, this might not be said about adaptive capacity. However, because there are few studies with clear approaches as to how adaptive capacity might be quantified, compared and assessed, and because there are so many yet uncounted variables whose interaction with a system and between systems can be assessed, there is much uncertainty and lack of clarity. It appears that the adaptive capacity is often named as adaptation option, which means activity or ability of a system to adjust, without quantifying or specifying how this activity could be measured, compared or evaluated.

Adaptive capacity indicators

Despite these issues, adaptive capacity should be taken seriously. It should be measured and assessed. It should be understood that exposure and sensitivity are degrees of the system. Adaptive capacity, as seen as ability is much more difficult to measure. Although some commonly used indicators of adaptive capacity exist, they all are not easy to count, because they are more qualitative than quantitative.

I overviewed the heat hazard-related adaptive capacity indicators from five studies (DG Environment, European Commission, 2007, 2011; Harvey, 2009; Kazmierczak, 2012; Preston and Smith, 2008; Rinner et al., 2010). The common indicator not only for heat hazard, but in general is the Gross Domestic Product (GDP). While the higher GDP country has, the more resources it can allocate and increase the adaptive capacity, or the abilities to adjust to the climate phenomena. It does not always have those anticipated results. Remember the example of an old person, drinking water and staying in air conditioned room. If the same situation occurs, no matter how high the GDP is, all the available measures will have been taken, despite that example, I do agree that GDP can contribute to adaptive capacity.

Similar to GDP, community service expenses or health sector expenses would be a better indicator of adaptive capacity, mainly because these two arenas are directly involved in the adaptation process. Other indicators, such as income, unemployment, social welfare recipients, households with air conditioning, home ownership, etc all influence local abilities to adjust to hazards. An interesting adaptive capacity indicator which could also be a sensitivity indicator is education. In looking at education, there is a dilemma: does education cause the sensitivity of a person or help him/her to cope with a disaster? The answer can be addressed differently, depending on a variety of factors. Another common set of adaptive capacity indicators is the health care infrastructure: the number of hospitals, surgeries, nursing care homes and/or nurseries, the number of doctors, etc., all of which are great adaptive measures in the case of any hazard because they are easily countable. Conversely, the other indicators, such as social capital, access to technology, perception cannot easily be measured and in most of the cases they serve as adaptive options rather than quantitative indicators of adaptive capacity or adaptation.

1.10 Vulnerability assessment

A vulnerability assessment is a judgment which states whether or not vulnerability is high or low (Birkmann, 2006). In other words, it is a process in which vulnerability is measured and compared spatially and/or temporally. Clarifying, or enhancing Birkmann's definition could be done by defining a vulnerability assessment as *a judgment of vulnerability factors and their composition, distributed spatially and/or temporally*. As previously discussed, vulnerability can be measured indirectly by a composite index which has been developed with specific indicators. The processes and approaches in this can be very complex, but they are usually unseen for the final user. It is important, however, to know what factors were used in the vulnerability assessment because each situation is very specific and varies depending on the purpose of the assessment.

Purposes of vulnerability assessments

There can be many reasons to prepare a vulnerability assessment: from establishing the vulnerability of a local agriculture's sector to increased precipitation, to assessing the impact of a future heat wave on a population in a great metropolis. The actors include, but are not limited to: policy makers, experts, citizens, governmental and non-governmental organizations, industry, etc. Based on their needs, the purpose of the vulnerability assessment can vary. GIZ (2014) highlights three main purposes to have a vulnerability assessment done:

- To identify current and potential vulnerable hotspots;
- To identify entry points for intervention;
- To track changes in vulnerability, monitoring and adaptation evaluation.

The first need to identify the vulnerable hotspots is a common purpose and has similarities to risk assessment. The outcome enables one to compare the impact of the climate change to various assets and systems, and explore the factors which cause the vulnerable hotspots to emerge. The second purpose is to identify the entry points for intervention. It is similar to the detection of hotspots, but additionally searches for possibilities to apply adaptation measures.

Although GIZ (2014) contends that adaptation measures would increase adaptive capacity, I disagree. I believe, because the definition of adaptive capacity is not clear, that adaptive capacity would reduced, rather than increased, because of an application of adaptive measures already taken (more about this issue can be found in the discussion in chapter 10.3). The third last, but not least identified purpose of a vulnerability assessment is quite new and is based on the tracking of any changes in vulnerability and the monitoring and evaluation of that adaptation. This continuous monitoring of applied adaptation measures over time allows one to evaluate those applied measures. Even when trying to be clear about the purpose of an assessment, it can be mixed with, or confused with impact and damage assessments.

Similarities to impact and damage assessment

The difference between vulnerability assessments and impact and damage assessments lies in the different approaches taken. A damage assessment is an approach used in biophysical vulnerability to calculate a negative loss, often expressed as population fatalities and injuries, monetary and economic losses and damage to physical structures. An impact assessment considers both negative and positive impacts such as climate warming resulting in milder winters and better transport condition on roads.

In the example below, the damage assessment is a part of the impact assessment and both are a part of the vulnerability assessment (figure 22). In this case, however, the vulnerability does not mean the vulnerability in the risk and hazard (biophysical) concept which is part of the

Crichton risk triangle (figure 18) and represents the susceptibility of the assets.

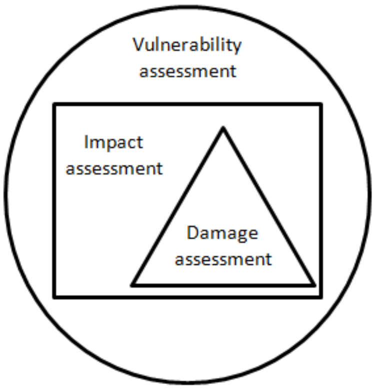


Figure 22: relation between vulnerability, impact and damage assessments.

Figure 22 represents the relation between the vulnerability, impact and damage assessments. It shows that the vulnerability assessment takes into account the damage assessment which includes damage to physical structures and the negative impact of a particular extreme event as well as the impact assessment including both positive and negative impacts. This shows that vulnerability can have a much broader meaning and could be composed of impact and damage assessments, but it is not necessary to include both. The converse, however, is not true of either impact or damage assessments.

Some authors (Benson, 2004; Wisner, 2004) name the time dimension as a biggest difference between vulnerability and damage assessments. The damage assessment often follows an extreme event as soon as possible in order to survey and assess the damages. The vulnerability assessment, however, considers more than the damages done to the subject and the process itself takes longer. This is especially true when there are more stakeholders and actors involved in the process.

In comparing vulnerability and impact assessments, the impact assessment focuses on consequences of a specific event (Birkmann, 2006; Vogel and O'Brien, 2004) or a continuous process such as climate change. The vulnerability assessment can assess those things as well and studies the reasons and original factors which caused the vulnerability to begin with.

Vulnerability, impact and damage assessment have different aims as well. The aim of vulnerability is to identify factors which make people and/or assets vulnerable and how these people and/or assets are exposed. A vulnerability assessment is a forward looking approach, while the impact and damage assessments focus on events that have already happened and what losses were experienced. It's important to note, however, that the vulnerability assessment often uses the data, indicators and patterns based on past events and their impacts (Benson, 2004; Birkmann, 2006; Vogel and O'Brien, 2004; Wisner, 2004).

Vulnerability is often confused with risk as well. According to Wisner (2004), a vulnerability assessment should focus on the likelihood of loss. However, vulnerability does not consider the likelihood in the same way as risk does. Contrary to Wisner, Preston and Smith (2008) state that vulnerability does not predict explicit outcomes or even the likelihood of outcomes. Instead, a vulnerability assessment represents where the greatest potential of loss exists, without defining its likelihood or probability.

Domains of vulnerability assessment

While the domain of a vulnerability assessment is similar to the purpose, the domain is more specific. In general, there are two common domain types of vulnerability assessment (GIZ, 2014):

- Explorative vulnerability assessment;
- Focused vulnerability assessment.

The explorative vulnerability assessment is intended for multiple sectors, usually the large area with coarse a resolution of data, high uncertainty and low accuracy and with few or no future climate change scenarios. This type of assessment requires fewer resources, less time and can be done in a short time. Often it is based on expert opinion and existing literature and data. The focused vulnerability assessment, however, is more specific. It focuses on one or a few specific sectors or locations, with high spatial resolution and data accuracy. That kind of study requires much more time, expertise and resources. It is possible that, when doing a focused vulnerability assessment, new method may have to be developed and new data would have to be collected. The focused vulnerability assessment would be required for concrete vulnerability reduction and adaptation planning (GIZ, 2014). In practice, an explorative assessment would be done first to identify the hotspots of vulnerability, and only after that a focused vulnerability assessment would be conducted to help reduce the vulnerability in a specific sector or a certain location.

Scale of vulnerability assessment

Because of the importance of spatial and temporal scales in the process of indicator selections, it would be imperative to consider the scale in the early data preparation stages, when the data availability is analyzed. In order to assess vulnerability, the data must have the same spatial and temporal scale. If the spatial scale does not match any of the datasets, it must be downscaled or upscaled to all have the same spatial scale. The same holds true for the temporal scale as well. If the data are from different time periods, the study can get much more complicated. This is why the scale must be one of the first things that is considered and dealt with in the process.

The data of a spatially coarse scale is usually aggregated and standardized by some authority, or some other initiative, at a state, nation or even, possibly, an international level. Typically, this kind of data is statistical quantitative data which is easy to compare, but does not have a high degree of accuracy. It also is usually produced over a long period of time. This kind of data allows one to compare regions over time and to provide assessments for national governments or other such initiatives to observe changes of vulnerability due to the impacts of climate change.

The data of a spatially local/detailed scale, on the other hand, has better resolution, is more complex but is also less standardized. Such data is often expensive to update and is collected by local authorities, private companies or individual initiatives. The data at a local scale can be very case specific and for a specific period of time, which makes the comparison of the data quite complicated. Local scale, data, therefore, is used mainly for only local applications (GIZ, 2014).

Vulnerability assessment approaches

There is no one definition of vulnerability and no one vulnerability assessment approach which can be used for all case studies. A change in even one indicator or one method could mean that a change in the approach taken would be necessary. Given this, it's obvious that there are a number of approaches which exist in real practice. In order to choose or develop the most suitable approach for a study, it's important to classify and select the best existing vulnerability approaches, based on various criteria. Birkmann (2006) systematized and listed vulnerability assessment approaches by the following criteria:

- Function;
- Thematic focus of vulnerability;
- Link to goal;
- Targeted audience;
- Spatial scale;
- Data;
- Level of aggregation.

The examples of vulnerability assessment approaches based on listed criteria can be found in the book "Measuring vulnerability to Natural Hazards" (Birkmann, 2006).

Although many approaches of vulnerability assessment exist, the common approach is defined by relative vulnerability which states how different vulnerability is between, for instance, the population groups, environmental areas, industrial sectors and activities etc. (Birkmann, 2006). It is nothing more than the comparison of composite indicator (index) between specific entities within a certain scope. The index of vulnerability can be developed by following the vulnerability assessment framework.

Vulnerability assessment framework

The vulnerability assessment framework presents the step by step instructions of how the indicator based vulnerability can be assessed. Some of the steps are optional, or could be ignored, depending on a variety of circumstances. If, for instance, no weighting has to be applied or the indicators are already normalized, those steps would not have to be repeated. Most of the steps, as could be expected, are related to the indicators. The largest part of the entire vulnerability assessment is the necessary preparation and analyzing of the input data. Depending on the hardware and software used to analyze the data and calculate the vulnerability resources, this could be a very rapid step.

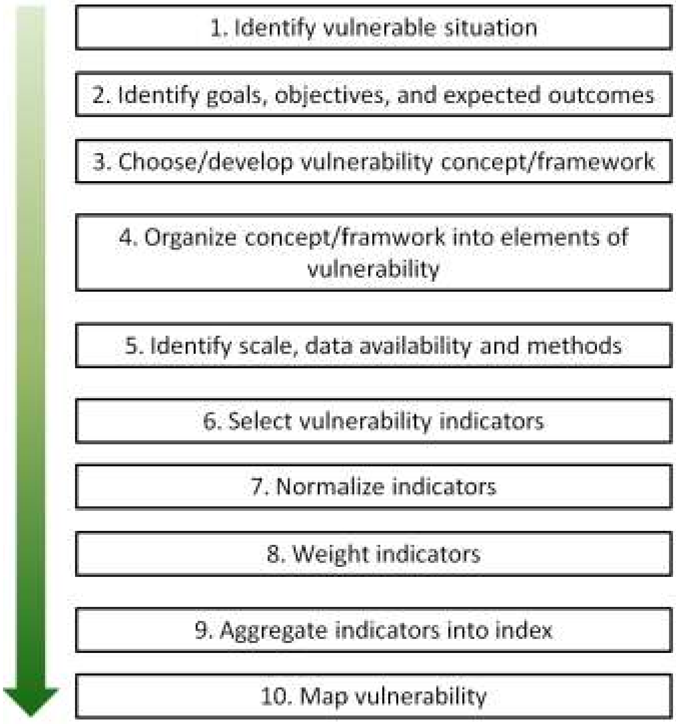


Figure 23: vulnerability assessment steps, based on common indicator based vulnerability assessment approaches.

Figure 23 shows schematically the main steps of an indicator based vulnerability assessment. Some of the steps, such as identification of vulnerable situation or consideration of vulnerability concept or framework, have been mentioned previously. This framework can be very handy not only for indicator based, but also for all types of vulnerability assessments. It serves as a guide and should be considered during all phases of vulnerability assessment – from the planning stage of the project, through the intermediate process of input data assessment and to the final stages when vulnerability has to be mapped and presented to the stakeholders.

The results of vulnerability

It is not enough to assess vulnerability only. A very important step is to map, evaluate and discuss the results of the vulnerability assessment. The vulnerability index, in and of itself (high or low) represents only the composition of the indicators, which can be useful if the spatial comparison or the ranking is important. However, even more important to the discussion is to go deeper into the composite (aggregated) index and explore the indicators and the factors they represent. The detailed analysis of the vulnerability hot spots insures a return to the individual indicator level and an identification of the causes of a certain vulnerability value and the factors they represent. The process of involving stakeholders increases the chances of an understanding of the vulnerability results and helps in the making of any necessary decisions concerning actions that might be taken. It must be remembered that the interpretation of the results requires caution. It must be remembered that vulnerability assessment cannot forecast or foresee the future. It can only help to understand the factors which cause a higher or lower degree of vulnerability. Specific decisions should be made, and measures taken, based on the factors studied. The interpretation and communication of vulnerability assessment results must be considered seriously, because after all is said and done, the vulnerability assessment in most cases does not reflect either the likelihood or the magnitude of future events (Preston and Smith, 2008; Schauser et al., 2010).

2 Urban landscape, climate and population

The concept of population's vulnerability to heat waves in this study is based on heat impact and population. The severity of heat impact is influenced by the urban landscape and its specific climate. Therefore, it can be stated, that conceptually the population's vulnerability to heat waves is a function of landscape, climate and population. This chapter introduces landscape properties, urban heat island, urban climate and its classification scheme. Moreover, it roughly explains how population's vulnerability within cities is influenced by socio-economic diversity and the effects of climate change. In the conclusion of the chapter there is a presentation of urbanization and how it can be shifted. There is no attempt to address these topics with detailed information, but rather to introduce the basics of urban areas, its climate and the population's segregation, which may help in understanding the conceptual setting of a population's vulnerability to heat waves.

2.1 Landscape properties

"Landscape" in this study refers to urban landscape and is defined by land cover, land use and urban morphology. Each of these landscape properties has an influence on the heat impact and helps to classify urban areas by different urban climate, and, as hypothesized, by different population groups, living within these areas. The overview of these properties helps to understand the meaning of classification.

Land cover and land use

"Land cover" and "land use" are commonly used, but often confused terms (Noble et al., 2000). According to the IPCC, the "land cover" is "*the observed physical and biological cover of the earth's land, as vegetation or man-made features*", while "land use" means a "*total arrangements, activities and inputs that people undertake in a certain land cover type"* (FAO 1999). Land use and land cover are heterogeneous and can be classified based on certain criteria. Kalensky et al. (2002) defines such classification as the process of systematic grouping into multi-level classes according to selected criteria. This process depends on scale, data source and geographical area. The classification of land use and land cover leads toward standardized identification. Land cover can be identified by satellite imagery (Loveland et al., 1999), but land use is much more complicated to detect via remote sensing (NOAA, 2016). Despite advanced technologies, land cover and, especially, land use are barely known at the global and regional scale (Watson, 2000). The identification of land use and land cover over time can reveal land use and land cover changes which are very important factors, affecting the functioning of Earth System (Lambin et al., 2001). Additionally these changes influence local and regional climate change (Chase et al., 2000), contributes to the global climate warming (Houghton et al., 1999), affects population's vulnerability (J. X. Kasperson et al., 1995) and is a major cause of the soil degradation (Tolba and El-Kholy, 1992).

Urban morphology

Although Moudon (1997) defines urban morphology as "*a study of city as human habitat*" which analyzes the city's evolution and transformation. This study considers urban morphology as urban form which focuses on physical structures and the form of the urban landscape. The urban morphology is described by shape and size of the building blocks and parcels and the layouts of the street network. The size and the shape of the building blocks and parcels in most of the cases are determined by predominant housing type (Knox and Pinch, 2000). Curdes (1993) highlights the three common forms of the building block:

- Rectilinear form. It is a traditional building block's form, easy to survey, efficient use of the space and simple layout of the streets. These blocks are in shape of rectangular, squares, hexagonal and triangular. Often found in European cities, such as Berlin, Cologne, Vienna, Rotterdam etc.
- Continuous curvilinear form. Their wide and shallow curvy forms give impression of spaciousness. The trend of such forms have started in mid to late nineteenth century and was very popular in 1930s in United States as well in Europe by 1950s after American practice was implemented in Europe.
- However, the curvilinear form based blocks complicated the traffic and caused accidents. The advanced development was presented as a loop road with *culs-de-sac* (dead-end). The single dwelling and semi detached houses aligned along the street were served by the dead-end circle and the road loops provided access to the arterial streets. This form emerged in New Jersey in 1930s by American Regional Planning Association and dominated in suburbs of most developed countries since 1970s.

The areas of the same morphological pattern are called "morphological regions". The morphological regions change over time (process is called "morphogenesis") when the new houses are built, the old ones are torn down, the parcels are amalgamated or subdivided and streets are modified (Knox and Pinch, 2000). Such processes are hierarchically organized and can address from a small scale changed inside a building to the morphological transformation of the whole quarter (Curdes, 1993).

According to Oke (1982), the urban morphology also can affect the urban climate and heat impact. Moreover, Daneke et al. (2011) developed a conceptual approach in order to measure the differences of urban climate. He addressed various morphological characteristics of building blocks.

2.2 Urban climate

Influence of urban landscape to urban climate was described by Oke (1976) more than forty years ago. But during years more and more comprehensive research toward this topic has been conducted (Erell et al., 2012). Today most of the cities experience major changes in the local climate, especially the ones in equatorial, tropical and subtropical climate zones (Burgess and Jenks, 2002).

According to the World Meteorological Organization's (WMO) database of terminology (WMO, 2017), urban climate is "*a climate of cities which differs from that of the surrounding areas because of the influence of the urban settlement*". The urban climate, compared to the climate of surrounding areas, experiences higher air and surface temperatures, higher pollution, lower humidity and higher variation of radiation balances than the surroundings (Kuttler, 2008). Kuttler (2008) distinguishes the following factors, affecting urban climate:

- Human activities, associated with the change of land use which affects the urban climate by a) sealing surfaces (conversion from pervious to impervious); b) removing vegetation; c) reducing of long-wave emission of the surface by street canyons and d) generating of pollution and anthropogenic heat. These factors influence the thermal and radiation properties of urban surfaces by changing their density, heat capacity, thermal conductivity, thermal diffusivity, thermal admittance coefficients, water storage content, atmospheric exchange rates and evapotranspiration.

- The airflow in the urban atmosphere is affected by type, size and arrangement which form different urban atmosphere layers.

Oke (1976) identified two relevant atmospheric layers (figure 24): the urban boundary layer (UBL) and the urban canopy layer (UCL). The UBL addresses the meso-scale concept and consists from roughness sub-layer, affected by roughness elements, turbulent surface layer and the mixed (outer) layer. The UBL is affected by greater meso-scale events, developed by major land use changes, large arrangements, units of the city (Oke, 1988) and the UCL below (Kuttler, 2008). The UCL addresses the micro-scale concept and is defined as a space between the ground surface and the bottom of the roof level. It covers dense city districts and the lower density sub-urban areas and outdoor spaces where most of the people are spending their time. The climate of UCL is mainly affected by materials and geometry and is most commonly observed by the standard climate stations and mobile automobile-based measurements (Oke, 1988).

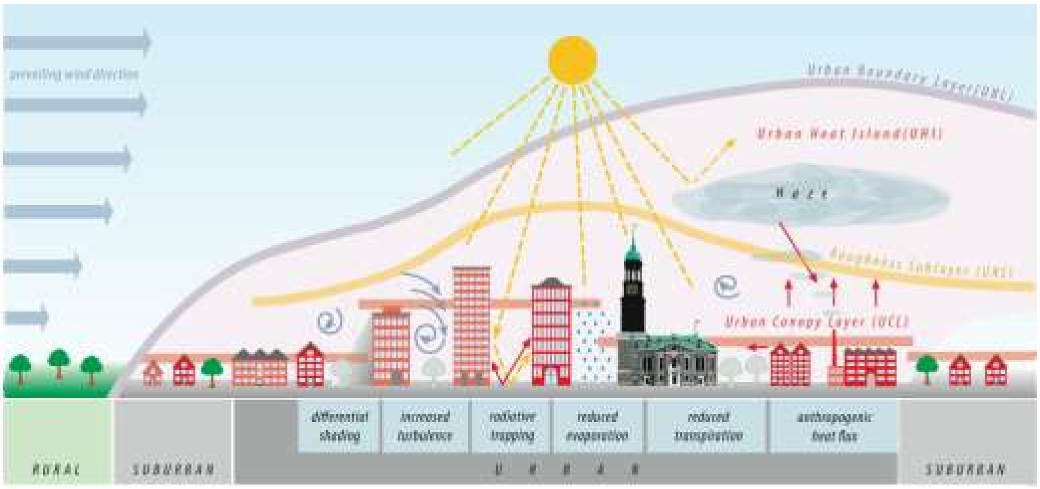


Figure 24: urban layers and effects of urban development on urban climate (Bechtel and Schmidt, 2011).

Because this study focuses on heat impact, knowledge of the underlying causes and processes for the heat within both layers is critical. (Oke, 1979) found that UBL receives latent heat from the following sources: anthropogenic heat from roofs and chimneys, heat from warmer UCL, heat from overlaying stable air by penetrative convection and heat produced by shortwave radiative flux convergence within polluted air. Meanwhile heat in the UCL result from more drivers:

- Anthropogenic heat from buildings;
- Canyon geometry causes greater short-wave absorption and lower long-wave loss due to deduction in the sky-view factor;
- Thermal properties of surfaces lead to greater heat storage and emits the heat;
- Reduced wind speed in UCL causes convergence of sensible heat.

The thermal changes in urban climate are caused by differences in urban energy which affect energy balance (also known as energy budget).

Urban energy balance

Although many energy balance representations exist, the energy balance of a single plane can be expressed by following equation (Arnfield, 2003):

$$Q^* + Q_F = Q_E + Q_H + Q_G \quad (3)$$

The Q* is the net energy, also known as surface net radiant flux. It is dominated by the incoming short-wave radiation during the day and by the long-wave radiation during the night. Fan and Sailor (2005) and Offerle et al. (2005) found that energy balance can be altered by anthropogenic heat emissions, caused by various human activities. The sum of surface net radiant flux and anthropogenic heat flux (O_F) is equal to the sum of turbulent fluxes (latent heat flux (Q_E) and sensible heat flux (Q_H)) and the soil heat flux (Q_G), also known as conductive heat flux (Arnfield, 2003). The latent heat flux is the energy atmosphere receives from evaporation of water from trees, soil, bodies of water and other moist objects. Sensible heat flux is the energy carried by vertical and horizontal winds and the soil heat flux represents the heat energy from the ground (soil) and buildings. The turbulent fluxes are caused by different use, type, structure of the urban surfaces and pollutants which absorb, reflect and scatter incoming radiation (Kuttler, 2008). More detailed energy balance representations can be found in research done by Arnfield (2003), Kuttler (2008) and Oke (1982,1988) which additionally address, for instance, the metabolic energy, emitted by live organisms, mostly by humans.

Heat (wave) impact

According to IPCC (2007), the temperature increase causes higher frequency and higher severity of heat waves. The historical temperature trends of 1950 - 2000 show a positive increase. For instance, Mietus and Filipiak (2004) analyzed historical temperatures in Gdansk (Poland) and found out that the duration of heat waves is increasing. The study in China, done by Wang and Gaffen (2001), showed that over the period from 1951 to 1994 the mean summer temperature has increased as well. Additionally, the study done by Schlünzen et al. (2010) found that in 1978 – 2007 the mean temperature in Hamburg had a steady increase by approximately 0,6 K/decade. IPCC (2013) declares, that even in the best case scenario, the global temperature likely will increase from 0,4 to 1,6 °C in 2046 – 2065 and from 0,3 to 1,7 °C in 2081 – 2100. Therefore, according to (IPCC, 2014a), it is very likely that heat waves will occur with a higher frequency and longer duration in future.

The heat impact in the urban areas depends on the macro-climate of the city and can be positive or negative. In cities in higher latitudes with a cold climate, the urban heat island can actually see a number of benefits: a decrease in heating demands (Svensson and Eliasson, 2002), better driving conditions and physical properties of roads and railroads (Stewart and Oke, 2012), lower physical expansion, and fewer deaths and injuries because of frostbite (Ruth, 2006; Schauser et al., 2010). Cities in warm climates experience in opposite effect, where heat makes as severe impact on people, their economy and natural surroundings.

Heat wave is responsible for 95% of the human losses of all natural disaster in post-industrial countries (Smith, 1992). During the heat wave in Europe in 2003 which was the hottest summer since the fifteenth century, 15 000 people have died in France alone (Poumadère et al., 2005). In 1995, the extreme temperatures and high humidity caused more than 1000 human losses in USA (Palecki et al., 2001). But the temperature alone is not exact measure, related higher mortality. A well contributing factor is humidity. High humidity accompanied by high temperature, causes a reduction in natural evaporation which lowers the efficiency of human body's natural cooling mechanism and causes a dangerous heat impact (Souch and Grimmond, 2004). The desire to find an appropriate measure which would accurately identify the impact of heat on the human body has been around a long time. In 1938 Büttner and Jensen (1938) found that the environment affects human body thermally through multiple factors. Later on, many indices were developed, but the basis for all models is the heat-balance equation for human body, based on Büttner's findings (Höppe, 1999):

$$M+W+R+C+E_D+E_{Re}+E_{Sw}+S=0 \qquad (4)$$

The heat-energy balance of human body consists from metabolic rate (M), output of the physical work (W), net radiation of the body (R), convective heat flow (C), latent heat flow to evaporate water through the skin (E_D), sum of heat flows for heating and humidifying air (E_{Re}), heat flow due evaporation of sweat (E_{Sw}) and storage heat flow for heating or cooling body mass (S). According to Höppe (1999) C and E_{Re} can be affected by air temperature, meanwhile the air humidity influences E_D, E_{Re} and E_{Sw}. The air velocity affects C and E_{Sw} and R is affected by mean radiant temperature. People can perceive these parameters by thermo-receptors and their bodies respond to the changes.

It is difficult to quantify how altering some factors may alter the heat-energy balance of the human body to create comfortable conditions. One of the often used measures of thermal comfort is the predicted mean vote (PVM) which was developed by Fanger (1972) and originally was created to measure indoor conditions (Höppe, 1999). But later on, the PVM was extended by Jendritzky et al. (1979) addressing short- and long-wave radiative fluxes. Additionally Jendritzky et al. (1979) developed a scale of absolute PVM values, ranging from 0 (no stress) to 3 (very strong stress). However, Mayer and Hoppe (Mayer and Höppe, 1987) identified that PVM was still too complicated for decision makers and others not from the field of bio-meteorology to easily understand and developed a new measure, called "physiologically equivalent temperature" (PET). PET is based on Munich Energy Model for Individuals which is similar to the heat-energy balance of human body, with a few additional parameters of Gagge two-node model (Gagge, 1971). Höppe (1999) defines PET as "*the physiological equivalent temperature at any given place (outdoors or indoors) and is equivalent to the air temperature at which, in a typical indoor setting, the heat balance of human body (work metabolism 80W of light activity, added to basic metabolism; heat resistance of clothing 0,9) is maintained with core skin temperatures equal to those under conditions being assessed*". Additionally, for the PET definition Höppe (1999) assumes that mean radiant temperature equals to air temperature, air velocity is set to 0,1 m/s and water vapor pressure is set to 12 hPa (when humidity is around 50% with the air temperature of 20°C). So PET is a simplified extended heat-energy balance of human body expression under certain assumptions. Instead of 8 variables (equation 4), it addresses only three unknowns which are the mean clothing surface temperature, core temperature and mean skin temperature. Also PET can be applied in different thermal environments for both, cold and hot weather. Additionally, compared to PVM and other indices, PET it is measured by °C which is easier to understand for non-experts (Matzarakis et al., 1999). Some of examples of how PET is calculated and more details about bioclimatic indices can be found in studies, done by Höppe (1999), Matzarakis et al. (1999) and Mayer (1993).

Another sector sensitive to heat waves is energy. Cities experiencing heat waves during the summer need more energy to supply an increased demand for air conditioning (Santamouris et al., 2001). If the energy price is high, it can cause devastating monetary loss. For instance, Rosenfeld et al. (1996) conducted a study and found that an increase in the price of electricity of 15% in Los Angeles could cost about 10 billion dollars, solely because of the impact heat would make on the city.

The heat also has a great impact on plants. Pavao-Zuckerman and Coleman (2005) found that high temperatures influence processes in the soil, such as the rates of leaf decomposition and nitrogen mineralization which can result in lower yields and limited growth. Such impact is dangerous not only to the forests, but also to the urban parks (Baxter et al., 2002). Additionally, the heat causes earlier flowering (Lavoie and Lachance, 2006) and alters the range of species (Parris and Hazell, 2005).

Heat indirectly promotes the urban sprawl by forcing people to move to the suburbs (Ruth, 2006) to avoid the heat stress. According to Oke (1982), the heat is causing more and more problems, especially in cities with higher population density and urbanization degree (Smoyer et al., 2000; Souch and Grimmond, 2004). The impact of high heat is especially seen within the urban heat island (UHI).

Urban heat island (UHI)

Many definitions of the UHI exist in literature. Oke (1982) identifies UHI as a thermal anomaly with vertical and temporal dimensions and is observed in all types of settlements. Later on, Oke (1987) extended the definition by stating that UHI is known as artificial elevated temperatures. And the most up to date definition states the UHI as the warmth difference between the urban and rural areas in the screen height of 1 – 2 meters above the ground (Stewart and Oke, 2012). According to Stewart and Oke (2012), the term of UHI was formed by Balchin and Pye in their study in 1947, after they performed micro-climatologic survey in the district of Bath, UK but Howard Howard (1833) was the first, who described and published about UHI (Yow, 2007).

UHI types

Although mostly the UHI is defined as temperature difference between rural and rural areas (Yow, 2007), the UHI occurs on the surface, at various heights in the air and in the ground (Oke 1995). Arnfield (2003) and Yow (2007) classified UHI in three types which can be described and investigated in many ways: sub-surface, surface and UHI in the air.

Sub-surface UHI. Sub-surface UHI appears under the ground surface. Although the sub-surface UHI are often neglected, it can cause positive and negative effects. In warmer latitudes the sub-surface UHI in urban areas maintain groundwater temperatures around 3-4 °C higher than in the rural areas which increases potential of geothermal energy and lowers the heating costs (Allen et al., 2003). Meanwhile in the colder regions where permafrost is common, the sub-surface UHI can damage the roads, buildings and pipelines (Hinkel et al., 2003).

Surface UHI. The surface UHI shows the difference between urban and rural surface, but not air temperatures (Yow, 2007). The surface UHI are affected by ground and caused by high surface temperatures. In most of the cases they occur in built-up areas (Kuttler, 2008). The easiest and best way to measure surface temperature is the technology of remote sensing which quickly obtain data using the infrared photographs (Kuttler, 2008; Yow, 2007). In comparison to measurements via ground stations, the satellites or radiometer mounted aircrafts are able to measure the radiant emissions from the surfaces remotely. The main advantage of this approach is the substantially higher amount of observations than the regular ground weather stations (Roth et al., 1989). The advancing technology increases spatial and spectral resolution of the sensors which enables to deliver more detailed information, related to urban climate (Voogt, 2004). Such information is very desirable for applications dealing with multiple cities or tracking the urban changes over time (Yow, 2007). Despite the benefits, the measuring surface UHI via remote sensing has its own deficiency, such as atmospheric attenuation, sensors' angling (Lagouarde et al., 2004), and mixed pixels' problem which cause difficulties to obtain "real" surface temperature (Yow, 2007). Another problem is the large temporal variation according to surface and atmospheric properties (Bechtel, 2012).

Air UHI. In general there are two types of air UHI - UCL (between the surface and mean roof level) and UBL (above UCL). Because of the higher UBL homogeneity, UBL experiences more consistent UHI impact than UCL (Oke, 1976). The UHI in UBL can extend high above the city and is known as "urban plume" (Kuttler, 2008). It affects mainly airflow and pollution dispersion (Kuznetsova et al., 2004; Oke, 1995; Sarrat et al., 2006), and is measured by aircraft, weather balloons and remote sensing (Grimmond, 2006; Mestayer et al., 2005). Meanwhile the UCL is more susceptible to the UHI effect (Erell et al., 2012). Most of the human activities take place in the UCL and therefore the canopy layer UHI has the largest impact on humans (Yow, 2007). The measure of UHI is the UHI intensity. The greater is UHI intensity, the greater impact the UHI causes. The intensity of UHI in UCL is the most commonly measured (Yow, 2007) and can be expressed as air temperature difference between urban (T_{urban}) and rural (T_{rural}) areas: $\Delta T = T_{urban} - T_{rural}$. Because rural areas cool much faster than urban areas, this causes great differences in air temperatures. Under ideal conditions, the difference can reach even 10°C (Oke, 1987; Yow, 2007). The UHI intensity increases after the sunset and is greatest around the middle of the night and decreases just after the sunrise (Landsberg, 1981; Oke, 1982). However, Oke (1973) states, that the UHI intensity is highest around 21:00 – 23:00, although the time might vary among different city sizes and among the seasons. The common practice to measure UHI in UCL is using the urban weather stations, distributed within the city and the suburbs. Usually the temperature is measured in the screen height of 1-2 meters (Stewart and Oke, 2012). This method is accurate and continuously provides air temperature at fixed locations, but its security and maintenance can be costly (Yow, 2007). Although the remote sensing technology could be used to measure UHI in UCL, the problem is that the surface temperature often differs from the air temperature in the screen height of 1-2 meters (Roth et al., 1989), therefore the remote sensing technology cannot properly measure the air UHI. Additionally the UHI in UCL can be measured by sensors mounted on the vehicles (Yow, 2007), bicycles (Melhuish and Pedder, 1998) or even using the methods of floristic mapping (Bechtel and Schmidt, 2011).

Factors affecting UHI intensity and altering urban energy balance

Oke (1987) identified that thermal and physical properties of construction materials, urban geometry, emissions of anthropogenic heat, surface roughness, and drivers, decreased evapotranspiration are the main factors which alter the urban energy balance and cause the UHI effect. Additionally, Oke (1982) identified that urban structure, land cover change and population's characteristics alter the energy balance in urban areas as well. But according to Böhm (1998), the UHI intensity can change independently of population, due to changes of urban morphology and life-style. In general I identified five groups of factors altering the urban energy balance and affecting UHI intensity:

Urban geometry and materials. Empirical studies (Bärring et al., 1985; Chang and Goh, 1999; Montavez et al., 2000; Oke et al., 1991; Westendorf et al., 1989; Yamashita et al., 1986) found a strong relation between urban geometry and air temperatures. Additionally, number of studies (Ali-Toudert et al., 2005; Bourbia and Awbi, 2004; Harman et al., 2004; Kusaka and Kimura, 2004; Unger, 1999) identified that energy can be trapped in the street canyons due to urban geometry and physical properties of urban materials which have certain thermal admittance. In 1991 Oke et al. (1991) concluded that geometry and thermal admittance equally affect the UHI intensity. The study done by Ghiaus et al. (2006) found that the building height, density and street orientation affects natural ventilation which also contributes to an increase in UHI intensity. During the night the wind flow is usually down the slope and during the nights the wind goes upward. This can be changed by weather patterns, topography and local flows and circulations (Brazel et al., 2005; Lemonsu et al., 2006).

Pervious and impervious surfaces. According to Yow (2007), land cover influences the spatial character of UHI For instance, green areas of parks and lakes cool down surrounding areas and form “cool islands”, while areas such as densely built zones, commercial and industrial areas increases temperature of the surroundings. Also, the study (Arnds et al., 2015) assessing the UHI intensity in Hamburg, has found that the highest temperature values were within industrial areas or the city center with high degree of soil sealing and with plentiful surfaces of high heat storage capacity. A relevant influencing factor of land cover is the lack of vegetation - the removal of trees and other vegetation eliminates the natural shading effect and enhances heat retention by limiting evapotranspiration which is known as a natural cooling mechanism (Bosselmann et al., 1995; Kuttler, 2008; Weng et al., 2004). Meanwhile man-made surfaces, also known as impervious surfaces, have an opposite effect. Impervious surfaces such as paved roads, squares, buildings’ roofs, facades and parking lots tend to absorb, rather than to reflect, the solar radiation. Absorbed radiation is afterwards emitted during the night time. The larger quantities of solar radiation are stored in the tall buildings and narrow streets which are less exposed to the night sky. Therefore the UHI effect is much greater in high density urban areas, especially during the summer time (Burgess and Jenks, 2002). The bodies of water can actually lower UHI intensity. According to Alcoforado and Andrade, (2006) and Nasrallah et al. (1990), the bodies of water within urban areas can lower the UHI intensity through advection.

Anthropogenic heat. The people, as individuals, contribute to the UHI effect as well. Our bodies emit the moisture and heat (Oke, 1982; Ruth, 2006; Taha et al., 1999). Moreover, in order to keep comfortable temperature in the buildings, the air conditioning systems transfer the heat from buildings to the outside. But it is only a small proportion comparing to the power plants, industrial factories and transport systems. Such heat is known as heat waste or anthropogenic heat (Burgess and Jenks, 2002) and contributes not only to the UHI effect, but also to the greenhouse gas emissions.

City size and population. According to empirical studies done by Hogan and Ferrick, (1998), Kuttler (2008), Park (1986) and Yamashita et al. (1986), the UHI intensity increases with increasing city size and/or population. Moreover, Oke (1973) conducted a study to find a relation between the city size and the UHI intensity for North American settlements. He collected mobile data in 10 settlements with population ranging from 1000 to 2 million and the results supported hypothesis, that UHI intensity is a function of the city size (considering population). The UHI appears to be approximately proportional to the fourth root of the population under the calm and clear conditions. Contrary, Stone and Rodgers (2001) found another relationship. They defined a positive relationship between the size of a residential plot and the excess flux of the radiant energy. The lower population density areas contributed to more excess radiant heat to UHI development than the higher population density areas. Therefore the authors suggested a strategy to mitigate UHI effects by employing zoning restrictions for the urban development and promote the infill and higher density development (Ruth, 2006).

Climate and weather. Additionally Arnfield, (2003), Oke (1982) and Chandler, (1965) identified that seasonal climate and daily weather conditions, diurnal cycle and geography also effect the UHI intensity. Oke (1982) added that seasonality might also influence the UHI via variations in surface cover, such as vegetation, solar influence and attenuation by aerosols. Other examples are based on various case studies. Although Oke (1982) identified the highest UHI intensity during the summer months, the greatest UHI intensity in Birmingham (UK) was detected in autumn (Unwin, 1980). Meanwhile the studies by Kumar et al. (2001) and Magee et al. (1999) showed that highest UHI intensity for Fairbanks (Alaska, USA) and Mumbai (India) was in winter. The studies in Ibadan (Nigeria, by Adebayo, 1987) and in Mexico City (Mexico, by Jauregui, 1997) showed that the greater UHI effect was experienced not during the wet, but the dry season. The main cause was the higher thermal admittance of the wet soil in the rural areas. Chandler (1960) has proven that the wind speed and direction can greatly affect the UHI intensity. The wind speed and direction can be changed by variation in topography (Kim and Baik, 2005; Sofer and Potchter, 2006). Also higher surface roughness and complexity help to form short air flow patterns (Livada et al., 2002; Tong et al., 2005). According to Oke (1973), the relationship between the wind speed and UHI intensity is a non-linear: approximated inverse square root. Ackerman, (1985) and Landsberg (1981) stated that cloud cover also has a great influence on UHI. Moreover, Arnfield (2003) reviewed a number of studies which confirmed that UHI intensity decreases with increasing wind speed and with increasing cloud cover, UHI intensity is greatest during anti-cyclonic conditions, at night and during the summer or warm half of the year (typical for temperate latitude cities).

According to Stewart and Oke (2012) the measure of the UHI between urban and rural areas is not sufficient to represent temperature differences between complex structures of the city. Therefore, the classification of more spatial representations of urban climate and landscape is required. The example of such classification is local climate zones.

Local climate zones

For a long time the UHI effect was analyzed only between the urban and rural. Such an approach was quite simple and enabled researchers to compare the climate effects in urban and rural areas. The urban areas are densely overbuilt with rough high rise and buildings, full of impervious surfaces which have a great heat capacity. Contrary, the rural areas contain much more forests and croplands with plenty of vegetation, meadows and water sources which chill off surroundings (Stewart and Oke, 2012). However, the rural and urban areas are not uniform by roughness of the buildings, surfaces and vegetation cover. Therefore, the areas need to be classified into smaller, micro-climate zones such as a) land use, b) land cover and c) urban morphology (Kaveckis et al., 2017).

The pioneer, who did the first city climate-based classification was Chandler (1965). He distinguished four regions of Greater London by its climate, built form and physiography. Later, in 1978, Auer (1978) divided the city of St. Louis, Missouri, USA into 12 land classes based on building and vegetation characteristics. In 1991 10 US cities were classified by Ellefsen (1991) into 17 urban terrain zones by their structure, street planning and dominant structure materials. The Auer and Ellefsen urban classification schemes were a guide for an urban climate zone scheme later developed by Oke (2004). He divided the city into seven homogeneous regions, based on their urban structure (dimensions of buildings and street canyons), fabric (materials), cover (permeability) and land use. In Europe, in 1991, Wilmers (1991) classified the city of Hannover (Germany) into climatopes by vegetation, structure of the surface and land use. In other literature, "climatopes" also refer to the values and criteria of buildings, urban structure, surface, wind, temperature and population density. According to Steward and Oke (2012) all of these classifications have a few limitations, despite previous efforts to clarify them. One major obstacle is that there is a lack of a complete set of surface climate properties that are not regionally or culturally specific or that do not have consistent names and definitions. While I agree with the fact that there is not a set of terms that can be applied across all regions and cultures and that have consistent names and definitions, the term "surface climate properties" is unclear. Oke (2004) defined them as urban structure, fabric, cover and land use. But, does he mean that an urban microclimate depends only on these factors? It's a question that may seem to be easy to answer, but may be more complex than originally thought. More details about this question can be found in the discussion in chapter 10.3.

Stewart (2011) tried to overcome the limitations of the previous classifications and developed a new local climate zones' (LCZ) scheme which represent a set of the 17 regions (fragment in figure 25) of uniform surface cover, structure, material and human activity. Each LCZ serves as an entity of a thermally homogenous landscape of the city and is named by surface property (Kaveckis et al., 2017). 15 of these regions are defined by surface structure and cover, the other two by construction materials and anthropogenic heat emissions (Stewart and Oke, 2012).

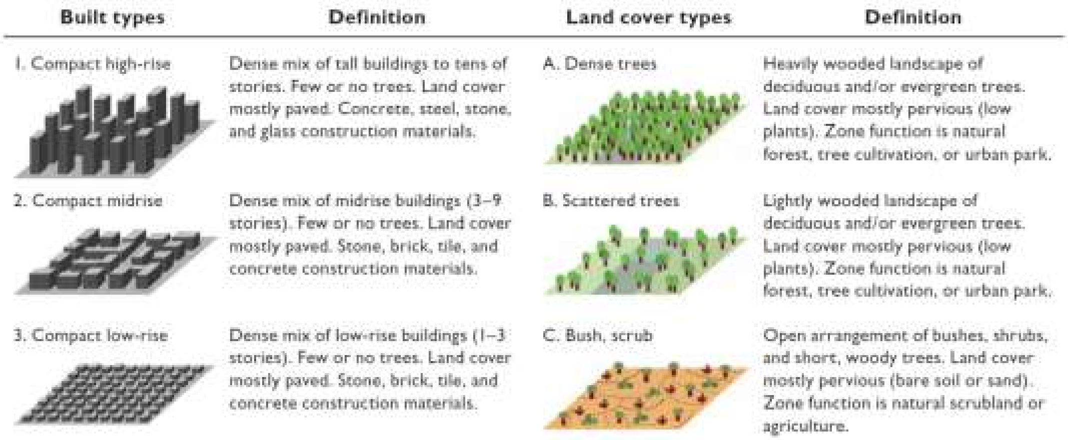


Figure 25: fragment of LCZ scheme with images and definitions (Oke, 2004; after Stewart and Oke, 2012).

The LCZ scheme has the following features for each zone:

- Associated with homogenous environments or ecosystems of cities, natural and agricultural lands;
- Ordered by height/packing of roughness objects and dominant land cover;
- Contains temperature measurements over dry surfaces at night;
- Has physical properties (part of table 5) which are measurable and nonspecific to place or time.

The aim of the LCZ scheme is to provide a thermal differentiation of LCZ classes. The thermal differences among the LCZ classes were measured by using the mobile temperature observations from case studies in Uppsala (Sweden), Nagano (Japan), and Vancouver (Canada) (Stewart and Oke, 2012). Together with the scheme, Stewart and Oke provide a list of geometric, surface cover, thermal, radiative and metabolic properties for each LCZ (fragment in table 5). These values are a great support in conducting various types of urban climate analyses.

Table 5: fragment of geometric, surface cover and thermal, radiative and metabolic properties for LCZ (after Stewart and Oke, 2012)

Local climate zone (LCZ)	Sky view factor	Aspect ratio	Building surface fraction	Impervious surface fraction	Pervious surface fraction	Height of roughness elements	Terrain roughness class	Surface admittance	Surface albedo	Anthropogenic heat output
LCZ 1 Compact high-rise	0.2–0.4	> 2	40–60	40–60	< 10	> 25	8	1,500–1,800	0.10–0.20	50–300
LCZ 2 Compact midrise	0.3–0.6	0.75–2	40–70	30–50	< 20	10–25	6–7	1,500–2,200	0.10–0.20	<75
LCZ 3 Compact low-rise	0.2–0.6	0.75–1.5	40–70	20–50	< 30	3–10	6	1,200–1,800	0.10–0.20	<75
LCZ 4 Open high-rise	0.5–0.7	0.75–1.25	20–40	30–40	30–40	>25	7–8	1,400–1,800	0.12–0.25	<50

Although the LCZ scheme is highly detailed and should be familiar and adaptable to the local characteristics of the most cities (Stewart and Oke, 2012), it is generic and cannot capture complexity of every urban area. An exact LCZ of two different cities with certain internal homogeneity is unlikely to be found anywhere in the world. More importantly, however, the LCZ does not reflect the socio-economic population's properties, which should somehow be included as a proxy parameter. This problem is a motivation to search for an appropriate classification method of social and economical properties.

2.3 Socio-economic diversity

The macro-spatial structure of cities is heterogeneous not only by the land use, land cover and urban morphology, but also by the different social groups living within. The social segregation is known from the early times when different social classes settled down in a certain areas of city –wealthy and educated people tended to live within city centers, skilled traders and craftsmen built their shops around harbor, market and city centers. The strong, uneducated and poor workers lived close to the industrial sites and farmers occupied outskirts of the city. Based on occupation people were closely connected to their location. But industrial revolution and automobilism changed it dramatically. With use of the public transportation and cars, workers can now live hundreds of kilometers away from the industrial site and still be able to commute to work and back. Today distance to work or the occupation might not be the main driver of social segregation. According to Duncan and Lieberson (1959), the 1950 Census in Chicago showed that the dominant factor of social segregation was ethnicity, but not the occupation. Other factors creating social segregation include religion, ethnicity, religious and other ceremonial buildings (Ley, 1983).

However, the occupation, wealth, education and ethnicity are not the only factors affecting social segregation. It can be also influenced by the age and family status. For instance, the dense urban housing, located within the downtown and inner city areas, is a less desirable option for raising the children (Michelson, 1976). According to Ley (1983), the high-density housing is associated with high-risk environment, influenced by heavy traffic and crime. Moreover, city core areas often lack schools, kindergartens and playgrounds. The housing within the city core usually is adult oriented with limited space, often sub-rented as a single room within an apartment. Meanwhile families prefer single spacious apartments or single homes with spacious yards. This suggests that the housing type can be related to the age, family size and social status. The abstract form of such relations in this study is represented by urban vulnerability climate zones (UVCZ) and is presented in chapter 5.1.

Social and economical diversity can drastically change the population's vulnerability to climate change (O'Brien et al., 2006). More than half of the world's population is poor and earn less than US$ 2 a day (UN-Habitat, 2003). Poverty is identified as an unacceptable set of properties which estrange individuals from human beings. The ability to be a human being includes a good nutrition, health, shelter and education, adequate income and expenses, social satisfaction and security (Gillis et al., 2001; Klugman, 2002). Poor people can hardly afford the necessary climate change adaptation measures, such as air-conditioning, heating, re-allocation and insurance. They have to rely on natural water and food sources which often are severely affected during the extreme events (Freeman and Warner, 2001).

It must be noted, however, that while all poor people are vulnerable, not all vulnerable people are poor (Bankoff, 2003). Elderly, children, females, people with limited mobility and diseases, uneducated and immigrants are among hazard-sensitive population (more about heat hazard-sensitive population, addressed in Greater Hamburg, read in chapter 6.1). During extreme events, these population groups, together with the poor, should be taken care of by the governmental/institutional services and supplied with shelter, emergency support, social help and compensations. However, capacities to provide these services can be affected during disasters. This is common in the poorer countries which live with sustain other economical and social stressors (Freeman and Warner, 2001). Unfortunately, even if a government has enough national capacity to deal with extreme events, rural areas with limited infrastructure cannot be properly serviced, and people in those areas look for shelter in larger human settlements, often cities.

2.4 Climate change effects on human settlements

Human settlements are areas of high concentration of human populated areas with economical and social activities and physical capital such as buildings and infrastructure. They serve as shelters for population with greater job employment possibilities and better public infrastructure. However, often these areas have existing urban problems, such as low air quality and poor water supply. Additionally they have higher vulnerabilities to the location-specific events, such as decrease in air quality and health, heat and cold waves, wind storms, water scarcity, urban drainage and fluvial flooding, diseases, concentrated resources, sea level rise and coastal flooding (Dawson et al., 2009; EEA, 2008; Schauser et al., 2010). The occurrence of such events in the settlements have a higher probability to affect higher amount of people (IPCC, 2007).

The increase in population causes people to settle in higher risk zones such as valleys, slopes and coastal areas, all of which are more susceptible to land slides and flooding (UN-Habitat, 2003). Today, more than half of the world's population lives in coastal areas. At the same time, coastal cities play a significant role in the world's globalization ad economy (Wisner, 2004). Coastal areas and low lying small islands are at particular risk because of the potential rise in sea level. In the United States alone, if the sea level rise by 0,9 meter, as it is projected, more than 4 million citizens would be at risk (Hauer et al., 2016). But the rise in sea level is not the only problem for coastal cities.

Cyclones (also known as typhoons in the Pacific and hurricanes in the Atlantic Ocean) are very common as well as complex disasters, inflicting heavy winds, coastal and fluvial (river) flooding. About 15% of the world's population is at risk from tropical cyclones (Smith and Petley, 2009). According to the IPCC (Susan, 2007), future cyclones may not be as numerous but will probably have a higher intensity, which means that there will be higher pressure on the urbanizes areas along the cost. The winds of the cyclones pile up water along shallow shelves along the coast, and then hit the coast causing a storm surge and/or coastal flooding

(Wisner, 2004). In addition to this, coastal cities can be affected from both sides: by coastal flooding from the sea and by fluvial flooding from inland rivers, if the city is situation anywhere close to a river. A good example of this is the city of Hamburg, Germany.

Hamburg was established in Northern Germany on the bank of the Elbe River, which flows into the North Sea. The gravitational force of the moon causes low and high tides twice per day, with a tidal range of 4,65 meters in total (Tide-forecast, 2016). During the late autumn and winter months, recurring storms with dominant North-West winds push the water back to the Elbe. This combination of high tide and storm surge can be very dangerous. Such an even happened in Hamburg in December 2013 when Northern Germany was hit by storm named "Xavier". Wind gusts of 140 km/h forced the closing of schools and at least one major highway (A-7) and closed Hamburg's international airport, cancelling all flights. Low lying areas, including the Fishmarkt (figure 26), were inundated with water.

Figure 26: flooded Fischmarkt – the impact of storm Xaver in the end of 2013.

Hamburg is susceptible not only to fluvial but also to coastal flooding. In June 2013, heavy rains in Central Europe caused heavy flooding along the Elbe river basin, causing significant damage and loss of property and human lives in Czech Republic, Poland, Germany, Slovakia and other countries. Part of the city of Lauenburg, not far from Hamburg, was evacuated because of the flooding of residential areas. The flood waters reached Hamburg a short time later, but, because there were good flood defenses and mitigation measures in place, there were no significant impacts on Hamburg. However, if the Elbe floods had been accompanied by a storm surge and high tide, it could have been more serious.

A second common hazard to large human settlements is extreme heat, causing stress to almost every system in the settlement. Heat waves have a very high impact on the health infrastructure, due to increased ambulance calls and increased hospital admissions. Heat waves cause water shortages and increase pollution, which can provoke social unrest and violence (Simister and Cooper, 2005). Failures in transportation systems, power shortages and outages increase the stress on a population. Buckled rails and overheated engines on public rail transportation leave people stuck on a train for hours during heat waves (Schauser et al., 2010). Most importantly, heat stress is one of the major hazards to human loss in developed countries. Heat stress affects the population and reduces their productivity, causes health problems and disease. It reduces their productivity and increases cooling costs and water consumption. Some studies identified highest losses to be among older people, especially those with poor health and or limited mobility (Blaikie, 2004; Cutter et al., 2001; Scherer et al., 2014; Smith et al.2004). For instance, during the heat wave of 2003 in Europe, the stress caused by extreme heat caused the loss of life to about 15,000 people in France alone. Most of those who died (82%) were over 75 years old (Poumdere et al., 2005).

2.5 Urbanization and its negative effects

It might be said that the worst conclusion in all this is that, due to population growth, more and more people are settling in hazard-prone areas (Smith and Petley, 2009). Urban areas that are heavily populated have a greater risk of disasters (EEA, 2013; Schauser et al., 2010). Oke, (1982) showed that heat has a higher impact in cities with higher population density and higher degree of urbanization (Smoyer et al., 2000; Souch and Grimmon, 2004). In 2014 the United Nations stated that the unplanned and rapid urban growth has a negative effect on sustainable development. This unplanned development causes rapid urban sprawl, pollution and a degradation of the environment. We also see that there is often a lack of adequate infrastructure and zero to little implementation of policies already in place, lowering the quality of life to those living in those areas. This higher concentration of people is more susceptible to technological and natural disasters, especially heat waves, which may be multiplied through the effect of the urban heat island. Today, urban areas are less equal than rural areas to cope with disasters, with millions of people living in poor areas.

Yet people still move to the cities to search for more entertainment, job opportunities, better healthcare and social interaction. Currently, more than have (54%) of the world's population live in cities. Future predictions are that by 2050 that number is projected to increase to 66% (United Nations, 2014). In order to mitigate the damages of such a process, it is important to know how urbanization will change in the future.

IPCC (IPCC, 2007) names urbanization as "*a conversion of land from natural state to cities*". Or in other words – it is a conversion from non-urban (rural) to urban areas. The differences between urban and rural is an unending discussion and one of the oldest and most pervasive geographical dilemmas (Woods, 2010). Paddison (2001) has identified three factors which differentiate rural and urban areas:

Statistical factor (Padisson recalled it as the ecological factor). It is physical factor and defines urban by population size and density which varies from country to country. The term "urban area" was developed by the census bureau to provide a comprehensive definition of a city (Bruegmann, 2006). In the United States, for instance, the areas with more than 2500 people are considered as urban. In Denmark, a population of 250 or greater is considered to be urban. Meanwhile in India, it is 5000 and more. In Japan an urban area which is called "Densely Inhabited Districts", the population usually is more than 5000 people. Each country or specific areas within the country have different thresholds of population size and density. And these thresholds have to be considered, before identifying the urban areas.

Economic factor. This factor considers the function and the use of the area. For instance, the main economical activity in the rural area is agricultural and production of raw materials. Meanwhile the urban centers usually focus on services and non-agricultural production, educational, administrative, political activities and the use of a diverse work force. Such interpretation of urban area greatly differs from the physical factor, is less discrete and harder to be defined.

Social character of the area factor. Often this factor is defined as the degree of urbanism, or the way of life in a particular urban area. The social character of the area considers the differences between the living conditions and the life style of rural and urban people, their values, behavioral characteristics, values, attitude to the surrounding environment and the way they perceive the world. The social character of the area can be described by studying supporting infrastructures (availability of gas utilities, electricity network, piped water, the entertainment and educational facilities etc.) and negative characteristics (crime, pollution, congestion, noise etc.) (Paddison, 2001). Diversity is another indicator of social character. Diversity, also known as openness, is often described as a composition of percentage of foreign born population with other social characteristics like age, life styles, sexual orientations etc. According to Florida (2002), the diversity factor is the engine of the city growth. The more diverse is the city, the more it attracts the talents.

Urbanization, the process of conversion from rural to urban, is an unending process. It can be segregated as waves of urbanization, sub-urbanization and re-urbanization and can vary among countries. The simple way to measure the urbanization is to compare the proportion of national population and the population living in the urban places (Paddison, 2001). For instance (figure 27), in 1960 about 40% of the population lived in urban areas in Lithuania. In Kenya this number was less than 10% and in Germany over 70%. Until 2014, the relative urban population in Germany had only a slight increase and did not go over the threshold of 80%. In Kenya the urbanization was more intense and today the number of relative urban population is more than 20%. Meanwhile in Lithuania there was a higher increase between 1960 and 1980-1990. During that time, it increased from 40% to little bit less than 70% (increase by approx. 30%). Afterwards, from 1990 to 2014 the number very slightly decreased. This shows that urbanization progresses quite differently among the countries.

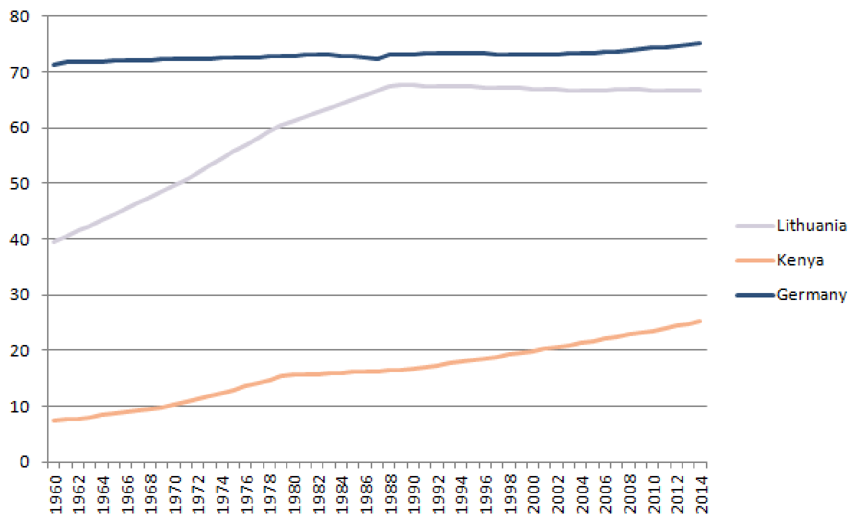


Figure 27: urban population change in Germany, Kenya and Lithuania from 1960 to 2014 (source The World Bank, 2016, data collected and analyzed in 01.02.2016).

In the global perspective, today's urbanization degree greatly differs from a half century ago. In 1950 more than 70% of the planet's population lived in rural areas and another 30% in urban areas. In 2007 the population of urban areas was greater than in rural areas. According to the projections (figure 28), by 2050 about one third (34%) of the world's population will be rural, the other two thirds (66%) will be urban (United Nations, 2014).

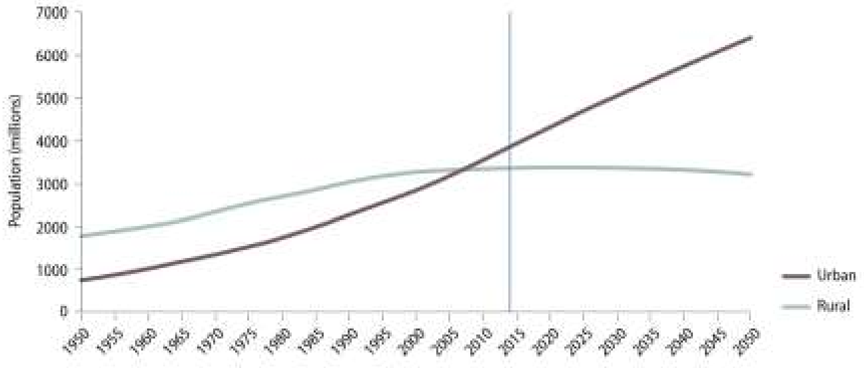


Figure 28: worldwide urban and rural population in 1950 – 2050 (United Nations, 2014).

As urbanization increases, cities continue to grow. Cities with a great concentration of population are known as mega cities. The mega city is home for more than 10 million inhabitants. In 1990 there were 10 such cities around the globe. Today this number tripled to 28 million which is about 12% of the world's urban population. According to United Nations (2004), over three fourths of the one hundred largest cities are exposed to at least one natural hazard, ranging from earthquakes, floods and storms, to extreme heat, cold and wildfires. Such diversity of different hazards forces us to think about different strategies to fight these hazards and reduce their vulnerability (Gencer, 2013a).

The megacities, however, are not the only vulnerable human settlements. Developing countries are experiencing the immigration of low-income populations into already overcrowded cities and settling in unsafe environments such as slums (Havlick,1986). Slums tend to be, in most cases illegal and informal settlements with self-built housing, often lack of standards like clean water, sewage and electricity, basic sanitation and other public services. Adding to the problem is the fact that these slums are often built in risk-prone areas such as river valleys and unstable slopes (Romero Lankaoet al., 2005). The result is that the cities often need to rely on therefore often they have to rely on national or international support (De Sherbinin et al., 2007). Often they are built in risk-prone areas such as river valleys and unstable slopes (Romero Lankao et al., 2005). People living in slums usually have poor health and low nutrition status (Wisner, 2004). More than 43% of all the slums are located in the developing countries which experience 90% of the deaths related to the natural disasters (UN-Habitat, 2003; United Nations, 2004).

Another negative consequence of this urban growth has to do with formerly administratively and politically independent settlements surrounding these developing mega cities. The developing metropolitan area, with its increase in population, incorporate these smaller settlements into their metropolises, creating peripheral municipalities and causing additional challenges to urban governance (Gencer, 2013b), management, tax collection and planning.

A third negative effect of urbanization is on agriculture, especially in the developing agriculture-dependent countries. Urban expansion into fertile lands decreases the local food supply, which is very important in these areas because of their limited transportation infrastructure. Limited food supply increases poverty and vulnerability to climate change effects. In addition to direct effects on the population, urban expansion to fertile lands and forests disrupts the water cycle, increasing areas of impervious surfaces and creating more soil erosion (Gencer, 2013b; Satterthwaite and Tacoli, 2002). More impervious surfaces also reduce the natural water filtration in heavy rain events and cause UHI effects during heat waves.

All of this indicates that urbanization does not always have a positive effect. If climate change is unavoidable, then urbanization should be monitored, maintained and shifted, as needed. Good urban planning, coupled with comprehensive social and economic development strategies can greatly minimize the negative impacts of climate change.

2.6 Urban planning, policies and zoning

From almost the beginning, cities are complex places, and the complexity and challenges increase with the growing size of the city. Cities, therefore must be planned and controlled carefully as they develop. Urban planning (also known as town planning) is the planning in spatial, or geographical, context. It is also known as “physical” and “spatial” planning. “Spatial planning” is a more neutral and precise term (Hall, 1975). The aim of urban planning and the policies that accompany it is to fight problems cities might face, such as the protection of the environment, social differences, the reduction of inequality, economic growth and an overall increase in the quality of life. Urban planning, and urban policies, however, are broad terms and can include a number of methods and activities, which vary in space and time (Hall and Barrett, 2012). Urban planning faces the problems created by urban and growth and the expansion of the city such as land use, construction and creation of an infrastructure. In addressing the social and environmental challenges related to rapid population growth and urban development, it attempts to control the development of designs and plans in order to improve city services and functions. Urban policies, on the other hand, create and implement regulations to deal with urban social disadvantage, the impacts of deindustrialization and the deprivation of economic assets (Hall and Barret, 2012; UN-Habitat, 2009).

Figure 29: example of urban plan of the Hafen City in Hamburg (source: www.hafencity.com).

The processes of urban planning are represented in urban plans. The urban plan is an official document which presents the planned urban changes in a certain area. One of the examples of an urban plan can be seen in figure 29 which represents the urban plan of the Hafen City project in Hamburg. Hafen City is still an ongoing project of urban regeneration. Aim of this project is to convert the old port and warehouse area into the residential, commercial and office zones. This specific urban plan shows existing and planned building activities, land use and zoning, infrastructure, borders and land surfaces. Such and many other plans, and policies are managed by urban managers.

Urban managers deal with sustainability, economic competition, social differences, demographic change, migration and traffic. Their challenge is to develop new methods through urban planning and urban policies in order to deal with these issues. Urban planners and urban managers are not alone when dealing with urban planning and policies. Also involved are the stakeholders, including, but limited to, politicians, business leaders, civil servants, communities and individual citizens, who all possess different levels of influence (Hall and Barrett, 2012).

Urban zoning is based on urban planning and policies. It designates certain areas for specific types of land use. The first time urban zoning appeared in United States in early 20th century in New York City after the local property owners were concerned about the land value of their properties that were adjacent to higher buildings which blocked daylight from their property (Cadwallader, 1995). Today the zoning, together with urban planning and policies, helps to control the city and deals with its "inner" problems. However, more and more cities are needing to deal with "external" stressors such as the increase in temperature and the forms of urban heat islands, higher precipitation and other extreme weather patterns which can be partly identified as a consequence of urban development and climate change.

Because of the negative impacts of climate change, urban planners have begun to unite to address the challenges of sustainable urban development. There have been many discussions, involving many experts to look at this. These discussions have proposed one way to increase sustainable urban development through a strategic spatial planning process. It focuses on a process of decision making that is flexible and not strictly defined by any one set of urban forms or values. Strategic spatial planning methods emerged in Europe in the 1990's and have spread to other developed, as well as developing, countries since them. These have resulted in new approaches of urban planning and management. Unfortunately, these new approaches are mostly in theory and concept and have not been significantly used to fully address the problems facing cities (Hall and Barrett, 2012; UN-Habitat, 2009).

One way to strengthen this strategic spatial planning is to model a future urban development scenario, which would explore possible consequences of various urban development patterns. Negative urban development patterns that would cause a greater vulnerability to climate change could be anticipated and avoided, and positive urban development patterns could be encouraged.

2.7 Urban development patterns

The term "urban development" is often used to refer to the change in the urban landscape. Although the word "development" can have both a positive and negative connotation (Oxford Dictionary, 2015), it's not usually specified and represent, in general, the urban changes. Burgess (1925) proposed an ideal construction of the city as separated into five concentric land use zones which represent the zones of urban expansion. The first zone was a downtown and was called as "central business district" (CBD). It contained banks, governmental offices and retail shops, cultural and recreational buildings. They were surrounded by wholesale trade business and their warehouses.

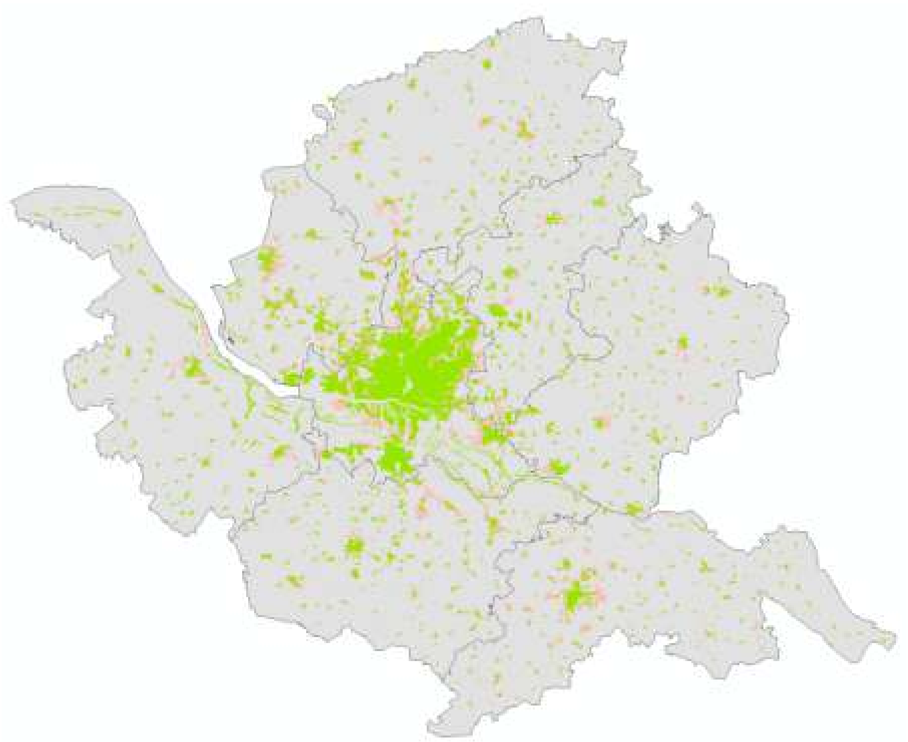


Figure 30: Greater Hamburg urban growth (red color) in 1960 – 2000. Green color represents the urban areas in 1960 and the red color is the further expansion till 2000.

The second zone (also known as a transition zone) was filled with factories and the dwellings of working people. The third zone was a belt of houses of independent workers, who worked in factories or the CBD. The fourth zone was a zone with better and richer residencies. Most of them were single dwelling houses with spacious yards. The last, the fifth zone was usually outside the city limits and was made of a ring of hamlets and villages. It is known as a commuter's zone. This zone was mainly suburbs with very limited industry and employment possibilities (Cadwallader, 1995).

The Burgess' city growth model represents a typical urban sprawl. Together with sprawl, I have chosen the concentration and de-central concentration as extreme urban development scenarios which are the only the examples of how differently a city can develop under certain political, economical and social conditions. Below I described these scenarios in details.

Concentration

Urban concentration (also known as urban centralization) is the process of concentrating population from the outskirts (surrounding the city or city center) to the city core. It is in contrast opposite to the urban sprawl and usually occurs when the city core grows more rapidly than the areas in the surrounding ring which experiences a loss in population (Paddison, 2001). Ideally the urban concentration is seen as a "compact city", as concept in urban planning and urban design. In an effort to achieve a more efficient management of waste and resources, this concept was first proposed by Dantzig and Saaty in 1974. The compact city has a relatively high population and building density and is based on an efficient public transport system. In the ideal setting, the urban layout of a compact city encourages walking and cycling in the commute to back and forth to work (Breheny, 1992). The ideal concentration model is the old medieval European city with a small central area, surrounded by a wall. The central area contains buildings with main functions, required for the city: city hall or castle, fountain and square, market, church and armory. This medieval pattern broke up with the onset of industrialization, when new ways of transportation emerged.

Figure 31: concentration to the city core of Hamburg city.

In modern times the CBD concentrated and centralized most of the services, administrative and bureaucratic activities. Today the core in most cities contains only a small proportion of the population and jobs of the whole metropolitan area. For instance, between 1990 – 2000 the city core of Paris lost about 200 000 jobs, while the suburban ring gained 20 000 jobs and the outer suburban ring got over 160 000 jobs (de Chenay, 2003). Once city centers have functioned independently, they started to compete with the multi-centered urban regions (Bruegmann, 2006).

Today, the concentration is reborn as new trends: for instance, the "New Urbanism" in the United States or "Stadt der kurzen Wege" ("The city of short pathways" in German) in Germany. The latter represents the European trend of "urban village" or the typical medieval town where all main buildings can be accessible on foot or by a bicycle today. The "New Urbanism" is an urban design movement, developed in the early 1980s in the United States. It promotes walkable neighborhoods and has a great affect on architecture, infrastructure, land use, urban planning and real estate development. Good examples of "New Urbanism" are the 20 square kilometers town of Celebration in Florida, Mountain House urbanistic project in California and many others (Boeing et al., 2014; New Urbanism, 2016; Reid, 1985).

Additionally, urban concentration also refers to the intensification and densification in terms of the buildings, activities and urban form. Urban activities are located closer to each other in order to ensure better access to services and facilities through the rapid public transport, walking and cycling. In the developing countries low income groups are living in the city center in a high density tenant blocks, shantytowns, subdivided houses and slums. Meanwhile the rich and the middle class live on the periphery in spacious and luxurious residences.

In this case, even greater densification within the city center increases social and environment problems (Burgess and Jenks, 2002). The densification policies of developing countries do not necessarily apply to developed countries, where the middle and wealthy classes are living in city center areas and the low-income population lives in the suburbs, where rent prices are much lower.

The compactness of the city affects the energy demand and environmental quality as well. It reduces energy consumption because efficient transport systems and shorter travelling distances require less energy. The compact groupings of buildings reduce heating demands in winter and give wind protection and limits energy loss overnight. It must be noted, however, that these benefits are specific to only certain climatic regions (Bergess and Jenks, 2002). It must also be noted that buildings built today with high energy retention can also be disadvantageous because it makes compact cities good targets for urban heat island effect. More about this effect can be found in chapter 2.2

Despite the shorter travelling distances to work, the downsides of a compact city are the high concentration of pollution, noise, squalor and crime (Paddison, 2001). The usually higher rent prices, the limited living space and connection to nature are other important factors decreasing the desirability to live in the inner city. Even in developed countries, workers with poor education are trapped in poverty, low wages, poor health and poor housing conditions, living in the inner city (Knox and Pinch, 2000).

De-central concentration

De-central concentration is related to de-centralization, in that it addresses the movement of people, employment and services out of the city core and inner city areas in into the suburban districts and further beyond the city limits (Knox and Pinch, 2000). De-central concentration can be represented by a polycentric model, which has a number of sub-centers, instead of one CBD. In de-concentration the attraction is not related to one central area, but distributed among sub-centers. The sub-centers are individually small monocentric representation with their own commercial, residential and industrial activities. These sub-centers are often located near the intersections of major highways (Cadwallader, 1995). In Europe, sub-centers often emerge close to the hubs of rapid transit systems such as major metro train or suburban train stations.

Figure 32: de-central concentration to Hamburg's surrounding districts causes greater concentration of population, social and economical activities in the sub-centers. The points are the sub-centers within Federal State of Hamburg.

The early model of de-central concentration was developed by Ebenezer Howard, the stenographer and writer, in his book "To-morrow: A Peaceful Path to Real Reform" in 1989. This model was known as "Garden city". It has a vision of gradual transformation of the existing concentrated cities into de-centralized garden cities, connecting a network of social city. Each garden city would have a population of 30 000 with 2000 more people in the adjacent agricultural areas. The concentric areas would be filled with open spaces and parks.

De-centralized garden cities would promote cooperative actions and collective ownership of the land which would increase the land values (Ward, 2005).

The structural organization of de-central concentration refers to a fragmentation and geographical dispersion of organized services, manufacturing and a public sector into sub-centers (Knox and Pinch, 2000). We have experienced the de-centralization of responsibility on the part of national powers for the delivery of services in a number of countries since the early 1980's. In France, Spain, Italy and Belgium, national powers have been de-centralized to subnational governments. Such de-centralizations have enabled appropriate autonomies to better respond to rising urban challenges. Parallel to this governmental de-centralization, the private sector has seen more centralization in their organizational structure, but has seen more de-centralization in their production and distribution (Richard et al., 1996).

Commuting patterns are often a major factor affecting urban space. Diverse economies and a mobile labor force have encouraged people to commute longer distances. Many cities around the world have expanded in size because of the de-concentration of their population. As commuting becomes easier, individuals want to live closer to nature, increase their personal space and decrease their cost of living, yet still have the same quality of city services as in the inner city. This caused the physical expansion of urban areas and increased the population density around the sub-centers within, or even outside, city limits. What follows naturally is a redefinition of urban boundaries (Paddison, 2001).

Suburbanization and urban sprawl

Paddison (2001) calls the suburbanization a new trend which became more popular during the second half of the twentieth century when an increased car industry and popularity of the automobile removed the functions of mass transit systems and they lost their power to be the mediator between home and work.

People successful in business started to build large homes outside the industrial and commercial centers. After 1950 urban de-centralization came to be viewed more in terms of suburbanization, addressing the change in urban development patterns. Suburbanization reflected a shift from the densification within the inner city and its core to expansion to the suburbs of the city. It was a dominant urban development trend not only in the Anglo-American world, but also in Western Europe. During the post war period in Western Europe suburbanization emerges as a dominant process of population redistribution (Paddison, 2001).

Harvey and Clark (1965) identified three main types of the suburbanization. The first type is the continuous development of the low density areas around most of the large cities. The second type is development along the axis of the city. The axis usually being a transportation network or natural obstacles such as a river, lake or sea. This type can be clearly seen in Hamburg, where "Achsen Konzept" is known as axial growth and was developed by Fritz Schumacher in the late 1920's, even though it was not implemented until the late 1950's. Its pattern is an urban growth around train stations and the road network. The axis' link the city center with suburban areas which are concentrated with housing, commercial and industrial areas (Daneke and Ossenbrugge, 2012). The third type of suburbanization is the sprawl of discontinuous patches. This kind of suburbanization is identified as the least economically efficient and esthetically attractive (Cadwallader, 1995).

Figure 33: Suburbanization (urban sprawl) pattern from the city core of Hamburg to the outer ring, suburbs or the surrounding districts.

The main reason for suburbanization was a growing disappointment with the quality of life in the dense central areas of the city (Cadwallader, 1995). The high cost of living, congestion, grime, squalor, noise and crime were additional negative aspects. In Germany, the post-war urban planning made cities less attractive. The urban development of the inner cities of that time was strongly criticized by Alexander Mitscherlich (1965). According to Mitscherlich, the post-war urban planning and architecture in Germany caused negative societal and psychological consequences. Therefore, the post-war period encouraged people to flee the inner cities, create families and seek for a more space and better quality of life and raise their children outside city core (Paddison, 2001).

Similar to the process of suburbanization, but with a negative aspect, is urban sprawl, defined as the "scattered low density urban development without systematic large-scale or regional public land-use planning" (Bruegmann, 2006). This lack of systematic land use planning causes many problems, one of which, in the U.S., is taxation. Local governments collect taxes from residents, industrial and commercial activities within city limits. The reallocation of these assets to the suburbs, and out of the legal boundaries of the city, causes a rapid decline in revenues and a rapid rise in city expenditures, including fire and police protection, social and education services and road and utility maintenance (Cadwallader, 1995). Other negative effects include a decrease in available agricultural land, too many dispersed employment possibilities, longer travelling times and increased pollution from car emissions, an increase in car accidents and limited and more costly public services (Britannica, 2000; Cadwallader, 1995).

3 Modeling and data processing

The chapter of modeling and data processing presents the operational options which have been used to process the data required to model future population's vulnerability in Greater Hamburg. The overview of these operational options helps to understand why the certain model for this study was selected, what the main factors influencing the model are and how the data can be transferred from a larger scale to smaller scale spatial units and vice versa. Application of these methods and model for Greater Hamburg can be found in chapters 5, 6.1 and 8.

The modeling of future population's vulnerability is a huge challenge. In the Greater Hamburg case study, the population's vulnerability is presented by urban landscape, climate and population which are related to a proxy parameter – the UVCZ. The UVCZ does not only differentiate the space by urban landscape, climate and population, but also changes over time – the urban development changes the urban space and attracts new population, the climate changes, and vulnerability is changing as well. It became apparent that a mathematical model which would be time sensitive and would represent spatial differentiation was needed. The cellular automata was identified as the most suitable mathematical representation to model the UVCZ.

3.1 Cellular automata

Cellular automata (CA) is a mathematical representation of physical systems, with the discrete space and time (Wolfram, 1983). CA was introduced by von Neumann in 1963 and was called "cellular spaces" or "cells". At that time CA represented a model of biological self-reproduction (Von Neumann, 1951). The first time CA was referred to geographical models was in 1979 by Tobler (1979). The task of CA at that time was to provide a computationally efficient technique for the investigation of dynamical systems. However, the complexity of the realistic geographical models was increasing and it was noticed that CA was capable of presenting their processes at a high level of detail. The interaction of a location with its surroundings was proved to be an important factor in land use change (Torrens and O'Sullivan, 2000; Verburg et al., 2004), as such structures simulate the dynamics that characterize a city's growth and development (Batty, 2007). The first attempts to apply CA to the context of land use planning, urban development and urban growth can be found in a number of studies (Batty,1997; Clarke and Gaydos, 1998; Couclelis, 1997; Engelen et al., 1999; Wu, 1998) toward the end of the twentieth century.

The base of the CA is the grid of cells. In the spatial context, the typical grid of cells is represented by a set of square spaces, separated by edges. Usually the grid does not have to be a correct square, therefore the dimensions of the grid are not restricted by the amount of columns and rows. Every cell maintains a certain state (or function). In the context of land use, each cell represents a dominant land use or land type within. The cell evolves and changes in a discrete time to the value which is affected by the neighborhood cells and defined set of rules. The value at each cell is updated synchronously (Wolfram, 1983). However, in land use modeling there are two types of cells, the dynamic, also known as land use functions, and static, the land use features. The dynamic cells evolve and are affected by neighborhood cells and set of rules. In the real world they are representing by residential, commercial, industrial and other dynamic land uses. Meanwhile the static ones do not change and maintain the same state over time. The static cells the in context of land use are represented by airports, larger areas of roads and infrastructure and others which do not change its function over time.

The neighborhood of the cell is defined as the surrounding area or adjacent cells. There are two types of CA neighborhoods (figure 34) – the von Neumann (the 4 adjacent by edges cells) and the Moor (adjacent plus diagonal, 8 cells in total) (Gilbert and Troitzsch, 2005). However, the neighborhood in CA is often not restricted by one rank or one cell radius. For instance, in Metronamica, the cell neighborhood is defined as a circular area with up to 8 cells far-radius around a cell. In total that would be 196 cells. All of these cells (their state) have an effect on the state of the surrounded cell. And of course, the surrounded cell has the effect on other cells. The neighborhood effect to a cell is calculated by analyzing the states of the surrounding cells. The more distant cells will have less effect than cells nearby (RIKS 2013). The neighborhood effect is calculated for all dynamic cells in the grid during a discrete time frame. Therefore, neighborhood calculation or modeling of the denser cell grid will require more computational power and will take a longer period of time to calculate.

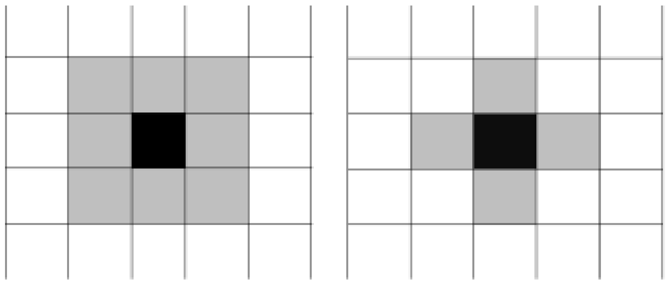


Figure 34: CA neighborhoods. Moore neighborhood on the left and von Neumann on the right.

The following figure (35) demonstrates a simple example of cellular automata in land use application. The current stage at time step 1 shows two industrial cells which would represent two industrial building blocks in the city, and one residential cell, adjacent to the industrial.

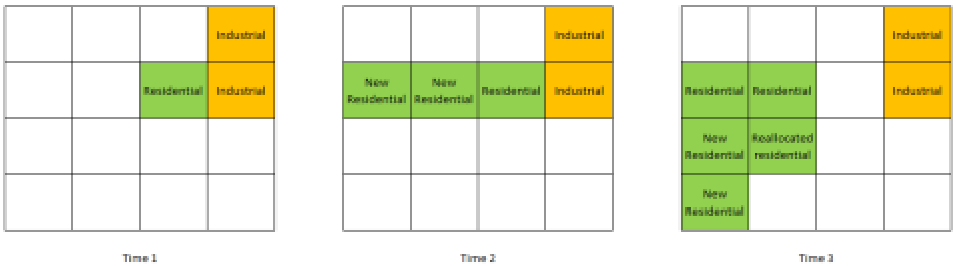


Figure 35: discrete time of new residential development and re-development.

Each model contains a list of rules which define how many and how the new and current cells should emerge, or change their state. The demand for this particular example (figure 35) is that every new time step two new residential cells emerge and there is no demand for industry, so it stays the same as it is in all three time steps. This answers the question of how many new cells should emerge. A second question is how each cell should emerge. Based on a given specific rule, it is known that it is preferable that any new residential development would occurs closer to residential cells. If there is an empty cell that is adjacent to two residential cells, it will have a higher potential to become a residential cell, than to stay an empty cell adjacent only to one residential cell. A second preferred condition is that a new residential cell would not be close to an industrial cell (a real life situation in which people prefer to live a distance from industry to avoid noise and air pollution). This application can be seen in the second time step ("Time2", in figure 35), when the emergence of two residential cells appears adjacent to the existing residential cell. In "Time Step 3" (time 3) it can be seen the emergence of two new residential cells and the reallocation (if it is possible, according to the given set of rules), of the pre-existing residential cell. If the inertial state of the cell is high, the cell will stay as it is and will not change its status, or function. It is possible to change its status to a "free" or "empty" cell. The demand (D) of residential cells for that next time step will be D+1. Cells will emerge with each time step until the demand is satisfied. These, and other like speculations of rules give great flexibility when using CA based land use application.

The list of CA rules and other factors can form specific models, as they are used in different disciplines. For instance the CA can be used to simulate forest fires, taking into account factors of wood type, cell of initiated fire, wind direction and the fire spreading coefficient. Another application could be the simulation of a dam breach, considering flood depth and digital elevation model. Meanwhile the interest of this study is the model, capable to represent the changing urban landscape – urban development.

3.2 Future land use modeling with Metronamica

One of the comprehensive CA-based models used in urban development is Metronamica. Metronamica is a spatial decision support system, developed in the Geonamica software environment. Both commercial products are created by RIKS and are based on Monitoring Land Use / Cover Dynamics (MOLAND) model. The main applicable fields of Metronamica are the urban and regional planning. Metronamica simulates dynamic land changes, based on environment, population and infrastructure.

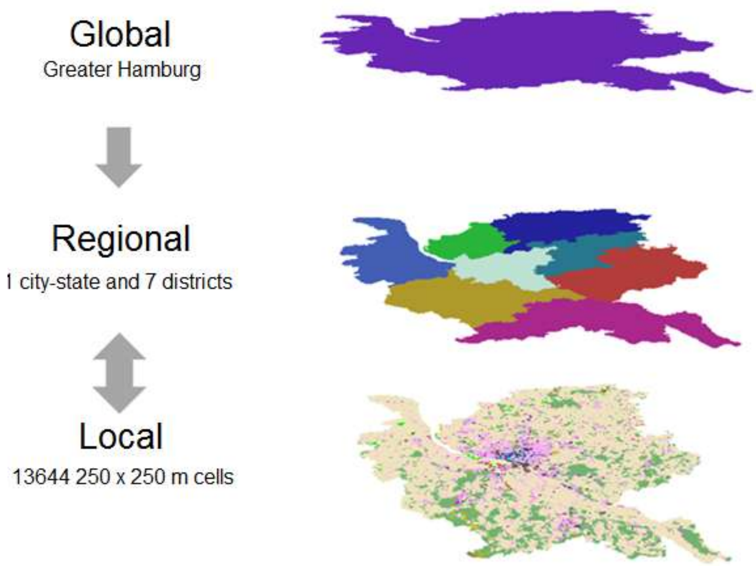


Figure 36: Metronamica models (levels) at three spatial scales for Greater Hamburg case study.

Three models with different spatial scales exist in Metronamica. Figure 36 represents these three models for the Greater Hamburg case study. The global model covers the whole GH case study area and is affected by total landscape and population changes which are the inputs into the regional and local models. The regional model is responsible for the dynamics of economic activities, landscape change and population's migration between the regions (districts and Hamburg city-state in our case). These activities are relocated among the regions at each iteration of the model. Relocation is based on attractiveness of the region and their local characteristics. Each region is competitive and attracts population from a global level and other regions (migration). In our case I do not use a regional model, due to economic and population inequality between the regions (Hamburg city-state and districts). One of the reasons is because the Hamburg city-state is a leader in economic activities and attractiveness of population and business in the area. The adjacent districts have little to no competitive power over Hamburg. Therefore, I use the local model of Metronamica which employs CA and acquires outputs (land demands) and population change from the global model (RIKS, 2013). The local model is constrained by land demands and CA restrictions. CA in the local model is used for land allocation for every time step. The study area in local model is represented as a mosaic of a grid cells.

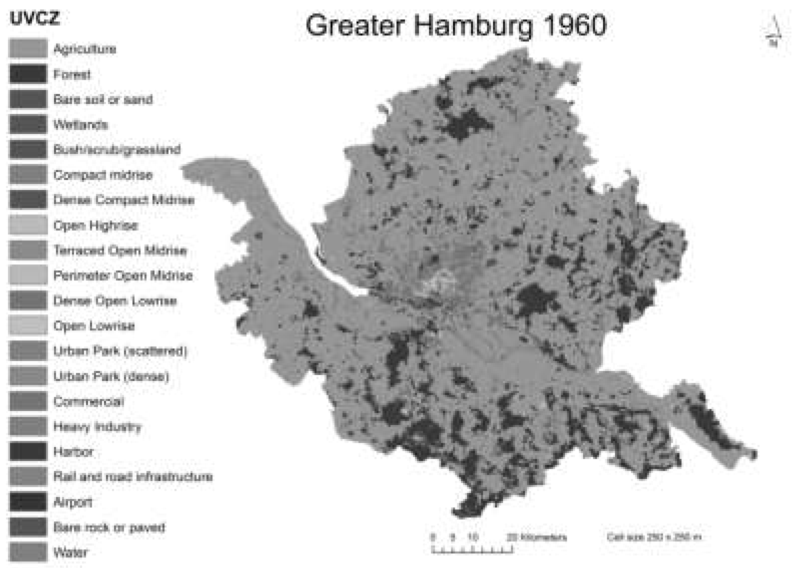


Figure 37: mosaic of Greater Hamburg in 1960. Each cell represents a class of UCVZ (Kaveckis et al., 2017).

The mosaic in Metronamica is a typical raster with three types of cells: feature (static), vacant (dynamic) and function (dynamic). The feature cells are static cells which do not change their state, but they might affect other cells in the neighborhood. The vacant cells are the “free” cells which do not have any function and can be easily occupied by the dynamic cells. In real a life situation that would be the agricultural land, bushes and other land which has potential to be urbanized. And functions are the cells which are actively modeled and occupy the vacant cells or compete against other function cells (RIKS, 2013)

The cells in Metronamica are allocated via the CA model. The allocation is based on the transition potential and land demand. The land functions must be able to allocate these demands. One may question how the model will know which cells can be occupied and which ones have to be abandoned and the answer to that is that for each cell the transition potential for each class (in our case the UVCZ) is calculated. Whichever class has the highest transition potential in a certain cell wins over other classes, and occupies the cell (RIKS, 2013). In other words, in this model the class with the higher transition potential score occupies the cell.

Transition potential is calculated by a specified algorithm for each cell which is a vector of factors. These factors are the effects of neighborhood, accessibility, suitability and zoning (figure 38). Additionally, the neighborhood effect has a stochastic perturbation in order to simulate unpredictable occurrences. The boundaries of the perturbation are controlled by the “α” (alpha) parameter.

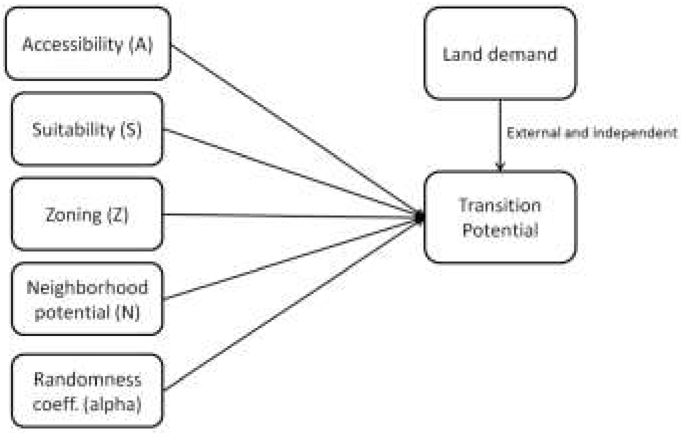


Figure 38: transition potential allocates land demand by effects of accessibility, suitability, zoning, neighborhood potential and stochastic coefficient.

Transition potential can be expressed by a following equation in Metronamica:

$$TP = (1 + (-\log(1 - random))^{\wedge} \alpha) * N * if\ (N >= 0; A * S * Z; 2 - A * S * Z) \qquad (5)$$

The physical suitability (suitability) and institutional suitability (zoning) are weighted and summed. The result is multiplied by accessibility. If the value of the neighborhood effect is positive, then accessibility, suitability and zoning are multiplied. If it is negative, then it is subtracted from its max value and multiplied with accessibility, suitability and zoning. If stochastic perturbation is considered, the random effect "α" have to be added (RIKS, 2013).

Accessibility

The first factor affecting transition potential is accessibility. In this case, accessibility is more a name than an exact measure of true accessibility. For this study it measures the effect of the proximity to specific features. In Metronamica, common accessibility features are usually transport networks such as local roads, highways or railroad systems, as well as any other vector based network. The closer the cells are to the vector transport network, the higher the score they receive for accessibility. Figure 39 shows the accessibility (proximity) of a commercial land function to primary and secondary streets. The closer to primary and secondary roads, the higher the accessibility rating, as well as the transition potential of the commercial class. Train, bus stations and highways, in this case, have no effect.

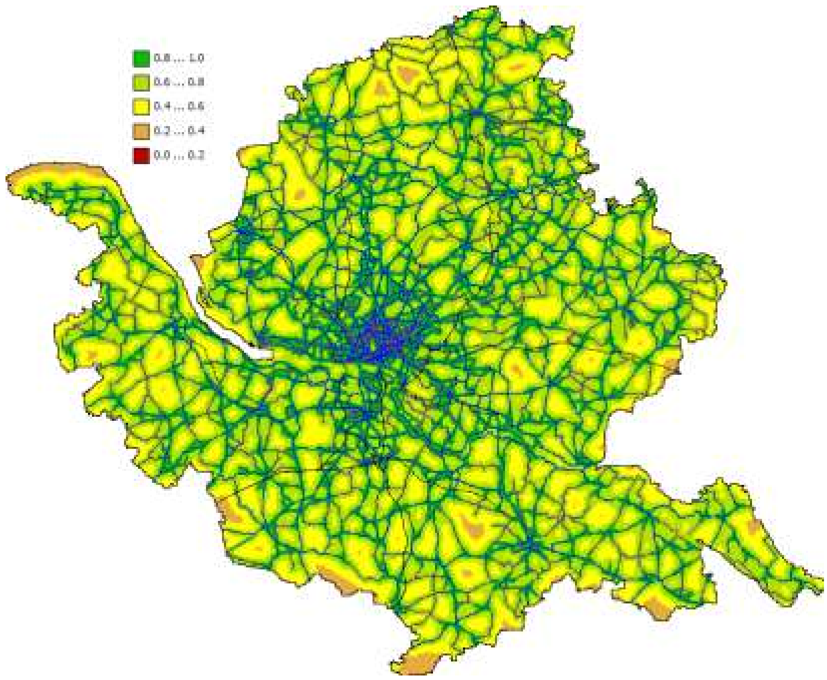


Figure 39: representation of accessibility of commercial UVCZ class to the primary (blue) and secondary (purple) streets in Greater Hamburg.

The case for accessibility can easily be presented as one of today's problems. Business and industry prefer to stay close to railway stations and highways because they have easier logistical planning, they avoid heavy truck bans in city centers and experience better business development in commercial zones. People prefer to have better access to public transport systems and/or live closer to a bus or metro stop. Contrary to business and industry, people do not prefer to live close to rail tracks and highways, in an effort to avoid noise and air pollution. Such differing values can be implemented in Metronamica via accessibility. In defining accessibility for each class it is important to know how each class is affected by each accessibility element (train stations, highways, etc.) and how much distance this effect is valid (the distance of cells). In other words, the accessibility score must be defined for each class to each accessibility element, based on the proximity between the cell of that class and the accessibility element. These relations can be adjusted, as needed. The total accessibility of the cell is the sum of all accessibilities from the different accessibility elements. In a later step it is added to the transition potential.

Suitability

Suitability (also known as physical suitability) is another important factor in Metronamica. Suitability measures whether or not a certain class is suitable to occupy a certain cell. Suitability is based on ecological, physical, technical or economical factors in each cell and defines if a cell can be occupied or not. These factors can act also as different suitabilities and have an impact on the final suitability score. For instance, an area may not be very well suitable for housing because of sandy soil, but it is suitable because of its low slope.

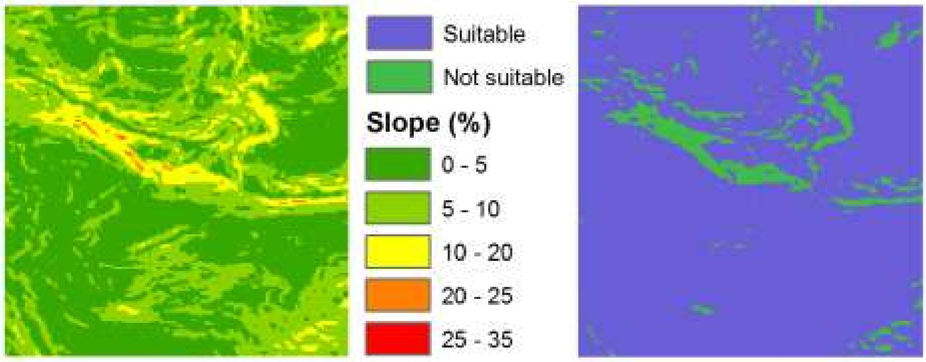


Figure 40: suitability map (right) of the slopes. The cells with the slopes steeper than 10% are not suitable.

In a real world, an easy example of suitability is a slope (figure 40). Slope is a physical suitability and defines the steepness of the land. Technically, in order to build a proper building, the slope has to be not higher than a certain threshold. This is valid for residential housing but may not be a problem for a forest. The application of ecological suitability could be applied to a development of a new wild animal park, based on vegetation. It would be given in the parameters that in order to establish the park, the vegetation cover must meet or exceed a certain threshold. The values of all suitability classes will be added together to give a total suitability result. Last, just like the accessibility score, the total suitability score is added to the transition potential.

Zoning

Zoning, or institutional suitability, is another composite factor of transition potential. Zoning defines the possible future occurrence of a class in a certain cell, based on planning and legislation. The difference between zoning and physical suitability is that there is no quantitative threshold, only a Boolean solution "yes" or "no". In Metronamica the zoning can be applied for a specific time period. For instance, the prohibition of any development for a certain period of time in a specific area can be implemented in the model with ease.

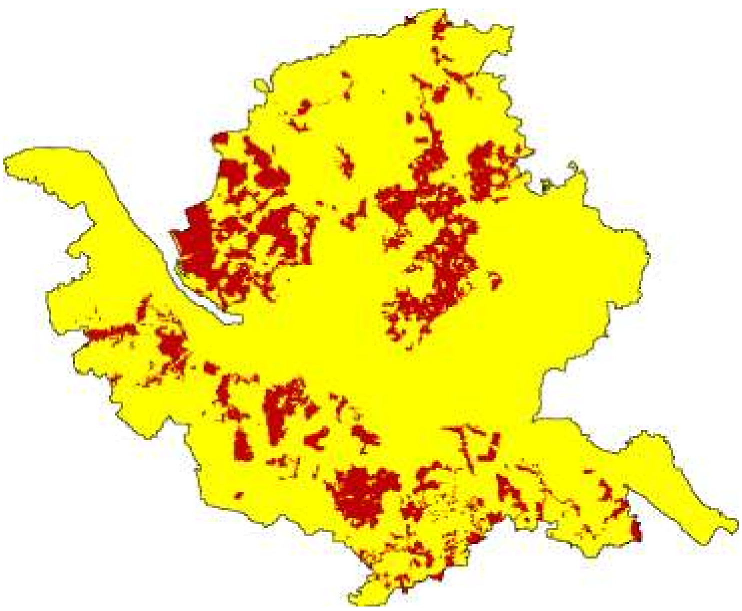


Figure 41: example of zoning - limited commercial development, due to nature protection laws, applied for historical time period 1990 – 2000 in Greater Hamburg. Yellow – allowed, dark red – limited.

Zoning is a common constraint in reality. National parks and many other environmentally vulnerable areas often have building restrictions, such as building height. High rise buildings are often prohibited for a variety of reasons. In Metronamica such kind of restrictions can easily be implemented as zoning layers with values of zero where it is not allowed to build (to be occupied by a certain land function) or values of one which does not restrict and a class is allowed to occupy a cell.

Different zoning, as well as accessibility and suitability, is combined into the total zoning. When the multiple zoning values are added and at least one of them has a value of zero the total zoning value is zero and this cell in zoning is restricted. Later, the total zoning is also added to the transition potential.

Neighborhood potential

The neighborhood potential is the most important factor and the main driver of the CA model in Metronamica. It is a composition of neighborhood effects (influences) between the classes (functions). This is seen in the figure below (figure 42). The positive neighborhood effect attracts a (red and green functions in the left figure 42) and negative effect repulses (pink function in the left figure 42).

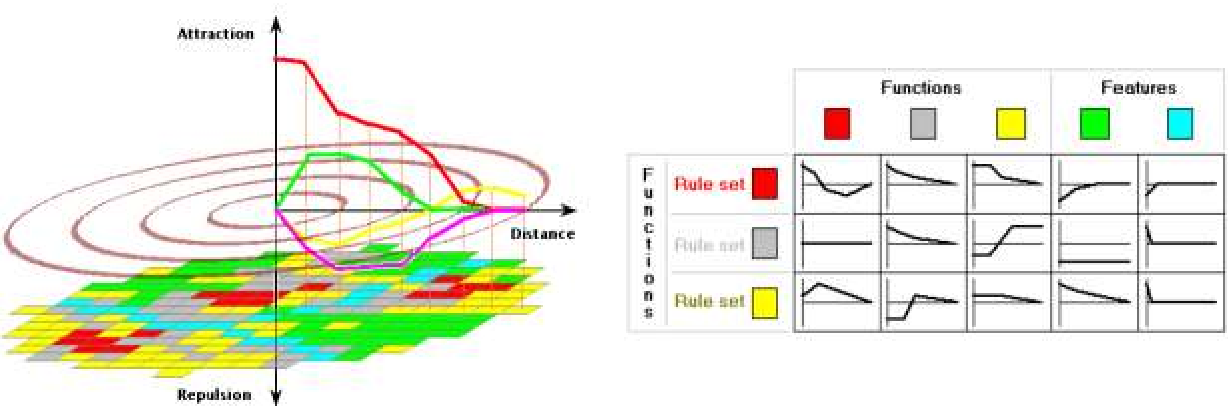


Figure 42: circular neighborhood (196 cells, on the left) shows the cell allocation after the transitions rules were applied. Classes (functions) and their influences are weighted by a distance (on the right) (RIKS, 2013).

The neighborhood effect is defined by influence between two classes and the distances between the cells of these classes. In other words, each cell in Metronamica's local model is influenced by other cells around in an 8 cells radius. The cells further than 8 cells away have no influence. The influence can be defined by influence functions (figure 43). If the function between two classes is negative, the cells of these classes repulse each other, if the function is positive, they attract each other at the certain distance.

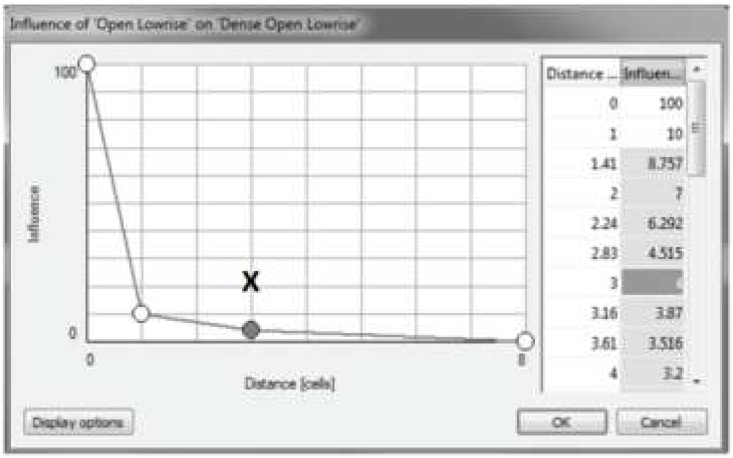


Figure 43: neighborhood rule (influence function) between two UVCZ classes. In this case the higher the distance means the lower influence (Kaveckis et al., 2017).

The influence function can be modified, based on user needs. For instance, the new development of residential class would be attracted by close proximity of urban park, but repulsed by industrial or commercial areas in the close distance. In total, the function is determined by 30 points and can represent various shapes (figure 43). The 8 cell radius maximum effect of influence can also be changed to meters, respectively in the resolution of cells. In Metronamica the influence function is divided into four sections (based on figure 43):

- Inertia (0) is the effect on an existing (previous) state of the class. It indicates its stability and indicates whether or not it is willing to be occupied by any other class (a residential high rise might hardly be converted to any other land function. Meanwhile a crop field near residential area has a very high probability to be occupied by other class. The lower is inertia, the higher probability of being occupied by other classes).
- Beginning (from 0 to 1) defines the conversion rate from one class to another. If there is no influence at range of one cell, there will very limited or no conversion. The conversion from industrial to residential is quite possible (loft apartments), but the reverse conversion from residential to industrial is less probably.
- Intermediate (from 1 to x) is the section between the conversion point (at range of one cell) and value of the influence function. It does not have to be linear or have only one value. It can have negative or positive values which would represent positive (attraction) or negative (repulsion) influence.
- End (from x to 8 or the function mark where it hits zero and remains) section in all the cases will lead to zero which means decreasing influence. The model assumes that the cells over 8 cells radius have no influence at all. But the threshold can be changed to one, two or any number of cells between zero and eight.

Of course, the neighborhood effect strongly depends on cells' resolution. Therefore, considering the same area, neighborhood potential for the grid of 200 x 200 cells can be very different than the grid of 50 x 50 cells. It means that greater resolution of the cell gives smaller effect of the neighborhood. The other issue is that with more classes comes a higher degree of complexity and many more influence functions. For instance, the local model of four classes (functions) would require the model to define 4 x 4 = 16 influence functions. Six classes increases the number of influence functions to 36. Therefore, it is always recommended to have as few classes as possible.

Random coefficient

Another parameter is the random coefficient. It is a stochastic parameter which controls the extent of the stochastic perturbation performed on the neighborhood effect. In other words – it simulates the effect of unpredictable occurrences and brings randomness into the process of simulation. Naturally, in the real world, even the strictest rules will be ignored and something unexpected will happen. For instance, the development might occur not exactly close to the existing residential, but in the buffer zone of 500 meters etc. Or a parcel of mid rise buildings will develop in the middle of low residential zone area, although there was a ban of mid rise buildings. Figure 44 shows the effect of high and low randomness.

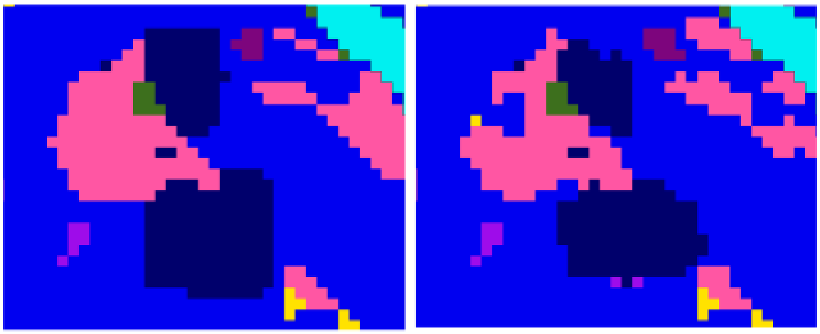


Figure 44: randomness coefficient effects on cellular automata - emergence of dark blue and pink cells.

The randomness coefficient determines the different (slightly) result with the same rules applied each time. This brings the application closer to reality. Figure 44 shows the effect of low (0) and high (1) randomness. When there is no stochastic perturbation (coefficient = 0), the cellular automata strictly follows the rules and the CA, highly based on neighborhood, creates almost correct round shapes. Meanwhile the high stochastic perturbation (coefficient = 1) gives a result of more random, not geometrically rounded, but more realistic clusters. In the end, the randomness coefficient is composed together with the neighborhood potential, suitability, zoning and accessibility into the transition potential. The class with the highest transition potential occupies the cell (if there is demand of that class). This procedure repeats every time step and is implemented via CA.

3.3 Aggregation and weighting

The word "aggregation" means a *"formation of a number of the things into a cluster"* (Oxford University Press, 2015). The aggregation also means a grouping or composing from many to one. It is very similar term to the composition. The aggregation or composition in this research is used mainly for two things: 1) the aggregation from many spatial units to one and 2) the aggregation or composition from a few indicators to one vulnerability index. The spatial aggregation merges a number of points, lines or polygons into one single entity and based on certain properties summarizes their attributes. Meanwhile the aggregation of indicators uses the mathematical addition or multiplication to calculate the index.

The process of aggregation experiences the similar problem as the vulnerability assessment – because each situation is unique, there is no best aggregation method. The solution is to analyze the situation and adopt the best aggregation methods according to the needs of the study. If vulnerability takes into account many indicators and data of various spatial levels, the aggregation method has to be simple, clear and well understandable, in order to keep complexity low. This is especially important in the intermediate and final stages of the research. Often even a simple aggregation is already complicated due to different data sources, units, classes and ranges.

It is even more complicated when combining qualitative and quantitative indicators: i.e. the physical hazard information of flood frequency with a socioeconomic indicator such as unemployment. Such indicators are also known as composite indicators or indices (OECD and Joint Research Centre, 2008). A single composite indicator (index) is much easier to understand, assess and compare, especially when dealing with the spatial indicators. The index, developed from the available data on the global level, is a good way to compare different countries, although the interpretation of one indicator can vary among the countries. Today there is no agreement of how many and what indicators should compose a good index. It's probably that such terms as "good index" and "bad index" do not even exist. There is a paradox here, that one index, developed by one research group can be composed by totally different indicators than another index developed by a second research group can possibly have the same name, the vulnerability index" the values and factors behind the two can be totally different. And, in fact, both of the teams may be right. Though, the scientifically approved and confirmed indices have steady composition, this is not the case when speaking of vulnerability. In most cases, the vulnerability (precisely the vulnerability index) is composed of more than one indicator, though there are no strict rules of what indicators it must include. This absence of a standardized vulnerability index limits us in comparing the vulnerability between different case studies. The index does assist in understanding complex and multi dimensional problems, but the list of indicators used in each stage of the study can be lost in the final stages of the study. Therefore, the practice of listing all indicators in each stage should be clear and transparent throughout the entire vulnerability assessment process. It should be consistently tracked so that if the final vulnerability index shows high extremes it can be explained (GIZ 2014).

The two most common aggregation methods for vulnerability index are arithmetic aggregation and geometric aggregation. The arithmetic aggregation method is simple and transparent. The indicators are summed and the sum is divided by the number of indicators (equation 6).

$$\mathbf{Index} = \frac{\mathbf{I_1 + I_2 + I_3 \ldots I_n}}{\sum_1^n \mathbf{I}} \qquad \textit{(6)}$$

If weights are involved, the following formula applies:

$$\mathbf{Index} = \frac{\mathbf{I_1 * w_1 + I_2 * w_2 + I_3 * w_3 \ldots I_n * w_4}}{\sum_1^n \mathbf{w}} \qquad \textit{(7)}$$

In this case, each of the indicators is multiplied by the weight and divided by the sum of the weights. Weighting is an important process and should be considered carefully only by qualified experts, because the different weights can have a major impact on the results. It is always recommended that the process should be simple and transparent. The weighting is discussed later on in this chapter.

$$\mathbf{Index} = \sqrt[n]{\mathbf{I_1 * I_2 * I_3 * \ldots . I_n}} \qquad \textit{(8)}$$

The other aggregation method is the geometric aggregation which is a multiplication of the indicators. The result is the n'th root of indicators' multiplication where "n" is the number of indicators. The geometric aggregation is more complicated to calculate and allows only a partial compensability. Compensability (or full compensability) is when a high score of one indicator can offset a low score of another indicator. Then the extreme values are obsolete. In geometric aggregation the very low score of one indicator only partly offsets a very high score of another indicator. Additionally, because multiplication is used, the zero value is not allowed, otherwise the index will be zero as well (GIZ, 2014; OECD and Joint Research Centre, 2008).

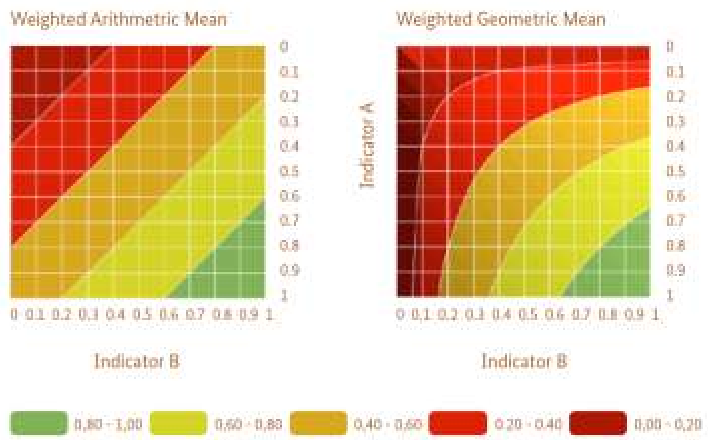


Figure 45: visualization of weighted arithmetic and weighted geometric means in range [0;1] (GIZ, 2014).

Figure 45 shows the results of weighted arithmetic and weighted geometric aggregations, using two indicators with values from zero to one. The result represents partly compensability by weighted geometric aggregation and a bias toward low values. Meanwhile the weighted arithmetic aggregation shows full compensability within the whole range. The other figure 46 presents the frequency distribution of the same values after the addition (left) and multiplication (right). The values after addition operation distributed more evenly and closer to the middle of the values' range closer to the Gaussian distribution with the mean of 38. Meanwhile the multiplication resulted in the higher frequency for the lower values and shifted distribution to the beginning of the range with the mean of 18. Therefore, in order to avoid the bias toward the low values and keep full compensability within the whole range, it is recommended to use the geometric aggregation.

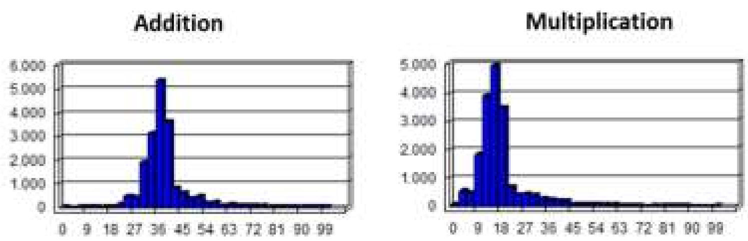


Figure 46: frequency of values after aggregating via addition (left) and multiplication (right).

In both methods it is important to consider the alignment of indicators' values. The low value means a low score and high value means a high score. If, for example, a low value of adaptive capacity means high score of vulnerability, the adaptive capacity indicator should be inverted (GIZ, 2014). In general there are no strict recommendations as to which aggregation method should be used. Some studies use the geometric aggregation, others use the arithmetic aggregation. The right way is to observe and analyze the results and decide on your own which the best results are. Usually the result depends on the data which has to be aggregated. For instance, if we want to calculate the potential impact by adding heat susceptibility and the relative number of elderly, and there is no susceptibility (susceptibility =0), and we add it to the elderly, then there will be a potential impact, even though there is no heat susceptibility. Such outcomes in vulnerability assessments should be avoided.

Weighting

Weighting is a process of defining the importance of an individual indicator against each other (OECD and Joint Research Centre, 2008). The higher a weight is assigned to a specific indicator it will have a higher influence on the final outcome. The distribution of weights should be careful, with a deep understanding of the vulnerability concept and composition of indicators. Often the weighting of indicators is done by experts, who decide which indicator has more influence on the final index.

Unfortunately for the vulnerability composition no weighting guidelines exist. Therefore most vulnerability assessments use the opinions of the experts or the data driven approach to assign weights on indicators. The data driven approach is based mainly on composed data and in many studies the weight among the indicators is equal (GIZ, 2014). Many of weighting methods, such as data envelopment analysis, benefit of doubt approach, multi criteria analysis, analytic hierarchy process and many others are described in detail by OECD and Joint Research Centre (2008). The most commonly used methods are the multi criteria analysis and analytical hierarchical process. They are frequently used together with experts' opinions and help to define the weights among the indicators.

3.4 Disaggregation[1]

"Disaggregation" has an opposite meaning to aggregation. It means a division or separation into parts ("Oxford Dictionary," 2015). Disaggregation is used in many sciences, but the focus of this research is the spatial disaggregation.

The typical spatial representations of population are based on census data with a rather high aggregation level which does not allow the mapping of the distinct social areas. There is a need to develop methods to map a population at the micro-level while keeping the data independent from any administrative areas. One of the common methods for mapping a population is spatial disaggregation (also called "downscaling) of census data which transfers coarse information into a more detailed scale (McCarthy, 2001b). Spatial disaggregation is based on the assumption that data of an entire case study area can be scattered within the area by means of local parameters (Steinnocher et al., 2010). The coarse spatial units with known data are called "source zones" and the finer scale spatial units to which the data is assigned are called "target zones" (fig. 47) (Li et al., 2007).

[1] Most of the text and figures in sub-chapter 3.4 was published as an article "Land use modelling as new approach for future hazard-sensitive population mapping in Northern Germany" (Kaveckis, 2017).

Figure 47: example of source zones (left) and target zones (right).

Disaggregation can lead to a common problem in geography which is called the modifiable area unit problem (MAUP). MAUP is a phenomenon associated with the use of aggregated data which varies, depending on how boundaries are drawn. However, practically speaking, boundaries have little relationship with the variables of interest (Openshaw, 1984). One other issue, however, is that the process of spatial disaggregation is complex because of a mismatch and heterogeneity (in terms of density) between boundaries of the source and target zones. A variety of disaggregation methods can be used to solve this problem (Li et al., 2007).

Simple area weighting (also known as a mass preserving aerial interpolation) is the simplest spatial disaggregation method. It is based on an assumption that the disaggregated variable is homogeneous within the source zones (which is not realized, or experienced in the case of population mapping). In order to use simple area weighting method, the simple overlay operation is done. The main problem with this method is the incorrect assumption that density within the source zone is homogenous and equally distributed. Some studies (Foley et al., 2005; Langford, 2006) showed the low accuracy, in comparison with other methods.

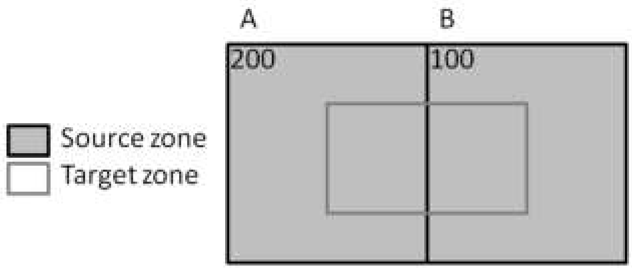


Figure 48: simple area weighting method.

The source zone in simple area weighting is overlaid with the target zone (figure 48). Both polygons have the same area, but contain different numbers of persons. Polygon A contains 200 persons and polygon B contains 100 persons. The target zone overlays ¼ of polygon A and ¼ of polygon B. Therefore, assuming that persons are equally distributed within the polygons, there are 200/4 = 50 persons in the A target zone and 100/4 = 25 in the B target zone. Hence in the whole target zone there are 50+ 25 = 75 persons. The simple area weighing method is easy to apply, but the homogeneity assumption does not come close to the real distributions of population. Therefore, it does not fit for the more advanced disaggregation applications.

Another method is the binary dasymetric mapping (Eicher and Brewer, 2001), also known as a mask area weighting. As an improvement compared to the simple area weighting masks (boundaries), the dasymetric mapping is applied within the target zone where the source data should be allocated. The mask or the boundaries can be any spatial ancillary information, such as urban climate vulnerability zones, or other spatial units (as example residential areas) which would be a guideline for the allocation of population.

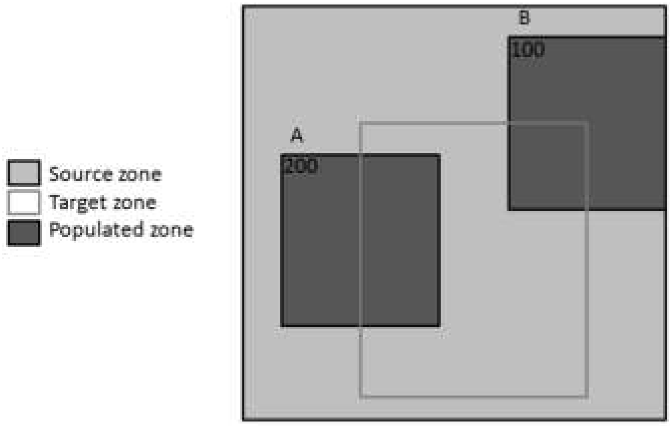


Figure 49: practical example of binary dasymetric mapping (mask area weighting) method.

In binary dasymetric mapping the source zone is overlaid with populated zones and target zone (figure 49). Compared to the simple area weighting (figure 48) where the population was displaced within whole source zone, this time the population is allocated only within the populated zones, the polygons A and B. The principle is the same – instead of the whole source zone, we must to identify the overlay between target and populated zones. ¼ of the populated zone B overlays with the target zone. This means 100/4=25 persons. Half (1/2) of the populated zone A overlays with the target zone. This means 200/2=100. The sum of the persons living in the target zone is 25 + 100 = 125 persons.

The binary dasymetric mapping masks out unnecessary areas, based on concentrated population with a fixed density. However, it is unable to represent the more complex land zones or other units with different densities. However, this method is much more advanced than simple area weighting, because the disaggregation is focused on one area, not the whole source zone. The binary dasymetric mapping needs ancillary information, such as the land type, populated areas or other such information which would mask where the source data should be allocated.

The third method is called the “classified dasymetric mapping”, also known as three class dasymetric mapping (Mennis, 2003) or dasymetric disaggregation. This method not only uses a homogenous mask, but also different zones with specific weights within the mask. The weights can represent population density or other population-related variable. Weights, as well as mask zones are ancillary information which also needed to be integrated additionally.

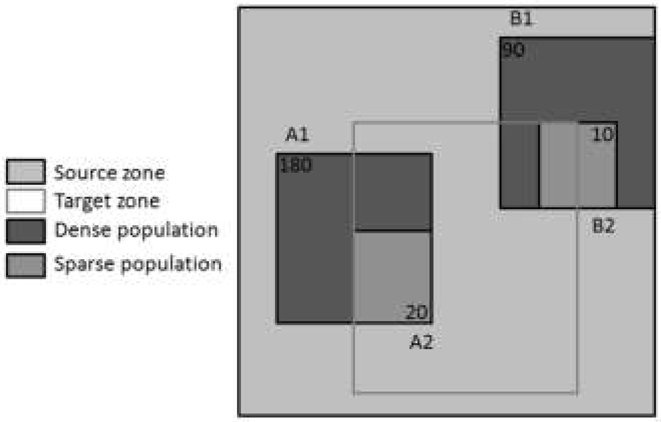


Figure 50: practical example of classified dasymetric mapping (dasymetric disaggregation) method.

In comparison with the simple area weighting and binary dasymetric mapping, the classified dasymetric mapping uses not only the masked source zone (populated zones), but also allocates weights within these populated zones. It means that in parts of populated zones different amounts of people can be allocated. In figure 50 this is represented as population density (sparse and dense). In a previous example, (figure 49), the source zone is overlaid with populated zones and target zone. But this time the populated zones are split to zones with different population density (dense contains three times more population than the sparse density). In the example (figure 50), populated zone A (A1 + A2) contains 200 persons, but within the target zone only half of it overlays with the target zone. The half of this target zone is sparse density (A2 with 20 persons), and other half is dense density with 180/3 = 60. Therefore 20 + 60 = 80 people can be allocated to target zone within the populated zone A. The next example, the populated zone B (B1 + B2) contains in total of 100 people. ¼ of the populated area is within the target zone. And ¼ of it is sparse density (33% population). Only half of it falls into the target zone which means 10/2 = 5 people. Other ¾ of populated zone B is dense population. And only 1/6 of it is within the target zone. Which means 90/6 = 15 people. Therefore, in B there are 5 + 15 = 20 people. In total, in the target zone there are 80 + 20 (A+B) = 100 people.

The classified dasymetric mapping is the most advanced disaggregation method. According to Langford (2006), it outperforms other spatial disaggregation methods and takes advantage of the binary dasymetric mapping method. It uses densities to define weighting and allocate population more precisely. It uses the most relaxed assumption of homogeneity and is closer to the complexity of the real world. However, the densities (weights) and masked area (as ancillary information) are required.

Due to the heterogeneity of the surface, it is important to obtain ancillary information of the source zone such as land use, land cover, urban morphology, remote sensing data etc, in order to make the disaggregation process more realistic. Such information increases the accuracy of the disaggregation process. Dasymetric mapping requires this ancillary data in order to indicate any variation in data distributions of the aggregated source data (Li et al., 2007).

Variations in data distributions of population focused applications can be presented as the population density. These densities can be developed via different approaches. One of them is the regression model (Yuan et al., 1997). The regression model uses the ancillary data to improve accuracy. The assumption used in regression models is that the ancillary data is equally distributed within the source area and the land classes have a uniform area density. This density is related to a specific parameter for each class of ancillary data, based on the population's concentration of the specific class. The common method is to develop regression equations by numerically solving the problem and using combination of values of aggregated source zones and ancillary data with unknown densities (Li et al., 2007). Langford (2006) noticed that increasing the complexity of a regression equation will improve the accuracy of the interpolation. The disadvantage of regression models is that the small errors between the estimated and actual values of source zones emerge (Tobler, 1979). Another issue is that regression analysis is not supported by current GIS and requires additional statistical software. The last, but not least, the obstacle is the densities of specific class are spatially stable for the whole study area (Li et al., 2007). The more advanced technique is global fitted regression model (Langford, 2006). This technique was initially created to insure that the populations within target zones matched the sum within source zones while allowing for variability in the density for each land class in a specific area. In this way, the estimated density of each land class is locally adjusted within each source zone by ration. Such an approach is more advanced than the simple regression model, which is simple and based on the relaxed homogeneity assumptions of density. Locally fitted regression models couple perfectly with a classified dasymetric mapping method and can be used for a realistic disaggregation (Li et al., 2007).

According to disaggregation quality studies, done by Langford (2006) and Li et al. (2007), the classified dasymetric method largely outperforms other techniques. However, this method requires a definition of relative densities for each land class. Densities can be defined by a sampling approach (Mennis 2003) or by the regression model (Langford, 2006). The sampling approach requires small source zones areas, while for larger source zones, the regression model can be used (Li et al., 2007).

3.5 Normalization

Vulnerability is a composite index with a combination of indicators with different units. Therefore it does not have its own measurement units. In order to composite (or aggregate) the vulnerability index, the indicators must be normalized. Normalization means a transformation of indicator values at different scales to values on a common scale without units (OECD and Joint Research Centre, 2008). It is also important to give meaning to the common scale (GIZ, 2014), such as the use of a scale between 0 and 10 in which 0,1 is a low score 5 is an average score and 10 is a high score. After this, the scale of measurement (metric, nominal, ordinal) should be identified. There are numerous normalization methods, each one developing different results of a composite index. From the common methods of normalization (Freudenberg, 2003; Jacobs et al., 2004; OECD and Joint Research Centre, 2008), the following ones are the most actual for the development of the vulnerability index:

- Ranking – it is the simplest normalization method. It is not affected by outliers and derives relative positions. However, it misses the absolute values, because the information on more specific levels is lost.
- Standardization (Z-Scores) – this method changes the values to a common scale with a mean of zero and standard deviation of one. The indicators with extreme values have a greater affect. The standardization should not be used when a good quality composite indicator, within a few indicators, is needed.
- Min-max method – this method normalizes values to a range between 0 and 1 (including extremes) by dividing the subtraction between minimum and maximum by the range of indicator values. Extreme values can distort the composite indicator. However, this method could widen the short range of indicators and increase the effect

of the composite indicator more than the standardization. One objection to this is that transformation becomes unstable when a new value is added.

- Distance to reference point – this method uses a relative position using a reference point. This method is based on extreme values which could be unreliable outliers.
- Categorical scale – this method assigns a value to categories. This method excludes a lot of information about the distribution of values.

In the process of normalization is important to pay attention to extreme values which may greatly influence the indicator. It is also important to verify the values after normalization to see if they are increasing in the right direction. If a particular value is expected to decrease with the increase of another value, the indicator should be the inverse. For example: using the value of adaptive capacity, it would be expected that as adaptive capacity increases, vulnerability should decrease. It should not be the opposite. A second issue in this normalization process is the thresholds of the indicators. Sometimes the thresholds are the minimum and maximum value of the indicator, but that is not always the case. For instance, if temperatures range from +10 degrees C to +42 degrees C, but the dangerous temperatures are above +25 degrees C, then it is not necessary to use the lower temperatures. In this case, normalizing only the temperatures above 25 degrees C would be appropriate. It would appear, then, that the lower threshold will be +25 degrees C, instead of +10 degrees C. The use of the knowledge of local stakeholders and experts, or at least data-based research is always recommended in defining the thresholds used in a study.

III. Future population’s vulnerability modeling and results – case of Greater Hamburg

Third part is the largest part of this thesis and presents the application of vulnerability modeling and assessment in Greater Hamburg case study. The assessment itself is not very complicated, but the most time and effort consuming activity is the modeling future indicators which have to be composed into the vulnerability index. In order to develop the model (chapter 5), the calibration using the historical UVCZ data should be done. Only then can the vulnerability indicators and their composed proxy parameters, based on various future scenarios, be modeled. The vulnerability indicators used in the Greater Hamburg case study are briefly covered in chapter 6. Meanwhile the future indicators as well as projections and scenarios used to develop these indicators, are overviewed in chapter 7. In chapter 8 future indicators are composed into the vulnerability index via a vulnerability assessment. Chapter 9 presents adaptation options and measures that can be taken to alter the impact of heat and lower the population’s vulnerability to heat waves. Prior to all of these steps, the case study area, the vulnerability and the modeling frameworks for Greater Hamburg must be presented.

4 Case study area, vulnerability and modeling framework

This chapter introduces the features and history of the case study area, its vulnerability and modeling framework of Greater Hamburg. The study area covers not only the Hamburg city-state, but also the surrounding districts of the neighboring federal states. The identification of vulnerability in Greater Hamburg was based on the vulnerability aspects presented in chapter 1. The defined vulnerability, the chosen concept and framework help to frame and understand how vulnerability is seen in the case study of Greater Hamburg. In the conclusion the vulnerability modeling’s framework briefly presents the procedure in which future conditions (vulnerability indicators) must be modeled through the proxy parameter.

4.1 Case study area of Greater Hamburg

The city-state Hamburg is the second largest city in Germany after the capital Berlin. Hamburg is located in northern Germany on the bank of Elbe River and covers 755 square kilometers which makes it second smallest federal state in Germany. Its good location and connectivity to the North Sea developed the city into one of the largest and busiest ports in Europe. The shipping and trade routes accumulate a lot of wealth, business and large numbers of travelers. Due to high internationality, Hamburg became the second city with the most consulates in the world after New York. Today the tourists come from all over the world to cosmopolitan Hamburg to visit its cultural and commercial life - like in the old times.

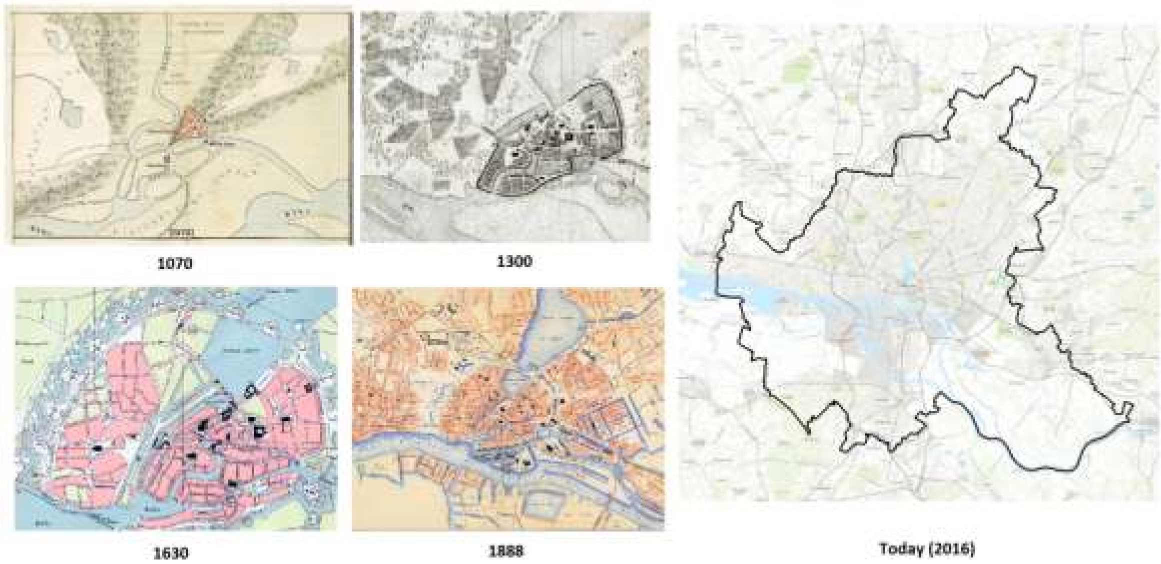


Figure 51: expansion of Hamburg city-state through the centuries (Malte-Brun, 1880; Neddermeyer, 1832; Wichmann, 1896, 1863; ESRI Topographic Layer, 2016).

Intense colonization of USA in XX century caused Hamburg to become a center of travelers and main Germany's gateway to the world. During the World War II, more than 55% residential and 60% of harbor area was destroyed by allied air raids. More than 55 000 people have died. After the war more and more people were coming to Hamburg to search for the jobs and better cultural life. In 1960's the number of people reached its peak – more than 1,8 million (Thomsen and Mcintosh, 2015).

Figure 52: docks (Landungsbrücken) in Hamburg, one of the most tourist attractive places in the area

Today in Hamburg city-state live little bit less than 1,8 million people. As a commercial and trading center, Hamburg is a very attractive place to work not only for Hamburgers. Due to very well developed HVV (Hamburg Transport Association) network (figure 53), people within surrounding districts of Lower Saxony and Schleswig-Holstein federal states can reach Hamburg in hours.

Figure 53: network of HVV (green and yellow) exceeds Hamburg city-state limits and reaches cities of Lübeck and Neumünster (Bluemap.de, 2014).

That is one of the reasons why the research study area is not limited by the Hamburg city-state only. The controlled urban sprawl along the main HVV transport lines of fast regional trains and well developed highways outside the Hamburg city-state limits (for instance to Pinneberg, Nordestedt and Ahrensburg) in the past decades (Daneke, 2013) allowed people to search for the better paid jobs in Hamburg and live on the countryside or in small towns and pay smaller rents than in central parts of Hamburg. Although the surrounding cities are not within the Hamburg city-state limits, many their citizens commute to Hamburg every day back and forth. Therefore, because the future urban expansion of Hamburg Metropolitan could advance even more, it was decided do not limit the case study area and go further behind the Hamburg city-state limits.

The case study area of this research is identical to the HVV network and through administrative point of view, covers three federal states: Hamburg, part of Schleswig Holstein (districts of Lauenburg, Stormarn, Segeberg and Pinneberg) and part of Lower Saxony (districts of Stade, Harburg and Lüneburg) (figure 54), although it does not have any administrative status. Some mention it as Hamburg Metropolitan Region, others as Greater Hamburg. I decided to use the latter name, because the actual Metropolitan Region of Hamburg is little bit larger, than the case study area.

Figure 54: Hamburg city-state (green) and surrounding districts of Lower Saxony State (red) and State of Schleswig Holstein (yellow).

Many regional studies in areas with different data standards and methods experience greater complexity and difficulty. The Greater Hamburg area is not an exception. For instance, Hamburg city-state and Schleswig Holstein shares the same Statistical Department (Statistik-Nord) and have common data standards and methods to develop future population projections. Lower Saxony, meanwhile, has a different Statistical Department which uses other approaches and data standards. These different departments and their different approaches and standards present challenges that are applicable to not only current and future data, but also to the historical datasets as well. The statistical departments had their own approaches and requirements in collecting and processing census data. For instance, for the same historical year, the Lower Saxony has the district level data of age groups which is missing for Hamburg city-state and Schleswig Holstein. Another challenge came from the high resolution census data. Hamburg city-state maintains detailed social data on a very detailed scale, while surrounding districts either did not have data at all or the data was not at the same detailed scale. This, and similar issues gave greater complexity to the study and required special approaches to deal with the complexity.

4.2 Vulnerability in Greater Hamburg

Based on vulnerability theory and methods presented in chapter 1, the vulnerability definition, interpretation, concept and the assessment framework have been adopted and modified, based on the best and the most common practices and availability of future local data.

Vulnerability definition

In the beginning of this thesis I reviewed the meanings of vulnerability by various research studies over a time frame. Some of them are very specific, others are abstract and could be applied in many cases. As it was stated previously by Timmermann (1981), there is no one and the best vulnerability definition. Each study is unique and has its own understanding and meaning of vulnerability. From all available definitions, I chose the IPCC definition which in the Third IPCC Assessment Report (McCarthy, 2001a) was described as a "*degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes*". Additionally it was named as "*a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its* *adaptive capacity*". This vulnerability definition names vulnerability as a degree to which a systems is susceptible to the effects of climate change and its ability to cope with those effects. If the system is not susceptible or it is able to cope, then the system is not vulnerable. While this definition is broad, it is well known and has been adopted for use in many case studies. In addition, many climate change and disaster scientists accept this definition as adequate. The IPCC definition names the main three factors of vulnerability - how the system is exposed to the climate change variability, how sensitive it is and how it can cope with these climate change effects. If one of these factors is high enough - the system is vulnerable. I believe that for the GH case study is important to know the external stressors and understand how they affect the system and how the system is able to cope with those stressors. While the IPCC definition suits the GH case study very well, I felt that the definition was still too broad and a more specific meaning of vulnerability within the GH case study was needed.

Vulnerable situation

The definition of vulnerability, and how it's understood depends heavily on the situation to which it's applied. For this case study in GH, the vulnerable situation was more or less known from early on in the project. Some of the factors were easily identified as I set up the project and others required additional analyses and were considered and applied into the study at a later date.

The most obvious factor in this study is temporal reference, which is the future. The aim of the study was to explore how future climate change will affect Hamburg. The scale of the vulnerability in GH is the cross-scale which includes both internal (within the system, such as population increase and change of social groups etc) and external factors (heat stress) that negatively affect the system. The domain of the vulnerable situation is not homogeneous; it is integrative and covers biophysical effects on the environment and the exposed population, as well as the properties of population and their abilities to cope with stressors. The space of the vulnerable system is considered to be Hamburg city-state area along with the adjacent districts. I identified the human population, with a strong focus on the elderly, to be the attribute value, or the subject which is under threat. Finally, I identified heat stress to be the major external stress factor. This is the set of factors which were used to describe the vulnerable situation in Greater Hamburg.

Vulnerability as end point

Vulnerability can be interpreted as a starting or an ending point product. When used, or seen, as a starting point, it's usually used as one of the first items to be entered into a study for adaptation and vulnerability reduction. In the GH case, vulnerability is not known yet and is still waiting to be composed from a number of indicators. This study, therefore, sees vulnerability as an end point in the research. However, in further studies in the future, the outcome of this research could be used as a starting point in order to know how to mitigate external stressors, decrease the sensitivity of the system or to increase its coping capacities.

Vulnerability concept and framework

The vulnerability concept, when compared to the definition of vulnerability or the vulnerable situation, represents a deeper understanding of vulnerability. The methods, data types and assessment approaches are very dependent on the vulnerability concept. Earlier in this paper I presented three common vulnerability concepts, based on three different view of vulnerability: biophysical, social and climate change. Because this GH case study considers the biophysical and social factors, and covers a longer period of time, the most suitable vulnerability concept for this study is the climate change concept. As in the definition of vulnerability from IPCC, climate change concept is broad, but allows us to deal with a complex system and helps us to understand how it is affected in the biophysical and social sense. The concept is not limited to risk and probability but also includes the system's ability to cope and resist the effects of climate change. Although this case study analyzes the effect of one hazard (heat wave) which is a typical biophysical concept, the hazard in this study is a continuous, not a discrete event. Likewise, the system itself is not static, but very dynamic. From the social point of view, this study requires not only an identification of the inner system's ability, but also the identification of the external stressors of climate change. This is why the climate change vulnerability concept serves this study well.

The most suitable vulnerability framework for this study is the hazard-of-place. This framework is the mix of biophysical and social frameworks and focuses on the geographical domain and considers both the biophysical and social impact to the system. The hazard-of-place framework can be both qualitative and quantitative, which makes it more complex but also more flexible. The Greater Hamburg case study is not an exception. Due to its complexity and geographical variation, the hazard-of-place framework was selected.

Indicator-based approach

Because the goal of the study is to assess vulnerability, it has to be measured. The desired outcome of the study is to find the specific vulnerability on the local scale and to evaluate whether or not the specific location has a high or low vulnerability. It is necessary, therefore, to have some sort of quantitative meaning. I have already discussed that vulnerability quantification is always a difficult task, but because vulnerability in the GH case is the end point product, it must be composed of indicators. If the factors are quantitative, then there combination must be quantitative as well. It must be concluded that the vulnerability assessment should be based on quantitative indicators.

Vulnerability assessment's framework

Common practices in the study of quantitative vulnerability to climate change (reviewed in literature review) and in the IPCC in the Fourth Assessment Report (IPCC, 2007) suggest that hazard-of-place framework be used. In assessing vulnerability, this framework can easily be supplied with quantitative indicators. However, as is seen in common practice, the indicators are very dependent on the availability of data. When the scope of the research is the future, data availability takes on an even more important role. After analyzing the vulnerable system of Greater Hamburg, looking over the available data at the local scale and looking at the possibilities to model future indicators, I developed a specific vulnerability assessment framework for the Greater Hamburg case study to the impact of heat on the population (figure 55). This framework is based on the IPCC approach and contains four main elements of vulnerability named in the IPCC's definition of vulnerability.

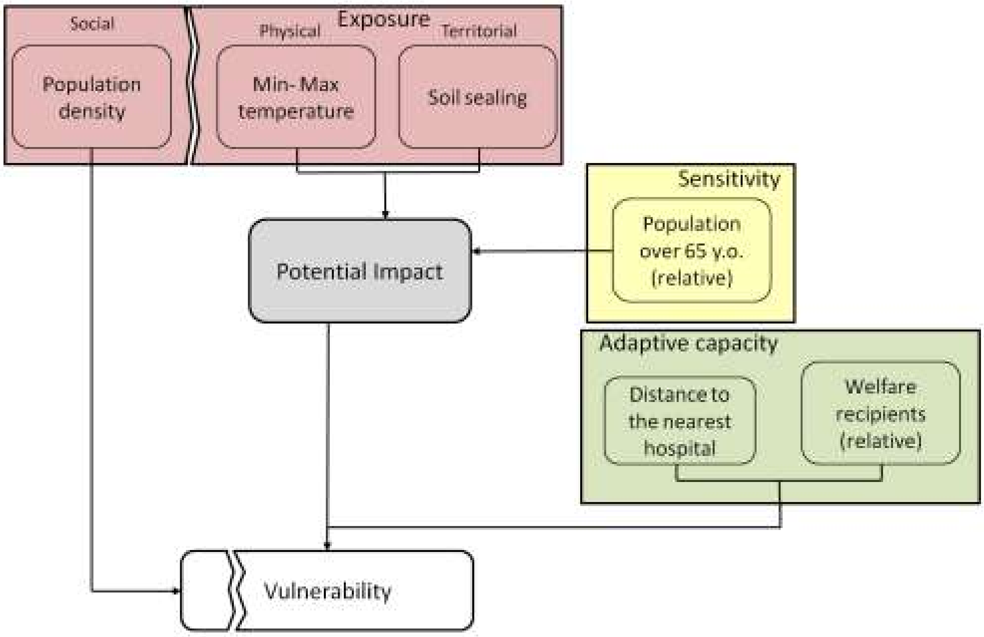


Figure 55: future population's vulnerability to heat waves assessment in Greater Hamburg framework, based on available data and modeling approaches.

Comparing to the original IPCC framework, this one has the potential impact element added to it. This potential impact measure is simply a combination of the exposure and sensitivity. It shows how the system is affected by external stressors and ignores the system's ability to adapt and cope with the consequences. Some studies (Kropp et al., 2009; Lissner et al., 2012) exclude the adaptive capacity from the vulnerability assessment because the adaptation's concept is unclear and there is a lack of quantitative indicators.

Vulnerability indicators[2]

Each vulnerability element contains at least one and sometimes a few indicators. The composition of the indicators helps measure the vulnerability element. For instance, in this case, sensitivity is represented by a relative number of the population over 65 (elderly), while adaptive capacity depends on the relative number of welfare recipients and the distance to the nearest hospital. The lower the number of elderly people causes a lower sensitivity and the lower number of welfare recipients and the shorter distances to the hospital would increase the adaptive capacity and decrease vulnerability.

The element of exposure is more complex. For this research I identified three types of exposure: physical, territorial and social. Physical exposure is based on the hazard's biophysical properties, i.e. higher temperatures. The higher temperature causes a higher heat hazard impact. Territorial exposure depends on the surrounding environment. During a heat event people in the park are less susceptible to the heat than people in the commercial district, due to more shade trees and a higher presence of water, causing a lower UHI effect and thereby lowering the temperature. Social exposure represents the density of the population, or the number of people exposed to the hazard. The higher the number of people in the population of the hazard-prone area, the higher the probability of loss. If there is no population present, then there are not potential losses and to do vulnerability assessment

[2] The detailed information about vulnerability indicators for Greater Hamburg and why they were selected, can be found in chapter 6

would not make any sense. An area with higher population density automatically would cause a higher vulnerability, while areas which are extremely sensitive and have limited adaptive capacities but low population density would not have a high vulnerability, and could be ignored. This is why the social exposure is isolated from the other exposure types in figure 55.

Absolute and relative vulnerability indices

I intend to assess two types of vulnerabilities. Absolute vulnerability considers population density and relative vulnerability, or just vulnerability, ignores population density. An absolute vulnerability assessment would be most helpful for emergency services during a discrete heat wave event because it would assist them in reaching more people in a limited amount of time. Knowing where the population that is most exposed to the hazard would help in managing health care resources and allocating ambulance services. A relative vulnerability assessment could be used for long term urban, landscape, social and political strategic planning. The physical and territorial exposure would show the areas most susceptible to heat and where the landscape and urban planning measures should be applied. In the meantime, the most sensitive and poorest areas should see an increase in programs to mitigate losses in the social, elderly and poorest populations. The relative vulnerability assessment, as a sum of all these indicators, would help decision makers develop new urban planning and social welfare strategies and adjust local politics to reduce the vulnerability for all in the long term. Both vulnerabilities should be assessed and analyzed in detail, because both are important in reducing losses and saving lives.

The scale of vulnerability assessment

Before the vulnerability assessment can be done, its scale must be known. Scale defines the smallest spatial unit, with a specific value which the study aims to find. The set of such units with values would be found in the results of the research. If needed, the spatial units can be aggregated to coarser (larger) unit, or it can be disaggregated to a more detailed (smaller) spatial unit. The scale of a vulnerability assessment depends on the case study itself. The migration in Europe, for instance, would be considered on a national scale. A forest fire modeling application would probably use a very local scale, like 100 x100m grid with timber values.

Because the effects of heat waves can be very local (Oke, 1982), the city scale which is used for many future heat-related mortality studies (Huang et al., 2011), is not detailed enough. For this study I decided to use the building block scale which would represent unique urban area by its climate, land use and cover, morphology and population's content.

Figure 56: scaling from global to very local (micro/building block) spatial units (focus of the research).

The building block scale perfectly fits to differentiate the composition of heat wave effects, the degree of urbanization and the population's properties. The scale of the building block depends on the urban density. Because the case study area is Greater Hamburg, the average building block is defined to be 250 x 250 meters. Therefore the vulnerability assessment within this study focuses on the same micro scale of 250 x 250 meter grid.

4.3 Vulnerability modeling framework

The vulnerability assessment in this study is nothing more than a combination of conditions and future vulnerability indicators. Because only future climate data is available, any future landscape or future population data must be modeled. Unfortunately this is not done easily, as I identified at the beginning of this research. I needed a spatial and easy to model proxy parameter, so I selected urban vulnerability climate zones (UVCZ) which differentiates the areas in the case study by the following conditions: landscape, climate and population; specific land use, land cover, urban morphology, housing type, degree of soil sealing, population density, and the relative number of elderly persons and welfare recipients. The composition of these indicators will form the population's vulnerability to heat waves in the assessment in Greater Hamburg.

As Stewart and Oke (2012) stated, the classes of the local climate zones (LCZ), on which the UVCZ are based, have specific relationships to certain local climate conditions. For instance, it is known that during heat events, higher density housing areas experience higher temperatures than low density housing areas. If we can assume that this relationship will remain constant in the future, then all high density housing areas will experience higher temperatures than the lower density areas. I assume a similar relationship should be between UVCZ and the population as well. I need to verify this hypothesis to see if it is true when population and social groups are unevenly distributed among different UVCZ classes. For instance, if high rise apartment blocks and higher density housing is occupied by young, mainly single inhabitants, and single homes are preferred by elderly citizens or if there is any other similar relationship between the social groups and UVCZ. Future UVCZ allocations could say a lot about future conditions which would be used as indicators to compose a vulnerability index.

The idea simply can be simply explained by figure 57. The indicators (conditions) would be related with (assigned to) spatial UVCZ proxy parameter, based on 2000 data, then the UVCZ proxy parameter would be modeled for the year 2050 and then the indicators would be re-assigned to the new or changed UVCZ cells. The relations between UVCZ and the indicators would be calculated via statistics. Conceptually it is like "packing" up the indicators in each UVCZ cell, modeling it and then "unpacking", but only taking into account the assumption that the relation between UVCZ class and indicators will not change over time. The indicators, I want to "pack" into the UVCZ are population density, the degree of soil sealing, the relative population older than 65 years of age (elderly), and the relative number of welfare recipients. These "packed" indicators I call "modeled" indicators, because they are modeled within this research study. The other indicators (future minimum/maximum temperatures and distance to the nearest hospital) are also modeled, but were produced by someone else. There, I call them "auxiliary" indicators.

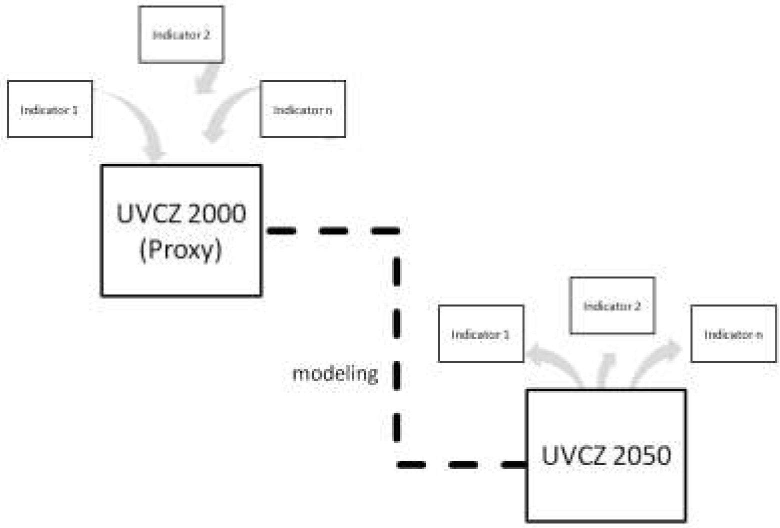


Figure 57: use of UVCZ proxy parameter.

The indicators' "packing" methods depend on the data resolution. The aim of "packing" is to transfer indicator data (source data) to the UVCZ. If the UVCZ resolution is higher (the cells are smaller) than the indicator's polygon, then the source (indicator) data must be disaggregated to the proxy parameter (UVCZ). If the UVCZ resolution is smaller (cells are larger) than the indicator's, then the data must be aggregated from the source to the proxy. Both, aggregation and disaggregation are explained in chapter 3. For instance, if four different population density polygons fell into one UVCZ cell, they must be aggregated into one value (average), assigned to that UVCZ cell. If the population density polygon is large and more than one UVCZ cell falls into the indicator's polygon, all the cells, no matter which class, will obtain the indicator value. If the mismatch of the spatial resolution between two datasets can be corrected by aggregation and disaggregation, the mismatch of temporal resolution can be a big problem. If we want to relate two datasets, and use this relation in other time steps, the time and both datasets that were acquired must match. The indicators' data must be acquired during the same period as the UVCZ data was. Of course, some data collecting campaigns, especially census data, takes a longer period but the shorter the time period between the gathering of the datasets is, the more accurate the relationships between them can be found. The "packing" procedure of modeled indicators is described in detail in chapter 6.1.

The "unpacking" (the box of "Statistics (new patches)" in figure 58) of the indicators uses statistics as well. However, if there are only seven potential housing classes and each of them has only one average indicators' value, the variety of new cells, filled with "unpacked" indicators' values, will be very low and will not represent a realistic distribution. For example, if the average population density in the area is "x", it does not mean that every other similar area has "x" population density. In reality similar areas have higher and the others have lower than "x" population density. Therefore, in order to include some of the randomness that blurs the clarity of discrete averages, I decided to implement a factor of randomness to the values assigned to the new "unpacked" cells.

For instance, if the average amount of people living in certain type of UVCZ was "y", in all the new that type UVCZ will receive values of y +/- 0,5 indicators' (based on 2000 data) standard deviation (SD). Another example, in the year 2000 the smallest percentage of elderly living in compact mid rise UVCZ was 7 and highest was 18. The average was 12. Meanwhile the -0,5SD was 10 and the +0,5SD was 14, all new or changed cells of compact mid rise will receive the value of relative elderly between 10 and 14. Such an approach represents more realistic distribution of indicators' values. The "unpacking" operation of four indicators is presented in chapter 7.6

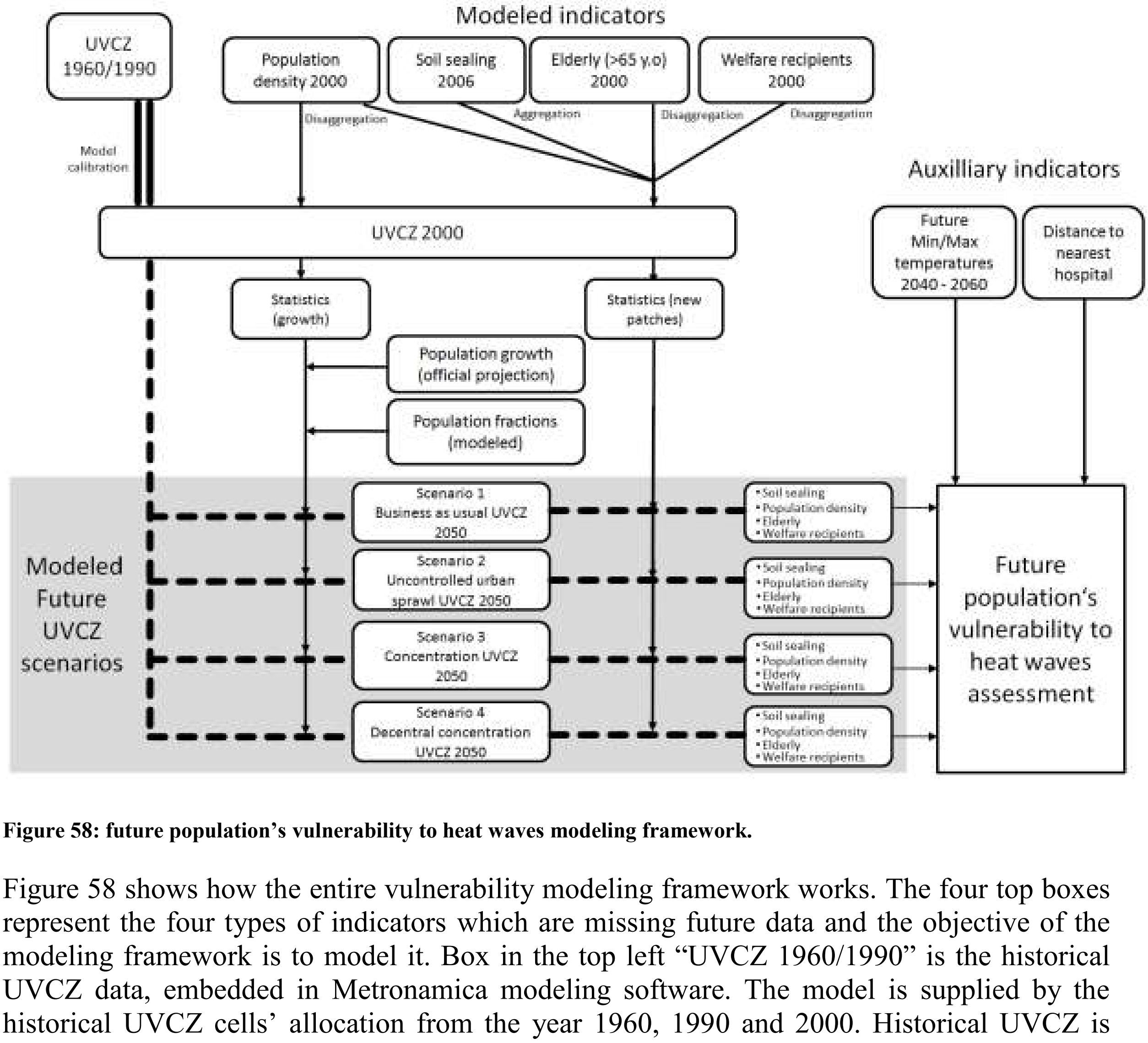


Figure 58: future population's vulnerability to heat waves modeling framework.

Figure 58 shows how the entire vulnerability modeling framework works. The four top boxes represent the four types of indicators which are missing future data and the objective of the modeling framework is to model it. Box in the top left "UVCZ 1960/1990" is the historical UVCZ data, embedded in Metronamica modeling software. The model is supplied by the historical UVCZ cells' allocation from the year 1960, 1990 and 2000. Historical UVCZ is required to calibrate the model and model the future UVCZ. UVCZ 2000 data is used as a proxy data. The statistics of aggregated and disaggregated ("packing") UVCZ 2000 data are used to assign "unpacking" values to the new or changed potential housing UVCZ cells generated by the model and based on four UVCZ scenarios which represents different urban development patterns in 2050. The urban development patterns were presented in chapter 2.7, while the details how they are implemented in the model and used in this study can be found in chapter 7.4.

A very important factor, influencing the four future UVCZ cells' allocations and related to urban development scenarios, is the population fractions. Each urban development pattern has different population's preference for housing. For instance, the highest preference of single housing, the dense open low rise, is typical for urban sprawl, while in the concentration scenario people would prefer to live in compact mid rise UVCZ. Such and similar population fractions were developed by experts, who defined how many people (percentage) should live in certain potential housing UVCZ type for each urban development scenario. The fractions are directly connected with population density per average of each potential housing UVCZ class (box of "Statistics (growth)" in figure 58) and the official future population growth projection. The higher the population growth is, the more UVCZ cells will be allocated. The population fractions together with population growth are considered as "Statistics (growth)" in the modeling framework and are used to model future UVCZ scenarios.

Finally, the future UVCZ scenarios (UVCZ cells' allocations) are assigned by "unpacked" indicators (population density, degree of soil sealing, relative elderly and relative welfare recipients). These modeled indicators are used together with the auxiliary indicators (the distance to the nearest hospital, the monthly average minimum and maximum temperatures) to assess the future population's vulnerability to heat waves for each UVCZ scenario. This will allow stakeholders and decision makers to identify which urban development scenario would cause the highest vulnerability and, of course where the high vulnerability would occur on the building block, the cell basis.

5 Development of UVCZ model

On the cell basis, the UVCZ is used as a proxy parameter to model future conditions – the vulnerability indicators. The UVCZ modeling requires significant a lot of preparation. It is important to know if the UVCZ have changed in the past – to know the historical UVCZ allocations (a minimum of two allocations from a different time). The next step is to identify the highest changes among the UVCZ classes and to interpret the reason for any of these changes. Following that the historical UVCZ allocations are added into the Metronamica model and the historical UVCZ changes are reflected by changing Metronamica's parameters which are the factors affecting the UVCZ allocation. This process is called calibration. During the calibration, the model's outcome is observed and the parameters are adjusted until the modeled result is very close to the real historical UVCZ allocation. This process usually takes many repetitions and can be very time consuming. However, prior to the model's calibration and the historical UVCZ allocation, the UVCZ classification itself must be presented.

5.1 Urban Vulnerability Climate Zones (UVCZ)

Although the LCZ scheme by Stewart and Oke (2012) has been successfully applied in many regions of the world, the LCZ classes show a particularly high focus on the Northern American architecture. The high diversity of dense urban structures in Europe which emerged through the rich history of settlements on the older continent is only partly addressed in this scheme. The second, more important aspect is that LCZ classes lack the linkage with the social population groups living within these classes. Because this study requires a proxy parameter representing not only the heat impact and landscape, but also the socio-demographic aspects of vulnerability, the additional properties of the climate zones are required.

The hypothesis of this study is that the socio-demographic factors of population have a strong relationship with the housing type (potential housing UVCZ). In addition, the heat and wind circulation within the local climate zone depends not only on the height and density of the buildings but also on their forms, their connectivity and their arrangement in the building block. Because the LCZ scheme could not offer the social-demographic classification, or the urban morphology, I modified Stewart and Oke's LCZ scheme (2012) by introducing subclasses.

The subclasses were based on a German energy-based planning scheme which was developed by Erhorn-Kluttig et al., (2011). This scheme was selected as an appropriate source of supplementary information after a comprehensive research of available local landscape classification systems in Germany was completed. This scheme emerged from the urban typology classification by Roth (1980) and Blesl (2002), in which they focused on German urban typology and buildings' heating demand. The German energy-based planning scheme contains 12 classes (figure 59) which were used to supplement the LCZ scheme with additional urban morphology and housing types. In addition to the LCZ scheme, the German scheme contains the average values of physical properties such as a range of the number of floors in a building, the area that is used and not laid barren, the number of households, the age of the building and the building density. Because the original focus of the German energy-based planning scheme is the buildings' heating demand, each class has values of average maximal thermal load and average thermal usage density. Although the classes in the German energy-based planning scheme focuses on heating demand, its morphological differentiation is a great additional input to the existing LCZ scheme.

Figure 59: graphical representation (icons) of the urban morphology classes in the German energy-based planning scheme (after Erhorn-Kluttig et al., 2011).

The combination of LCZ and the German energy-based planning scheme was called UVCZ which means the “urban vulnerability climate zones”. It is a heat and socio-demographic vulnerability-related climate zones classification for Northern Germany, but can be applied for the whole Germany and many other European countries. It differentiates the urban areas not only by land use as land cover as a LCZ scheme, as Steward and Oke do, but also by the urban morphology and housing type, as is assumed by socioeconomic properties. It describes both – urban vulnerability and urban climate zones. The additional advantage is that the UVCZ scheme is focused on European architecture based building block types and has more diverse classes with the corresponding morphology and housing types.

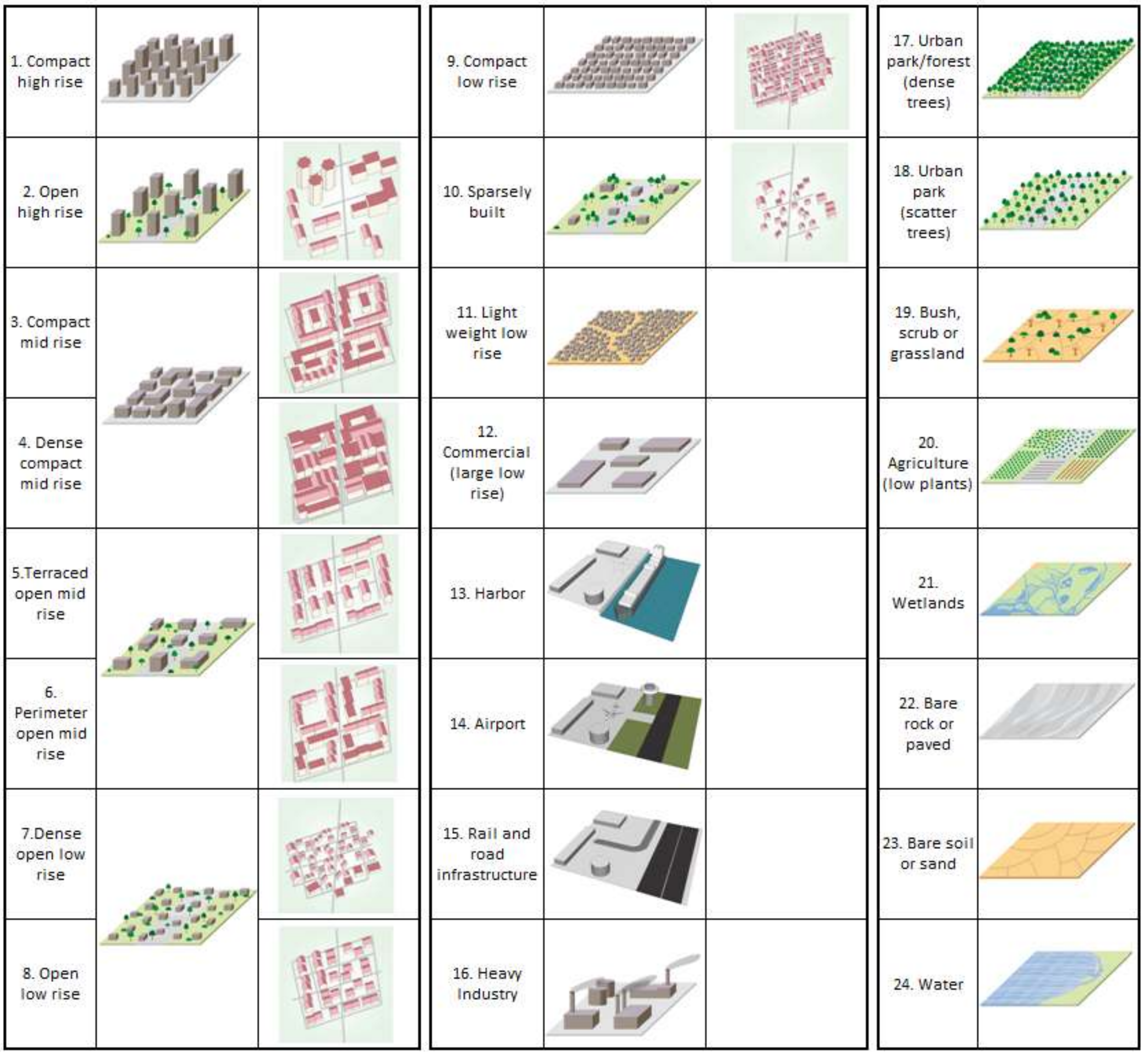


Figure 60: UVCZ scheme with 24 urban structure/morphology, land use and land cover classes for Greater Hamburg area.

The UVCZ scheme contains in total 24 (forest and urban park with dense trees shares one class) classes (figure 60). 11 of them are residential, suitable for population housing, others are for industry, commerce, infrastructure and nature. In the following section each class is described in detail. Some of the details are taken from Stewart and Oke (2012) scheme, some from the Germany energy-based planning scheme (Erhorn-Kluttig et al., 2011) and others have been surveyed specifically for the Greater Hamburg case study in the field. Detailed properties, such as the age and height of the buildings can vary among other case studies. The socio-economic properties of the population living within the potential housing UVCZ classes were not known at this stage, but their analysis can be found in chapter 6.1.

Compact high rise

The compact high rise is one of the UVCZ which does not exist in Greater Hamburg and hardly can be found in the entire country of Germany. This zone is often occupied by a dense mix of tall skyscrapers with tens of floors and limited space between the buildings. The space between the buildings is limited, as well as a sky view from the narrow street corridors between the buildings (highest canyon aspect ratio among all UVCZ). The buildings within compact high rise groupings are usually the tallest, in comparison to other UVCZ. Their dominant materials are steel, glass and concrete. The land surrounding them is mostly paved with few or no trees or grass. The compact high rise building has a high heating and cooling demand. Heavy traffic around them produces much of the pollution and heat around them as well. Common functions of high rise buildings are commercial (hotels and offices) and residential space (apartment towers). Compact high rise UVCZ are found in city core areas and central business districts, as well as downtown areas.

Figure 61: illustration of compact high rise zone in Chicago, USA.

Open high rise

The open high rise can have similar building height as compact high rise (tens of floors, in Germany it ranges from 6 to 15), although the building density is lower. Buildings are built in an open and geometric arrangement. The sky view factor is double that of the compact high rise. The dominant building materials are the same as for the compact high rise - concrete, steel and glass. The impervious surface coverage is smaller and the street network is coarser with meshed dead ends. Scattered trees and small grass covered areas fill in between the buildings. Traffic around these areas is often moderate, as is the buildings' heating and cooling demand. Most of this type of building are residential and serve as high rise housing estates, tenements and apartment blocks. The first floor, however, may be occupied by retail and medical services. The number of households in this kind of building is quite high and can vary from a low of 30 to a high of 500. Open high rise buildings were built in Germany from 1960 to 1980 and were built within the periphery of and in densely populated cities.

Figure 62: open high rise in Hamburg and Vilnius (Lithuania).

Compact and dense compact mid rise

Both compact and dense compact mid rise buildings have common properties. The buildings in these zones are separated by narrow streets and inner courtyards, with space between them being tight, or minimal. The sky view factor is slightly greater than the compact high rise and construction materials are the same: stone, tile, brick and concrete. Usually these UVCZ are covered by impervious surfaces and a very small amount of vegetation. The cooling and heating demand, as well as traffic is average. Use of these UVCZ varies from residential to commercial, with some industrial area included.

Compact mid rise

The average buildings height of compact mid rise is not high, ranging from 2 to 6 floors. They are often single attached buildings with street oriented alignment. The building type is from small to large multi-family housing. Inner courtyards are tight, often accessed by driveways. The streets around them are nearly always form a square shape. Common usage of them is residential with some commercial activities in the lower floors. The number of households per building varies from as low as 2 to as much as 20. Most of the buildings were built after 1900.

Figure 63: compact mid rise in Hamburg.

Compact dense mid rise

The average height of compact dense mid rise is higher than the compact mid rise - from 4 to 8 floors. They are single attached, street oriented buildings with very limited open space and often with no or very small inner courtyards. The dominant type is a large multi-family dwellings, retail outlets, offices, service, public and administrative units. The streets are very narrow and form a rectangular network. The number of households are from 0 – 50 per building. Often such buildings are found in old towns and are built from 1800 and earlier.

Figure 64: dense compact mid rise in Hamburg.

Terraced and perimeter open mid rise

The terraced and perimeter open mid rise classes are taller than 3, but lower than 7 floors. The sky factor is from 0,5 to 0,8, which is much higher than compact and compact dense mid rise. The buildings' materials are steel, stone, concrete and bricks. The traffic, heating and cooling demands are low. The common functions are residential (multi-dwelling, tenements and apartment blocks), institutional (research or business parks, universities), commercial (offices and hotels). They are often built within the periphery zone of the city.

Terraced open mid rise

The terraced open mid rise has an open irregular shape, often built as line oriented attached buildings. The alignment is regular and north-south oriented, often along the street. The street network is coarse-meshed. The typical building use is residential housing, consisting from small and big multi-family housing arranged by 2, 3 or 4 units. Often a building has 8-30 households. The number of floors can vary from 3 to 6. Such houses were built in Germany from 1950 – 1970. The most common areas where they were built are in the outskirts of medium and larger cities, adjacent to single home districts.

Figure 65: terraced open mid rise in Lüneburg, Hohenfelde and Bramfeld (Hamburg).

Perimeter open mid rise

In comparison to terraced, the perimeter open mid rise is more spacious, with a closed perimeter which creates inner green courtyards. These courtyards, however, because they isolate the inner yard, block ventilation, causing higher nearby temperatures to be higher than in the terraced class of housing. The building alignment is mainly street orientated with wide open spaces. The street network is nearly square shape. The use of the buildings is mainly residential, partly retail with possible local services in the first floor. The housing type is the old mansions, as well as small and big multi-dwelling units. Within the building live 1 – 30 households. The number of floors is from 2 – 6. The years built are starting from 1900. The perimeter open mid rise can be found in the central part of the city (core as well).

Figure 66: perimeter open mid rise in Eimsbüttel and Barmbek (Hamburg).

Compact low rise

The compact low rise class is low, 1-3 floors high, attached or closely spaced buildings. Buildings are small and situated along a narrow street corridor, therefore the sky view factor is 0,2 – 0,6 (similar to compact mid rise). The dominant construction materials are stone, brick, tile and concrete. The amount of green areas (pervious surface) is quite low, with land between the houses being mostly paved. Traffic varies from low to moderate and heating and cooling demand is moderate. In most of the cases such type of housing is used for residential purposes (single dwelling, high density terrace and row housing) and retail shops (commercial). The compact low rise emerged as high density sprawl and can be found in central or inner city, densely populated towns and villages. Because this type of housing exists in a very limited number of places in Hamburg, I decided to exclude this UVCZ from the list.

Dense open low rise and open low rise

The dense open low rise and open low rise UVCZ are similar to previously discussed compact low rise housing, but it has a lower density and more vegetation. The building height is similar as well, limiting to 3 floors max. The buildings are small and can be detached or attached in rows or a grid pattern. Because of lower building density, the sky view factor is quite high 0,6 – 0,9. Many houses have yards or gardens in front or behind. The pervious surface percentage is higher than impervious. The building construction materials are wood, brick, stone and tile. The traffic, cooling and heating demands are low. The common use is residential as single or multi dwelling housing, low density terrace and row housing, or commercial as small retail shops. The dense open and open low rise can be found in the cities and their suburbs (periphery), also in commuter and rural towns.

Open low rise

The buildings within open low rise UVCZ are larger (not taller) than buildings in dense open low rise, but the density is lower. The open low rise is an open regular, detached single large housing with spacious surroundings around. It is denser than the "Sparsely built" UVCZ. The buildings are aligned along the streets or in the middle of the block. The most of the buildings are used for residential housing, to host from 2 to

12 families. Most of the buildings are built after 1900. The open low rise is commonly built in suburbs and the outskirts of cities.

Figure 67: open low rise in southern Germany.

Dense open low rise

The dense open low rise is the most common UVCZ in the Greater Hamburg case study area. This UVCZ has higher density than open low rise and contain less space between the houses which are attached or detached single buildings. The street network is dense, but regular. The limited front or back yards and gardens contain significant amount of vegetation. The frequent use of this UVCZ is the residential (single or two family housing) and scattered small retail buildings (commercial). It contains a maximum of two households per building and the year built is after 1918.

Figure 68: dense open low rise in Hamburg and Lüneburg.

Sparsely built

The sparsely built housing is the most spacious UVCZ of all residential type zones. It is common in rural areas and is spread across natural landscape. The sky view, as well as the amount of pervious surface is very high. In comparison to others, the buildings are mostly detached single buildings, aligned along the streets or roads. The street pattern is sparse and mostly depends on topography. The traffic is very low but gets higher if closer to the main roads or highways. Buildings' materials are brick, wood, concrete and stone. The heating and cooling demand is very low. The buildings are mainly used for residential use as small double or single family housing and sometimes, agricultural use. Large areas between the houses contain green gardens and farms and meadows. In most of the cases one building hosts one family (household) and are built from around 1918. This type of housing can be found on the periphery of cities, as low density suburbs, in towns and villages and as newly developed low density urban areas. The "Sparsely built" UVCZ are dispersed and spatially covers quite a small amount of area in Greater Hamburg case study area, therefore is has not been represented in 1960 topographic maps and were excluded from the list of the potential housing UVCZ in the Greater Hamburg.

Figure 69: sparsely built, very isolated single home housing with a lot of pervious surfaces and possible agriculture areas around in Lithuania.

Lightweight low rise

The lightweight low rise is another UVCZ which cannot be found in the Greater Hamburg case study area. In most of the cases this UVCZ is located in developing countries, in the slum area. It contains basic one floor packed buildings, separated by narrow roads. The buildings can be attached or detached, and constructed from lightweight materials, such as wood, metal, clay or bricks. The infrastructure is very limited, as is the traffic. Usually almost no vegetation can be found and most of the surface is paved or gravel. Space between buildings is limited and, due to a shortage of good infrastructure, there is usually no cooling or heating demand. The lightweight low rise is used typically for informal settlements, cheap housing estates, mobile and shanty housing. In most cases lightweight low rise housing can be found on the periphery of large developing cities as well as in rural towns.

Commercial (large low rise)

The commercial (or large low rise) is a non-residential type housing, used for commercial (offices, shopping centers and storage facilities) and light industrial (warehousing) activities. The buildings within large low rise zone are 1-3 floors tall, large with paved spaces in between. This gives a good sky view rating. The dominant buildings' materials are steel, concrete and metal. There is a high ratio of impervious surfaces and very limited or no vegetation. The traffic flow varies from moderate to heavy, including heavy trucks transporting the goods. The heating and cooling demand is between low and moderate. The commercial zones usually lay in the periphery if cities.

Figure 70: commercial UVCZ in Hamburg often packed with vehicles and automobiles.

Harbor

Harbor is a special UVCZ which is used for transporting passengers and goods. Buildings' morphology in harbors varies from city to city. However, most of harbor areas are paved, contain many storage facilities, and have a transportation infrastructure. The buildings are low rise (except cranes and other special equipment), but large, no more than 3 floors (similar to commercial). The areas are paved with no vegetation or trees. The sky view rating is high. The main materials are steel and metal. Considering that main cargo transportation is train based, the traffic flow is average, while the cooling and heating demand is low or none - because of the individual containers' cooling systems. Naturally the harbors are located near the rivers, seas or lakes. The water, air and noise pollution varies between low to moderate. The cargo terminals and storage often are within the periphery as well as city area where the further harbor development is restricted.

Figure 71: harbor UVCZ in Hamburg and Karlsruhe (southern Germany).

Airport

Airport is another special UVCZ which is used for transporting goods and passengers. The airports' buildings are low rise, but large, usually used as terminals, hangars for planes, other facilities. The buildings are not higher than 3 floors with the exception of the control tower. The sky view factor is high. Naturally, there are very limited or no trees at all in the airport, but usually a lot of grass. The largest area of the airport is paved (runway, taxiways etc.), however, the other areas can be covered with grass or bushes. The main buildings' materials are concrete and steel. The traffic flow is heavy and the cooling/heating demand is moderate. Very heavy noise and average air pollution is typical for airports. The airports' location varies from country to country – from countryside, to the periphery or the city area.

Figure 72: environment of Hamburg's airport.

Rail and road infrastructure

The rail and road infrastructure is the paved zone, containing huge road and rail junctions, highways' elements, rail and public transport facilities. The buildings are low rise, but large, with no heating and cooling demand. Most of the areas are paved with little or no vegetation. The sky view factor is high. The dominant materials are concrete and steel. The traffic flow is heavy. The noise and air pollution is heavy, as well as the anthropogenic heat. Usually the heavy rail and road infrastructure is built within periphery, though the development occurs closer to city center. This zone by its physical properties is similar to "Bare rock or paved" UVCZ.

Figure 73: rail and road infrastructure in Lüneburg, Hamburg, Berlin and Poland.

Heavy industry

The heavy industry zone usually contains factories, refineries, mills and plants. The low and mid rise structures, such as tanks, towers and factories are the base building type in heavy industry zone. The sky view is reduced due to the height of the buildings. The area is mostly paved with no or very limited vegetation. Structures' materials are steel, concrete and metal, as well as bricks. High air, water and noise pollution dominates in the area together with high anthropogenic heat quantities. The heavy industry usually is found in the periphery of city or in the countryside.

Figure 74: heavy industry in Austria and Karlsruhe (southern Germany).

Urban park/forest (dense trees)

The urban park (dense trees) or forest zone contains a heavily wooded landscape with various types of trees. The area is usually heavy packed, with very limited sky view. Usually this UVCZ has no cooling or heating demand. There is very low or no traffic at all. The area is covered by pervious surface with few or no roads or buildings. The zone can be used either as natural forested areas and tree cultivation sites in the countryside, or the maintained urban forest (park) areas within the city.

Figure 75: forests and urban parks with higher density of trees in Hamburg, central and southern Germany.

Urban park (scattered trees)

The other urban park area with scattered trees is the moderate or light wooded landscape with various types of trees and other vegetation. The area is looser and contains more open space with pervious surfaces, such as meadows, grass, playgrounds. This area also can be identified as intermediate area between forest and grassland. The sky view factor is greater. There are usually few to no roads, no traffic and no buildings, and, therefore, no cooling and heating demand. This UVCZ is also used as natural forest, tree cultivation sites or urban parks in city areas.

Figure 76: urban park (scattered trees) in Hamburg, Lithuania, Geneva (Switzerland) and Maastricht (Netherlands).

Bush, scrub, grassland

The bush, scrub or grassland is a natural open land spaced with bushes and scrubs or only grass. It can have also have limited packs of short trees. The sky view factor is very high. There is no traffic, as well as heating or cooling demand and buildings. This UVCZ can be used also as agriculture (pasture) or recreation land within the city limits.

Figure 77: bush lands and grasslands with limited trees in Indiana (USA), Lithuania and Southern Germany.

Agriculture (low plants)

The agriculture zone is based on low plant cover. If no plants are planted, then the UVCZ is likely the "Bare soil or sand" UVCZ (see below). It has common properties as a bush, scrub and grassland UVCZ. The sky view factor is very high. Usually this UVCZ contains a few or no buildings/roads, the use is for agricultural purposes. No or low traffic, and no cooling or heating demand. This UVCZ can be used as agricultural or natural, low plants area. Mostly found on the country side, also as limited areas within the city.

Figure 78: agricultural lands in Hamburg, Lithuania and southern Germany.

Wetlands

The wetlands are the natural non or light forested areas which are tidally, seasonally or permanently waterlogged with stagnant or circulating water. The sky view factor is high. No buildings or roads, as well as traffic. No cooling or heating demand. In some cases can be used as a park for recreation purposes or as a natural conservation area. Usually found in the countryside, close to the water sources.

Figure 79: wetlands in Indiana (USA) and Lithuania.

Bare rock or paved

The bare rock or paved UVCZ can be either natural or artificial. The sky view factor is very high. Usually has few or no buildings and no vegetation. The surface is paved or rock based. Surface varies from gravel, bedrock, to asphalt or concrete. By its physical properties, this zone is similar to the "Rail and road infrastructure" UVCZ. The bare rock surface is common in quarries and natural rock deserts or geological shields. This UVCZ can be found in the city as larger parking lots and in the countryside.

Figure 80: paved and rock surfaces in Hamburg and northern Italy.

Bare soil or sand

The bare soil or sand contains featureless landscape on pervious ground which is predominantly soil or sand. It has few or no trees, as well as roads or buildings. If the plants are absent, it can also be identified as “Agriculture” UVCZ. This UVCZ has a very high sky view factor and low or no traffic as well as no cooling/heating demand. It can be found in the city (beaches) or in the countryside.

Figure 81: sand on the eastern coast of Pacific Ocean (USA) , eastern coast of Baltic Sea (Lithuania) and the northern bank of Elbe river (Hamburg).

Water

The water is flat and contains large bodies of water, such as lake, river, reservoir, sea. The sky view factor is very high. Water UVCZ can be found within the cities (lakes, rivers, harbors, bays) or in the countryside.

Figure 82: coast of Baltic sea, close to Lübeck (Germany), lakes in Lithuania and Elbe river in Hamburg.

Most of the above discussed UVCZ classes are typical for the Greater Hamburg case study, but also can be applied in other European countries and perhaps other continents. In that case, the zones should be reviewed and adjusted. As always, it is important to identify the classifications in the early stages of the research.

5.2 Historical UVCZ changes

The historical UVCZ allocations are necessary in order to calibrate the model. The calibration requires two historical UVCZ allocations of different time periods. The model would consider the pattern of changes between two historical UVCZ allocations and could model future UVCZ using the same pattern. Of course, additional historical UVCZ allocations of different time periods could be added as well and would represent different patterns which could be used in the model. For the Greater Hamburg case study, I obtained three historical UVCZ allocations, dated in the years 1960, 1990 and 2000. The historical UVCZ development in Greater Hamburg reflects the city development from more than a decade after the end of the Second World War (1960), through the fall of the Berlin wall (1990) and to the modern times of today (2000). These changes reflect development of the modern Greater Hamburg which was heavily bombed during the war, and resurrected to become one of the most attractive cities in Europe.

This chapter analyses the UVCZ changes from 1960 to 2000 for the area of Greater Hamburg. It also presents how the data was collected, processed and evaluated. Because the historical UVCZ data was difficult to obtain it was important to review any primary and secondary data input, vectorization and quality control. The statistical analysis gives an overview of the main UVCZ change patterns during the different time periods. The UVCZ 1960/1990/2000 data afterwards is required as input data to the Metronamica CA model. Metronamica requires cell-based data of a minimum of two time periods in order to identify the pattern of the UVCZ change. Therefore, the primary objective was to acquire a good quality UVCZ data of the Greater Hamburg area for three time periods: 1960, 1990 and 2000.

Data source

It's possible to ask why I did not use the existing land use datasets such as the EEA developed CORINE and Urban Atlas. The answer would be that, first, there is no historical land use data for 1960. Secondly the aggregation degree of CORINE and Urban Atlas classes is too high to be used in this study. And, third, the classes of publicly available datasets do not fully represent the UVCZ.

Because none of the datasets of EEA or other agencies represent classification for each scheme, it was decided to perform a manual vectorization for 1960, 1990 and 2000 topographic maps of Greater Hamburg. The objective was to identify the historical UVCZ and their changes. The case study area covers more than 8525 sq. km, 755 of which belong to the Hamburg city-state. It would be a very time consuming and laborious process to vectorize each UVCZ class for the entire area, including all natural areas as well. In addition, since three different time periods are included, it would be necessary to multiply the vectorization process by three. The focus and priority, therefore, of vectorization was building occupied (urban) UVCZ (both housing and non-housing classes). In topographical maps, these UVCZ can be identified by the pattern and size of buildings. The other UVCZ such as agriculture, forests and other natural, non-populated areas are less important. They, therefore, were acquired from the EEA CORINE datasets, even though there was no information for 1960. However, based on the differences seen between 1960 and 1990, it is possible to know which natural areas did not change. The other ones, then, were affected by urban development. Figure 83 shows the missing natural areas which were occupied by a building environment.

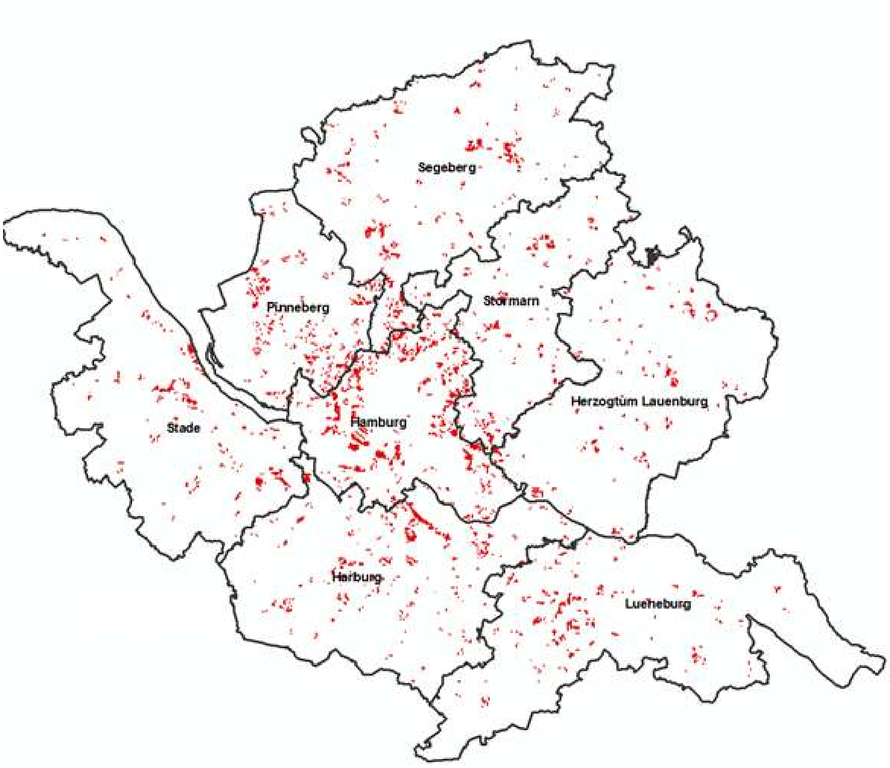


Figure 83: missing non-building occupied UVCZ data for 1960 dataset.

While it is known which of these missing UVCZ areas experienced change in 1990, there is no information concerning what type of natural areas were there before. My solution to establishing this information was to fill the missing data with natural areas from the CORINE 1990 dataset with agriculture UVCZ because most of the land occupied by new urban development was agricultural land. Since the focus of the Metronamica model is not natural land, but only the function (urban) classes, the model is not particularly sensitive to natural lands, so it was decided that the study would not be significantly skewed by using this solution. The following scheme (figure 84) presents the datasets for the three time periods.

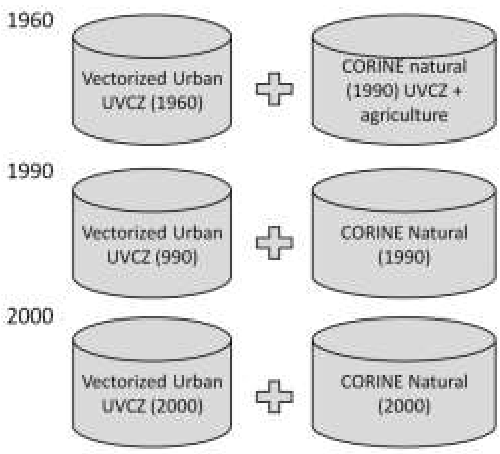


Figure 84: contents of datasets for the three time steps. The natural UVCZ classes were obtained from CORINE.

Secondary data

The source and input for vectorization was the paper topographic maps. All maps were acquired from the Institute of Geography, University of Hamburg, Germany. Maps were scanned and georeferenced in order to digitize them. The following figure (figure 85) presents the topographic maps' fragments of the same location for three time periods.

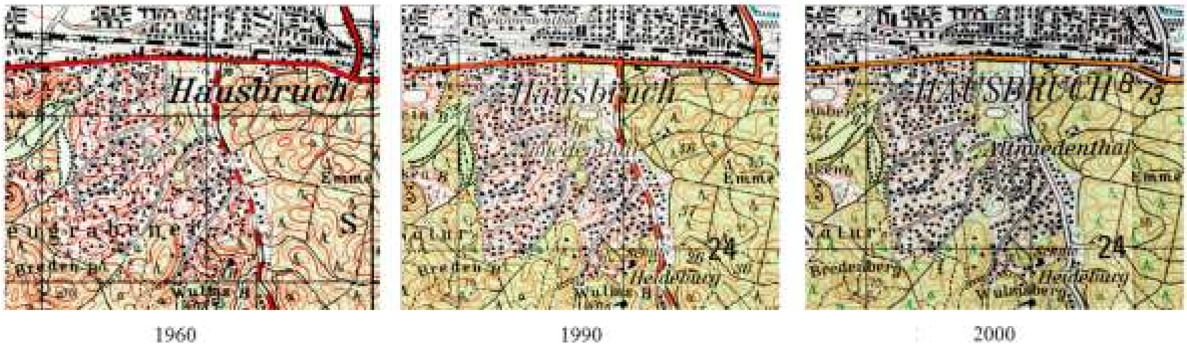


Figure 85: topographic maps' fragments of Hausbruch area for three time steps.

When it was difficult to identify the building structure and UVCZ in the topographical maps, the historical Google Earth aerial imagery was used.

Process of vectorization

The interpretation of topographic maps and vectorization was done by one person. First he had to understand and interpret the UVCZ scheme and only then to vectorize the maps. During the first vectoriozation session, the 1990 and 2000 maps were vectorized. It was later decided to vectorize the 1960 maps. Maps were vectorized using ESRI ArcMap software and vector polygon features. Following that the spatial analysis of merge, update and other operations were done to update the layer with the CORINE datasets. Moreover, the other operations were done in order to fill the gaps between the vectorized features. Throughout the process it was important to control the process, correct possible issues and convert the grid raster to the cell resolution of 250 meters.

Vectorization's quality control

The process of vectorization was controlled in order to keep the quality and consistency of UVCZ interpretation. To do that, I randomly picked up some areas and overlaid them with topographic maps. Below are a few examples.

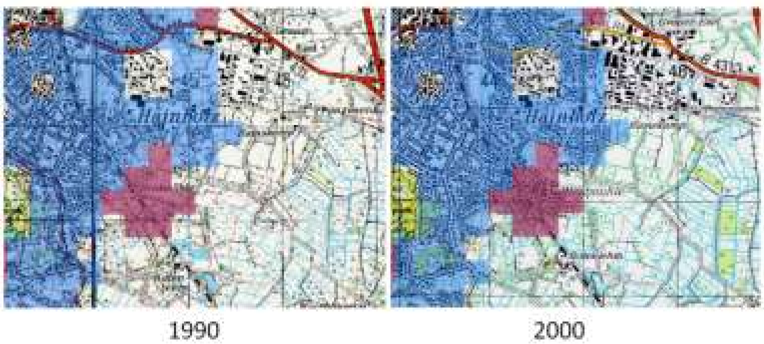


Figure 86: vectorization of Heinholz area. Blue color represents existing (1990) dense open low rise UVCZ and red its new development (2000).

Figure 86 presents the development of dense open low rise UVCZ on two different time period topographic maps. Blue shows existing UVCZ and the new development is marked in red. In the example the urban expansion in the Heinholz area is represented quite well. The urban densification in the eastern side of the area belongs to another UVCZ class.

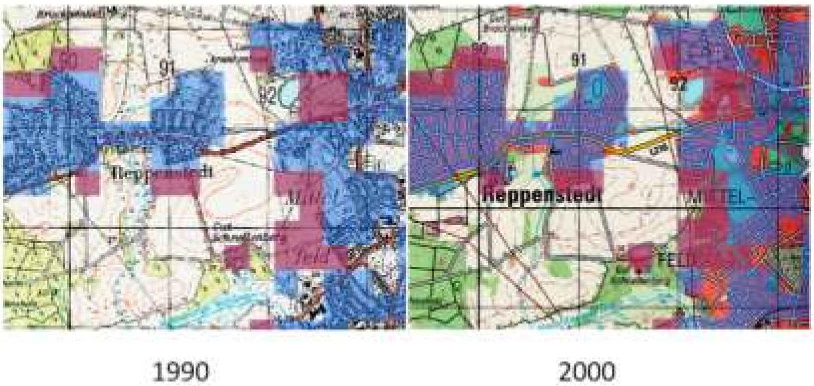


Figure 87: vectorization of Reppenstedt area. Blue color represents existing (1990) dense open low-rise UVCZ and red its new development (2000).

The digitization for the Reppenstedt also went quite well (figure 87). While the topographic map from 2000 contains different symbols, it is not an obstacle in indentifying urban expansion.

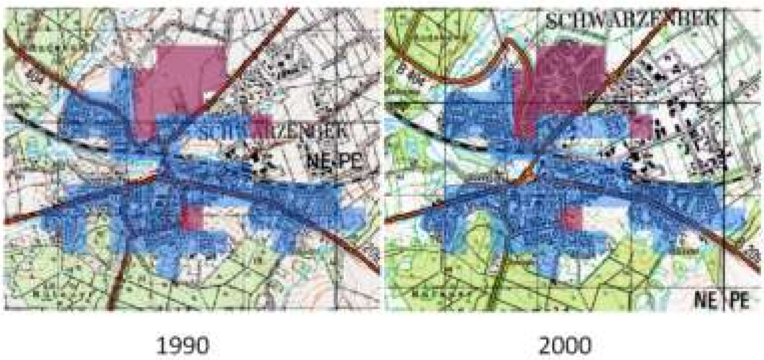


Figure 88: vectorization of Schwarzenbek area. Blue color represents existing (1990) dense open low rise UVCZ and red its new development (2000).

Figure 88 clearly shows a new development on the North side of the town. The other two cells standing alone are questionable, but the changes may have occurred when the vector to raster lay was converted. In general, the digitization in the Schwarzenbek area is fine.

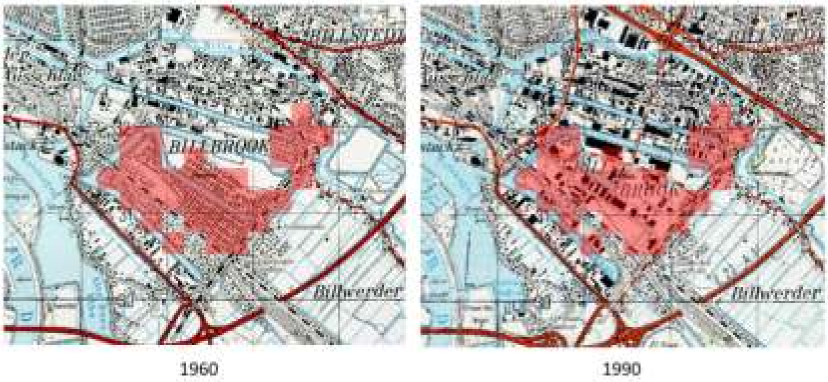


Figure 89: vectorization of Billbrook area. Red color represents the change from dense open low rise to large low rise (commercial).

Figure 89 (above) shows the changes between 1960 and 1990. As seen on the map, the South part of Billbrook was covered by high density, small houses. In the 1990 may we can observe the change to large building blocks, similar to large low rise areas (commercial).

Observed issues and solutions

The results of the vectorization process were evaluated by local experts who are familiar with UVCZ structures in Greater Hamburg. Here I present only few problems identified after the vectorization process. One problem was detected in the overestimated harbor area (figure 90). In Hamburg the harbor area is situated in the Southern part of Elbe River. The development to the East is blocked by Elbbrücken bridge (red line in figure 90).

Figure 90: result of harbor‘s vectorization (1990 – 2000). Red line marks the real eastern edge of the harbor area (background: Google, 2014).

The solution was to ignore all vectorized harbor UVCZ to the East of the marked line and change it to the large low rise (commercial) UVCZ. Other minor issues were detected in the north side of the Elbe River. A few harbor areas were changed to a newly developed compact mid rise urban UVCZ (Hafen City) and to the urban park in Altona district.

A larger issue dealt with the heavy industry UVCZ. The problem was that interpreter did not identify any heavy industry UVCZ in the topographic maps for year 1960. The solution was to perform an additional vectorization of the heavy industry UVCZ within Greater Hamburg. Figure 91 shows that a majority of heavy industry zones were established in 1960-1990, although some part of them already existed before 1960. After 1990, new development of heavy industry was mostly the electric plants and small factories.

Figure 91: vectorization of the heavy industry UVCZ (background data source: Google, 2014).

In total there were a few control surveys performed and a few more minor issues were detected which were immediately corrected. In the end the experts agreed that the historical UVCZ datasets are fine and they can be used as input to the Metronamica model.

Statistics and analysis of UVCZ changes 1960 – 1990 -2000

However, in order to represent historical UVCZ development, the urban development patterns have to be analyzed. Therefore the following information gives a good overview of the historical UVCZ analysis and its changes between 1960, 1990 and 2000. Figure 92 presents the UVCZ changes for two periods: 1960 – 1990 and 1990 – 2000. It is apparent that many more changes occurred between 1960 and 1990, representing three decades, than between 1990 and 2000.

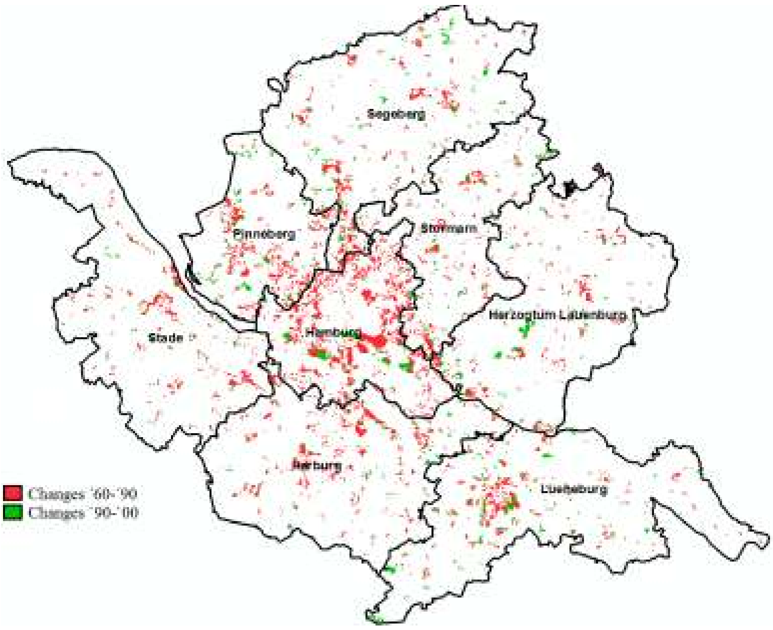


Figure 92: the UVCZ changes in Greater Hamburg between 1960, 1990 and 2000.

Many changes occurred during the first period in Hamburg city-state area, especially in the center and North parts. As we will see later, the center part experienced an expansion of harbor and commercial areas, while the changes in North are typical urban expansion. Pinneberg, Lüneburg, Stade and Harburg districts also saw many changes between 1960 and 1990, especially close to the cities. Between 1990 and 2000, most of the changes (mostly as small clusters) occurred outside cities and are most noticeable in the outskirts of the

Lüneburg, Lauenburg, Pinneberg and Segeberg districts. Both patterns show some signs of controlled urban sprawl which actually was typical pattern in Greater Hamburg in 1960 – 1990.

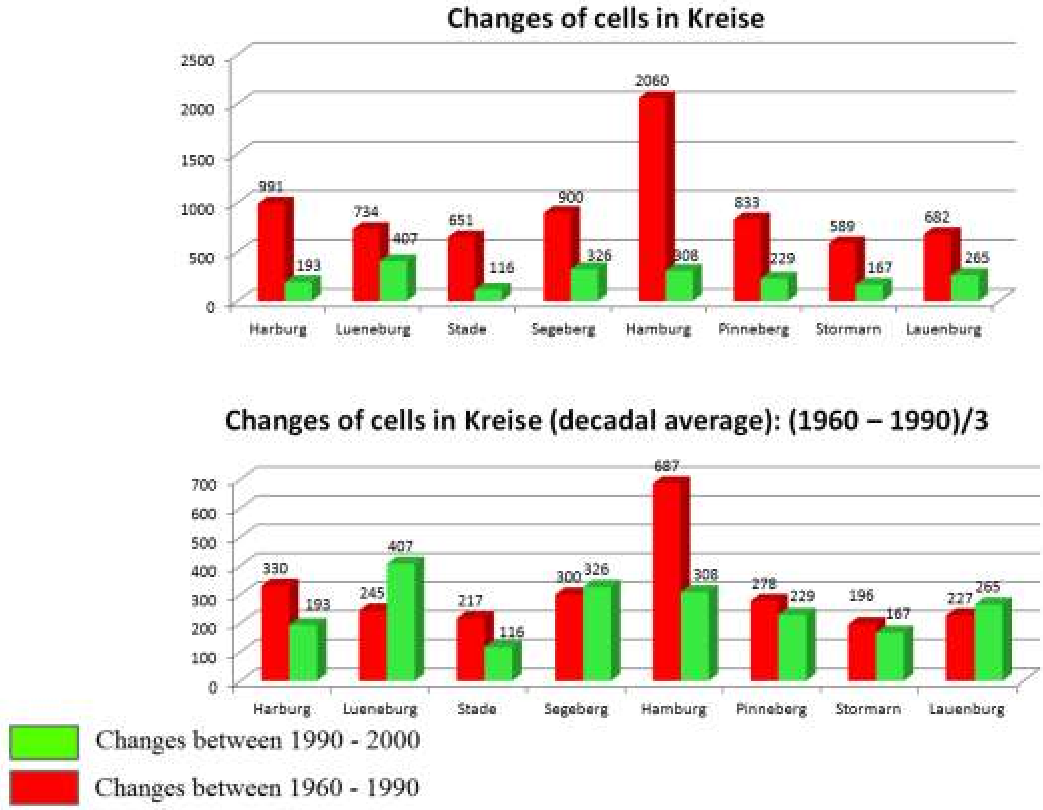


Figure 93: cell (250 x 250m) changes‘ count in Kreise (districts) in total (upper graph) and decadal average (lower graph).

Figure 93 shows the total and decadal average changes' cell count for each district and Hamburg city-state for the two time periods. The decadal average of 1960 – 1990 changes was calculated by dividing the total number of changed cells by three. Even then it is obvious that many more changes occurred in Hamburg city-state during the first time period than in other districts. Some of the changes are the commercial and harbor development, with the rest being residential expansion. It is possible that one of the most important reasons for urban expansion is the development of the transportation network. Before this, people settled closer to the Hamburg city from which they could easily reach their work as well as enjoy the benefits of a large city. By 1990-2000, the improved public transportation allowed people to live a greater distance from the city center and commute to the city using the rapid regional surface trains. It is interesting to note that the Lüneburg district experienced many more changes between 1990 and 2000 than they experienced between 1960 and 1990. This is contrary to what is noted in Harburg, Stade and Hamburg. In the latter case, the suburbanization process in the Greater Hamburg district took place between 1960 and 1990, when more people were moving to the outer surrounding districts. In the district of Lüneburg, however, the entire process happened later between 1990 and 2000.

Table 6: 1960-1990-2000 cells' changes by UVCZ.

	Cells						
Potential housing UVCZ	**1960**	**1990**	**Change (%)**		**1990**	**2000**	**Change (%)**
Compact mid rise	54	55	1,9		55	55	0
Dense compact mid rise	38	37	-2,6		37	37	0,0
Compact low rise	3	5	66,7		5	5	0,0
Open high rise	19	63	231,6		63	63	0,0
Terraced open mid rise	1142	2043	78,9		2043	2130	4,3
Perimeter open mid rise	417	456	9,4		456	456	0,0
Dense open low rise	7540	12035	59,6		12035	12896	7,2
Open low rise	502	806	60,6		806	919	14,0
Other urban UVCZ							
Commercial (large low rise)	278	977	351,4		977	1083	10,8
Harbor	318	435	36,8		435	545	25,3
Airport	62	128	106,5		128	128	0,0
Rail and road infrastructure	61	151	147,5		151	150	-0,7
Heavy industry	41	119	190,2		119	129	8,4
Urban park (scattered)	297	304	2,4		304	290	-4,6
Urban park (dense)	501	507	1,2		507	654	29

Table 6 represents the cell counts by specific UVCZ for both time periods. We can see a high increase in terraced open mid rise buildings (more than half) between 1960 and 1990. A similar situation is seen with the open high rise UVCZ – there is a relatively large increase during the first time period over the second time period. The opposite situation is seen with the compact mid rise UVCZ, which increased during the second time period, 1990-2000. This increase reflects the development of a new district, "Hafen City", which was once part of the harbor area. Although the relative changes in compact low rise UVCZ are high, the changes do not play a significant role among all UVCZ classes. We can see that during the 1960-1990 period there was a significant absolute increase in dense open low rise, as well as a relatively high increase in commercial, heavy industry and road/rail infrastructure. This increase in dense open low buildings is indicative of urban sprawl. The increase in commercial and road/rail infrastructure reflects the economic development of the time. It is worth mentioning the expansion of the harbor UVCZ, because it would be expected to be a natural finding that the intensive expansion of harbor development of the past is not continued to the present. This would explain the decreased harbor expansion during the second time period (1990-2000). The following information introduces the spatial comparison between the most common UVCZ change in Greater Hamburg.

Agriculture to dense open low rise

The changes from agriculture to dense open low rise were the most common changes among all the changes in both time periods. Agricultural land close to the cities is expensive, but has an even higher value when converted to residential land. This kind of large scale conversion clearly shows signs of urban sprawl.

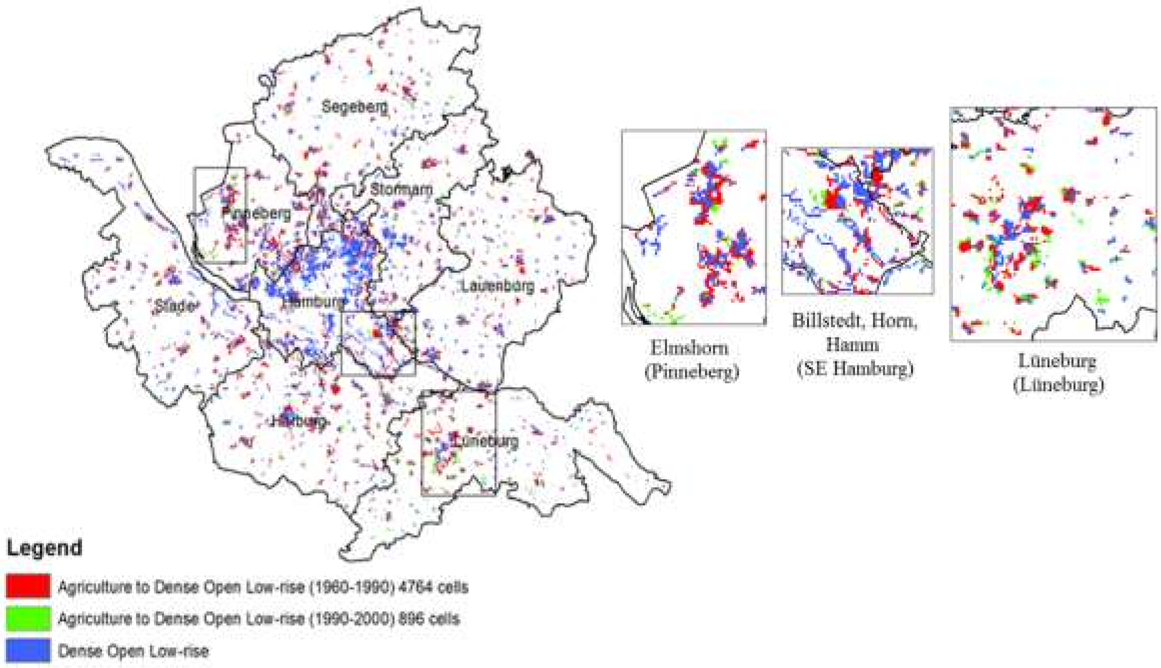


Figure 94: agriculture to dense open low rise changes.

Figure 94 shows the changes occurring in the Greater Hamburg area in a practice way. Preexisting dense open low rise zones are shown in blue. The red and green colors represent the development between 1960 and 1990 and between 1990 and 2000, respectively. Much new development happened in the outskirts of Northern Hamburg and in the Southeast (Horn, Hamm, Billstedt) between 1960 and 1990. The districts of Harburg, Pinneberg and Lauenburg also experience significant development during this time.

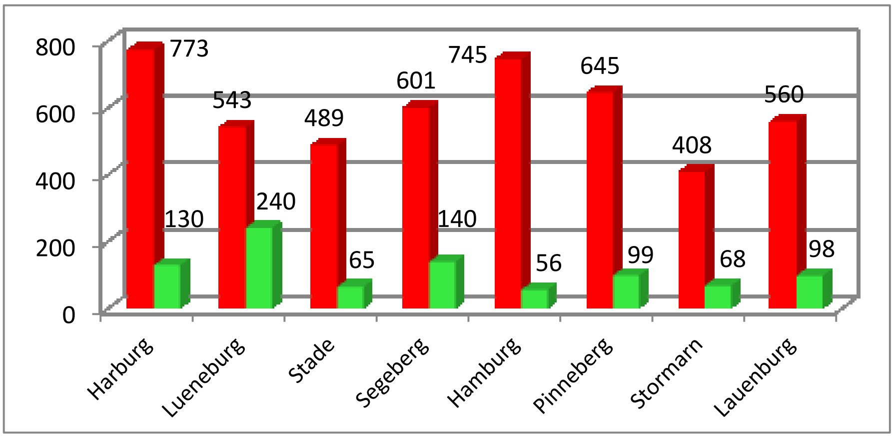


Figure 95: cells' count of agriculture to dense open low rise among the districts in 1960-1990 (red) and in 1990 -2000 (green).

According to the statistics (figure 95), most of the change from agriculture to dense open low rise occurred in the Harbug area (extensive expansion and formations of new residential clusters) during the first time period. Hamburg city-state was in second place to Harburg, but only during the first time period. Between 1990 – 2000 Hamburg city-state experienced the lowest amount of dense open low rise development among all areas. Interestingly, between 1960 and 1990, the Lüneburg district had one of the lowest numbers in development, with move of the conversion boom happening during the 1990-2000 time period. This boom was actually about five times higher than what was happening in Hamburg city-state. The reason for this phenomenon has already been explained: the process of suburbanization in Greater Hamburg was common in the earlier time period, while in Lüneburg it was quite later, 1990-2000.

Figure 94 shows the situation in Lüneburg, with the main development around the city of Lüneburg in both time periods. Between 1960 and 1990 the main development took part close to the existing dense low rise areas and in 1990-2000 the development occurred further outside the city, as clusters of new residential areas. Interestingly, in Pinneburg, development between 1960 and 1990 happened mainly around already existing areas, showing urban sprawl, and in the later period, 1990-2000, the development was focused on specific areas and occurred as larger clusters. A similar trend can be seen Southeast of Hamburg, in Billstedt, Horn and Hamm areas.

Agriculture to terraced open mid rise

Another common conversion was from agriculture to terraced open mid rise house which is a different class than the dense open low rise. In the open mid-rise buildings the alignment of the buildings is terraced, the average height of the buildings is higher and the area around the housing contains a bit more green space.

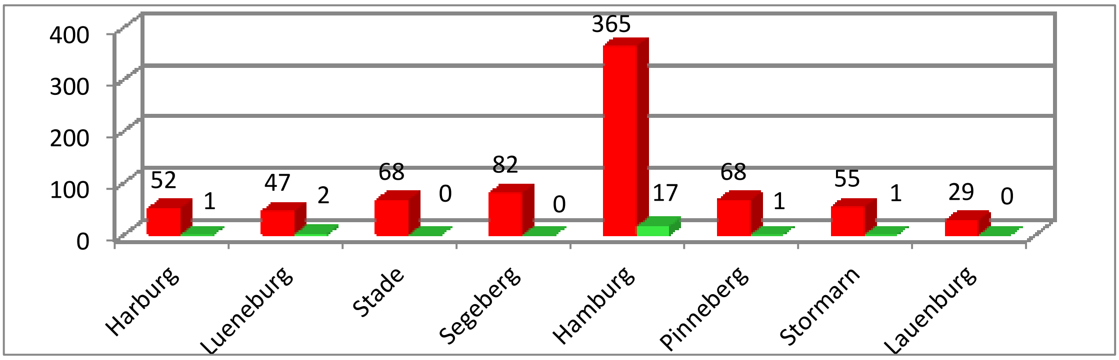


Figure 96: cells' count of agriculture to terraced open mid rise among the districts in 1960-1990 (red) and in 1990 - 2000 (green).

Figure 97 shows Hamburg city-state as a leader of terraced open mid-rise conversion in both time periods. In other districts the development was five times lower. During the later time period, there was no or very limited such development, even in the Hamburg city-state area.

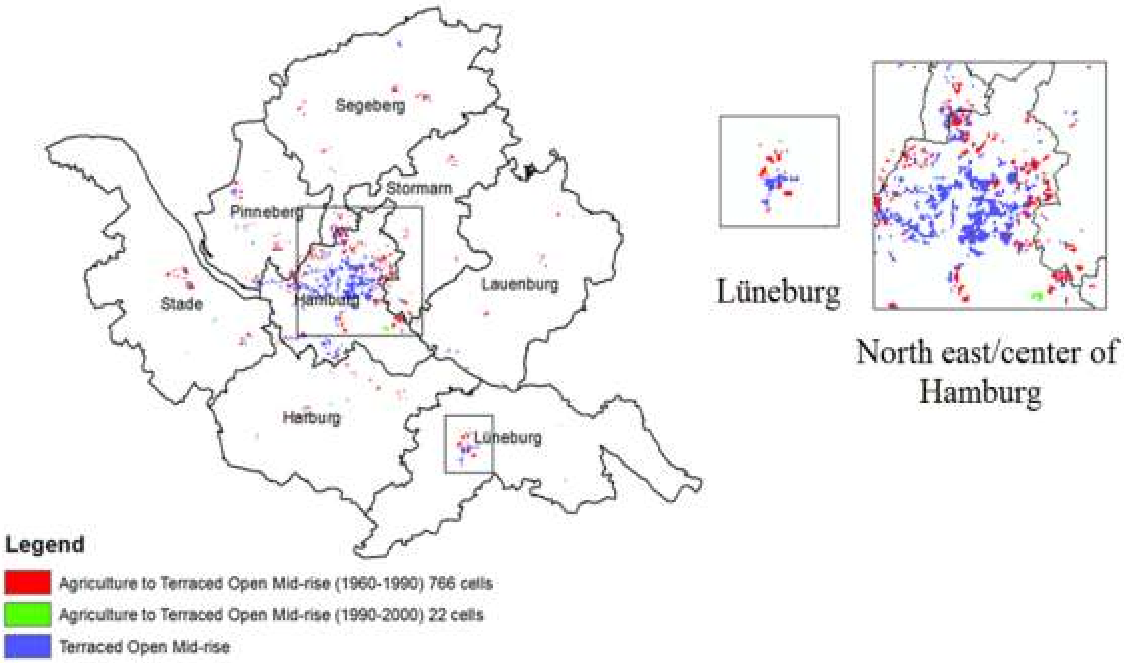


Figure 97: changes of agriculture to terraced open mid rise.

Most of the pre-existing terraced open mid rise UVCZ are in Hamburg city-state. It is not surprising, then, that the majority of new development occurred in Hamburg (figure 97). Some changes, as clusters of new development, however, can be seen as occurring close to the cities and town in the Northern part of Harburg, the centers of Lüneburg, Segeberg, Stade and Pinneberg.

A closer view of Lüneburg and the Northeast/center parts of Hamburg can also be seen in figure 97. There are two types of trends identified in Hamburg: 1) some of the development occurred close to existing terraced open mid-rise housing, showing an expansion pattern; 2) other zones developed as isolated clusters around the sub-centers. In the far Southeast of

Hamburg, during 1990-2000, only one cluster of new development terraced open mid-rise housing appeared.

Agriculture to large low rise (commercial)

Another change that is commonly seen is the change from agriculture to large low-rise, also known as the commercial class. The large low rise buildings usually are various types of warehouses, but can also be retail stores and shopping centers. The change from agriculture to commercial is typical commercial development which has a positive impact on local economy.

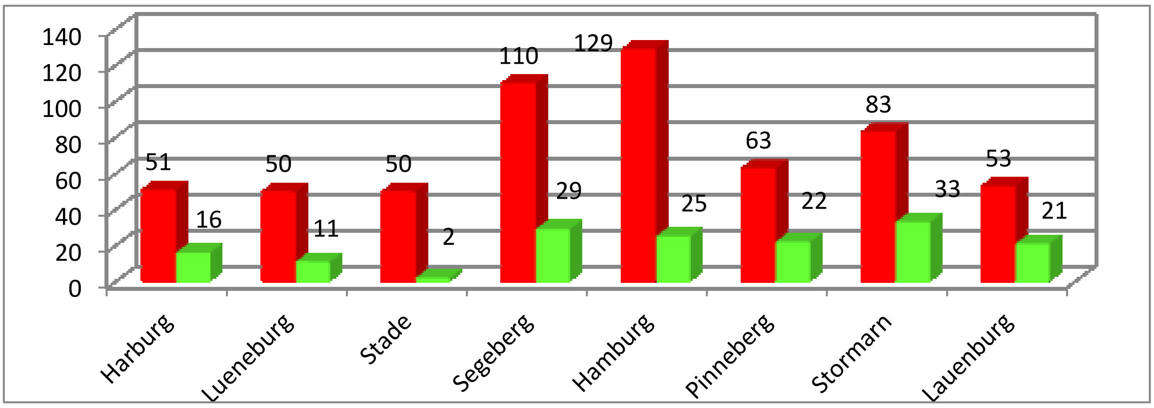


Figure 98: cells' count of agriculture to large low rise (commercial) among the districts in 1960-1990 (red) and in 1990 -2000 (green).

Figure 98 shows much higher commercial development during 1960-1990 than 1990-2000. Even taking into account that the first period is three times longer, it's still a huge difference. It must be remembered that during 1960 and 1990, all of Europe, but especially Germany was recovering from the Second World War. This period was very favorable for trade and commerce, which is reflected in the historical data. Most of the commercial development occurred in Hamburg and the Northern districts such as Pinneberg, Stormarn and Segeberg. The Southern districts of Harburg, Lüneburg and Stade experience a slightly lower degree of development. A similar trend can be seen during the later period, between 1990-2000. While this development trend may look strange, since the Southern districts are close to the Southern bank of the Elbe River, as well as the harbor, the higher commercial development in the North (not close to water transportation) is still plausible when it's remembered that commercial development is not limited to heavy goods needing transport by ship.

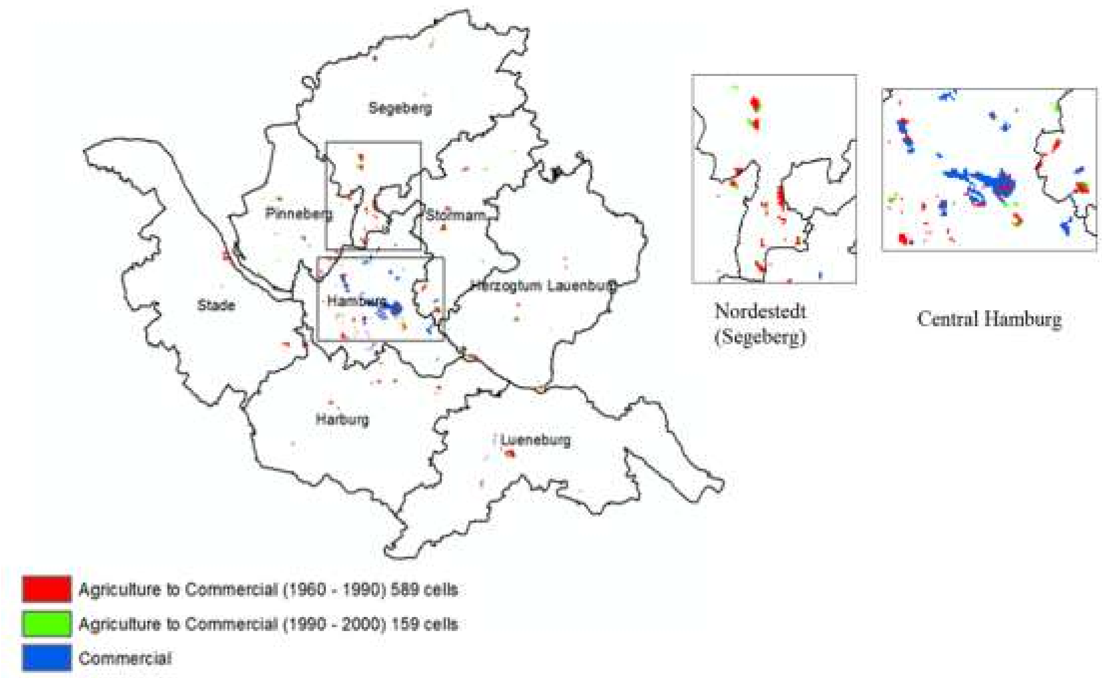


Figure 99: changes of agriculture to large low rise (commercial).

Spatially the development of new commercial areas is clustered over the entire area. In Stade new development occurred closer to the Elbe river and farther away from the city. In Segeberg the new commercial areas concentrated mainly in the south, near the Norderstedt. Harburg, Lauenburg and Pinneberg experienced the commercial conversion as small isolated clusters. This may have happened in these specialized areas because they were encouraged via urban zoning and planning which often offer reduced taxes and an economically friendly environment. It's interesting to note that in many cases the newer development (1990-2000) was located close to the already developed sites of 1960-1990. This trend is noticeable in Harburg, Pinneberg, Lauenburg, Storman and partly Lüneburg. This may have happened because of the expansion of existing business and storage facilities, or the development of new companies nearby. Another interest thing to note is that most of the commercial development before 1960 was in the Hamburg city-state, but not in the surrounding districts. This could have been caused by limited transportation networks and bad connectivity to the Hamburg and surrounding cities.

Many commercial areas existed in Hamburg before 1960 (blue color in figure 99). Some of the new development that occurred show signs of expansion of the existing zones. However, there are many small stand alone red cells representing isolated small size business (on large scale) developments. During the later period between 1990-2000, most of the new development is identified as commercial expansion. This can be observed especially in Nordestedt (district of Segeberg). The most intensive commercial development is seen as big clusters occurring near Segeberg between 1960 and 1990.

Agriculture to open low rise

The other common change was from agriculture to open low rise. Open low rise is very similar to the dense open low rise UVCZ, except that open low rise has larger buildings, lower building density and more green area around it.

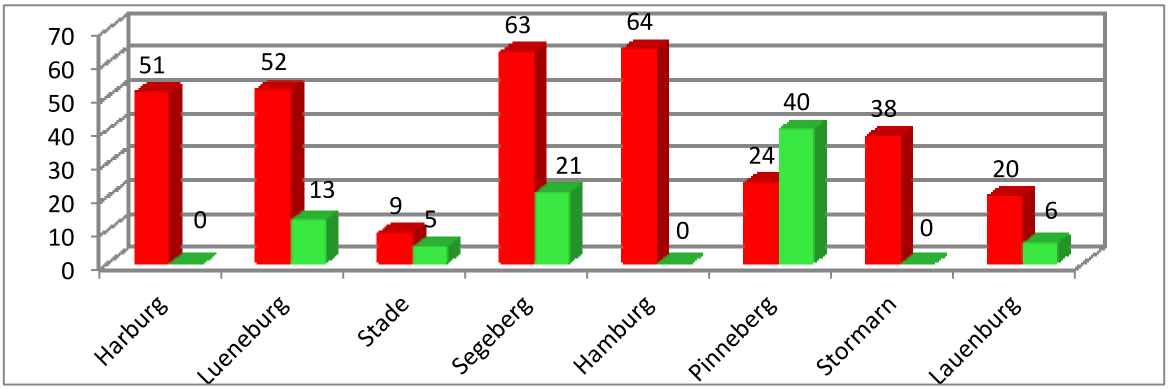


Figure 100: cells' count of agriculture to open low rise among the districts in 1960-1990 (red) and in 1990 -2000 (green).

The changes among the districts in both time periods are quite diverse. During the 1960-1990 time period the higher intensity of open low rise development occurred in Hamburg, Segeberg, Harburg and Luenburg, while there is less development in Pinneberg, Stormarn and Launeburg and with very limited development in Stade. During the later period most of the new development happened in Pinneberg (almost twice more than in 1960 – 1990) and some in Segeberg. In other districts the commercial development was rather low. Moreover, no new development during 1990 – 2000 occurred in Stormarn, Harburg and Hamburg city-state.

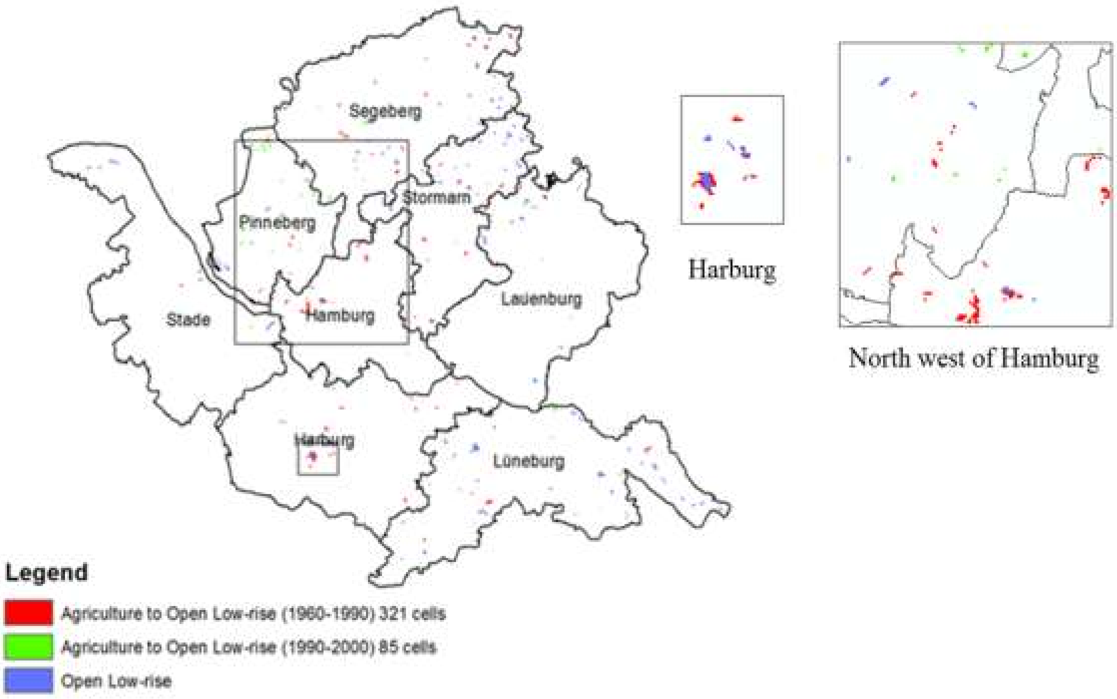


Figure 101: changes of agriculture to open low rise.

In general, open low rise is quite loose UVCZ with low density housing, often developed as isolated cells. Such a pattern is very similar among all districts. Small clusters or developments of isolated cells have very limited or no connections with previous developments, except some areas in Northwest of Hamburg and the center of Harburg (figure

101). In areas Northwest of Hamburg the developments of open low rise can be identified as having larger clusters with few extended cells, adjacent to existing open low rise zones.

Dense open low rise to terraced open mid rise

The last significant conversion is between dense open low rise to terraced open mid rise. The reverse of this conversion (terraced open mid-rise to dense open low-rise would be technically challenging, but the conversion from lower to high density residential housing is typical urban densification.

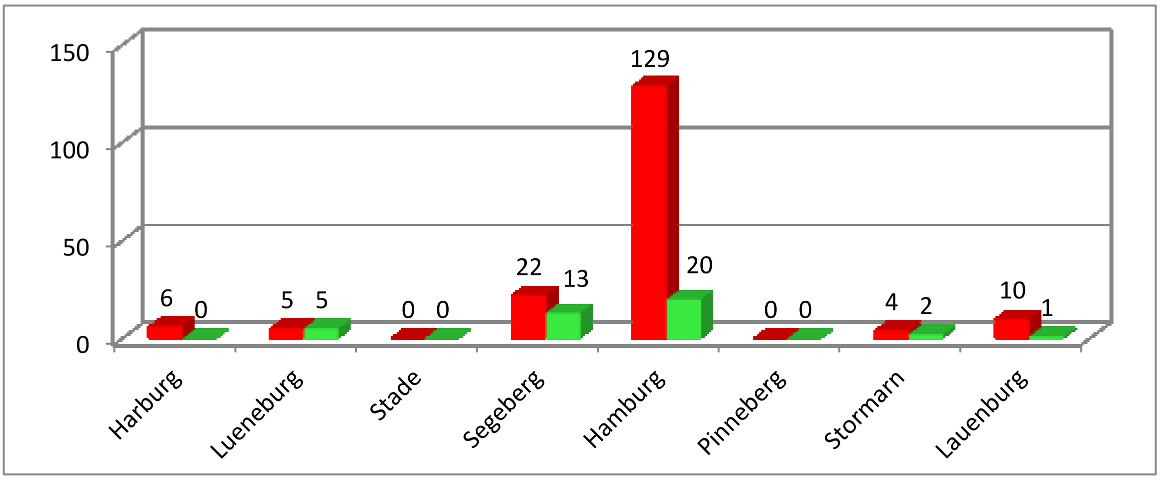


Figure 102: cells' count of urban densification process - dense open low-rise to terraced open mid rise, among the districts in 1960-1990 (red) and in 1990 -2000 (green).

Most urban densification development happened during the earlier period in Hamburg city-state area (figure 102) and with much lower magnitude in Segeberg. The other districts experienced very few or no densification (conversion from dense open low rise to terraced open mid rise) at all.

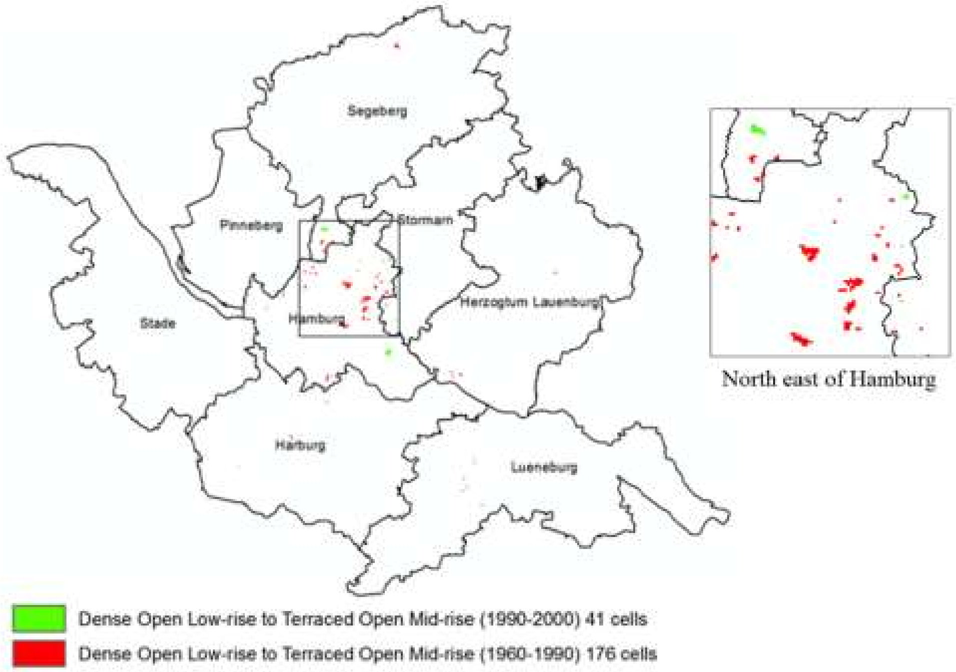


Figure 103: changes of dense open low rise to terraced open mid rise.

As we discussed previously, most of the densification appeared in Hamburg city-state and district of Segeberg. During the 1960 – 1990 development occurred in the Northwest and Northeast of Hamburg. Some of the clusters are quite large (figure 103), although few isolated developments occurred as well. During the 1990 – 2000 period there were even fewer developments, most of them were larger clusters in Hamburg Southeast and South of Segeburg, with isolated cells in Lüneburg.

Conclusions

The 1960 – 1990 time period experienced many more changes than the 1990 – 2000 period. Even considering that the first period is three times longer, it still dominates the development of dense open low rise, terraced open mid rise and commercial UVCZ classes. Such extensive development is a consequence of economical, industrial and residential boom after the Second World War. The developments of two time periods differ not only by magnitude, but also by spatial pattern. The 1960 – 1990 changes mainly occurred in the central areas of the Hamburg city-state, while during the 1990 – 2000 the densification within the city core and the expansion in the suburbs. The development of dense open low rise and commercial UVCZ was common for both time periods. The identification of such patterns helps to make a decision, if the same pattern could be valid in the future and if needed, implement it in the model where it would serve as a baseline (BaU) scenario.

5.3 Model's calibration

The previously identified pattern of UVCZ changes have to be represented in the model, in order to use this pattern for modeling future UVCZ allocations. Therefore the model has to be calibrated. This sub-chapter presents the results of calibration of the Metronamica model for Greater Hamburg. The model was calibrated for two time periods: 1960 – 1990 and 1990 – 2000. The information highlights the statistical information of the calibration. This information is supported with maps and visual figures which help to assess the spatial quality of the calibration results. Additionally I present influence of Metronamica's main factors and variables. Deailed information about Metronamica can be found in chapter 3.2.

Meaning of calibration

In statistics, calibration means an opposite action of regression, when a certain variable is predicted from other known variables (Dodge et al., 2003). In this case, the 1960, 1990 and 2000 data are the observations, the known variables. And the task is to find the coefficients of these variables. Therefore, in calibration the coefficients (parameters) are changed until the output of the model is as close as possible to the actual observations.

Neighborhood potential

As it was mentioned earlier, the four main factors (or variables) affect the allocation of UVCZ. The most important factor is the neighborhood potential. The neighborhood potential is a function and influences the relationship between two UVCZ classes (figure 104). Figure 104 shows the neighborhood potential of dense open low rise on itself. It shows the influence of existing dense open low rise to the new dense open low rise cells, depending on distance. The closer distance results in a higher influence which means a higher attractiveness.

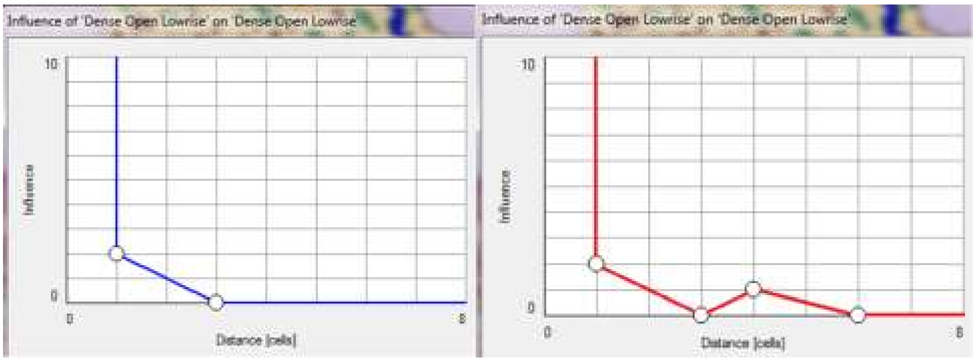


Figure 104: visual representation of neighborhood potential as influence. The user in Metronamica has an ability to change the neighborhood potential. Both graphs show the different effect of dense open low rise on new development of itself.

The left graph of figure 104 shows the decreasing influence (attractiveness) from the first (influence = 2) to third cell (influence =0). It means that the influence is lower with a distance of two cells away from the existing dense open low rise UVCZ than the of distance of one cell. All areas further than two cells away do not have any influence – there is no attractiveness. The right graph shows the different neighborhood potential. If the distance is one or two cells, the influence is the same as in the previous graph. This time, however, the influence increase a bit if the distance is four cells and then, a distance of six cells, the influence is back to zero. Such a function would, therefore, cause a higher attractiveness in a two cell radius and a small attractiveness between a three and six cell radius.

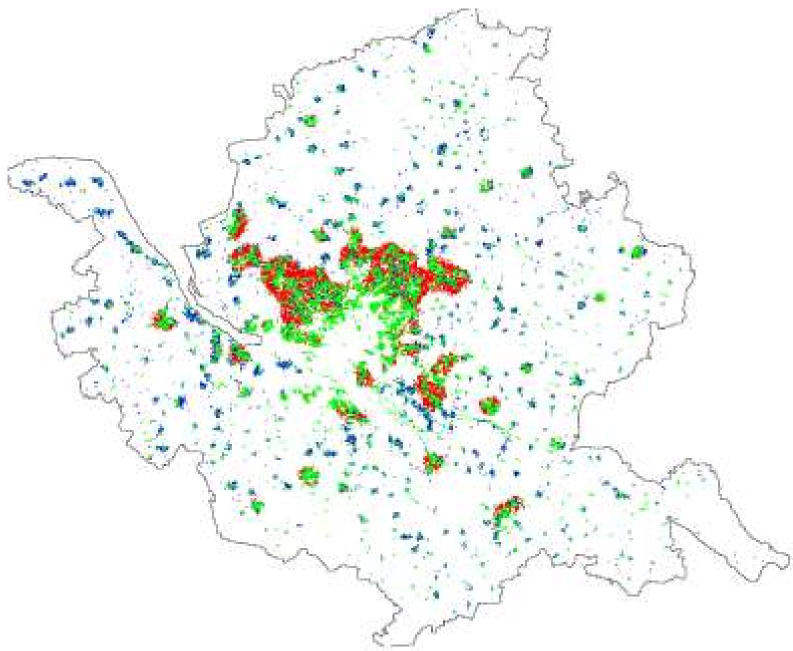


Figure 105: result of different value of neighborhood effect in Metronamica on dense open low rise UVCZ for Greater Hamburg.

Figure 105 represents the effects of previously discussed neighborhood functions. The green color represents what already exists. The blue color indicates the modeled UVCZ affected by different neighborhood potential functions. The red color represents the "right" function in figure 104, meaning the greater influence and greater attractiveness, if there are more cells nearby (green cells). The blue color represents the influence of the left, the blue graph, where influence is limited by a distance of more than two cells. That type of development is spread out and affects smaller clusters of existing UVCZ. These representations show the different effects of neighborhood potential. This particular example illustrates only one UVCZ class and its influence on itself. Although the UVCZ scheme contains 24 classes, the Greater Hamburg case study has a total of only 21 different UVCZ: 12 of them are functions have must be modeled; 5 are natural UVCZ (vacant) and the rest of the 4 classes are unchanged (features). All 21 UVCZ classes have influence on the 12 function classes, which Metronamica must model. This gives, in total, 144 neighborhood potential variables which must be considered and adjusted in order to calibrate the model. The calibration of the neighborhood potential, therefore, is the most time consuming step, although there are other factors in Metronamica that are necessary as well.

Accessibility

Accessibility in Metronamica represents a function of proximity to certain spatial elements. One of the good examples is the transportation network and its infrastructure. The certain segments of the infrastructure have a different attractiveness to a specific UVCZ. For instance, the area closer to the highway has a higher potential for commercial than the residential area. Residents may be annoyed by the noise of the cars, while the business would like to be closer to the main roads, to lower their transportation costs and save time.

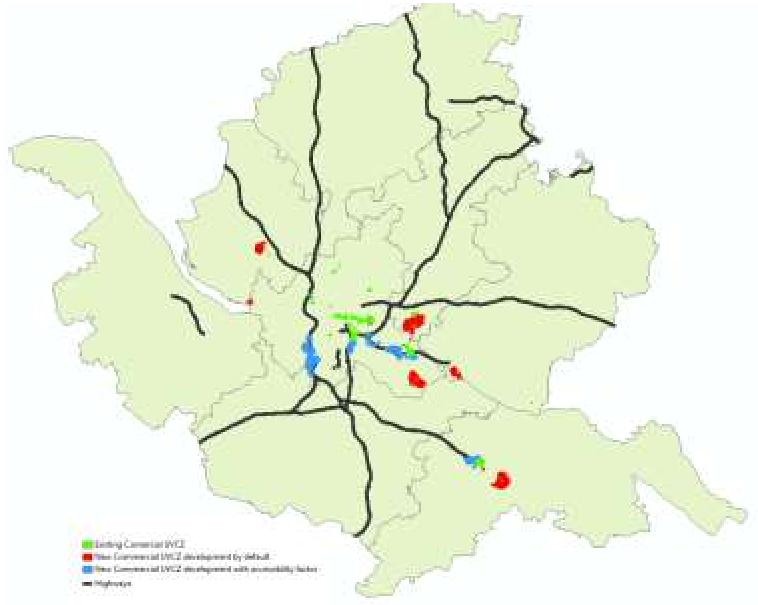


Figure 106: highways and the commercial UVCZ (green – existing, red – no affect of accessibility, blue – with affect of accessibility.

Figure 106 shows the effect of accessibility on new commercial UVCZ development. The red zones show the development ignoring the accessibility factor and blue shows the development where rules of accessibility were applied. In this case the areas within 3 cells close to highways had the highest potential for new commercial UVCZ. If there would be two equal areas with the same neighborhood potential and other factors, the area closer to highways or any other accessibility layer would have priority and would be occupied. Moreover, the accessibility can be represented not only by the transportation network, but by city centers, sub-centers or any other point locations which would be attractive to the certain UVCZ. Such ability to use the proximity function in the modeling helps to represent a more realistic development of the city.

Randomness coefficient

Even strictly planned urban development does not always follow the plan. There is always some unpredictable actions or consequences which can be described as randomness. The randomness in Metronamica is presented as a random coefficient (or alpha parameter). This parameter controls the stochastic perturbation effect and simulates any unpredictable occurrences. In Metronamica the randomness brings the urban development pattern closer to reality and has a range from 0 to 1 where 0 means no and 1 means a very high randomness.

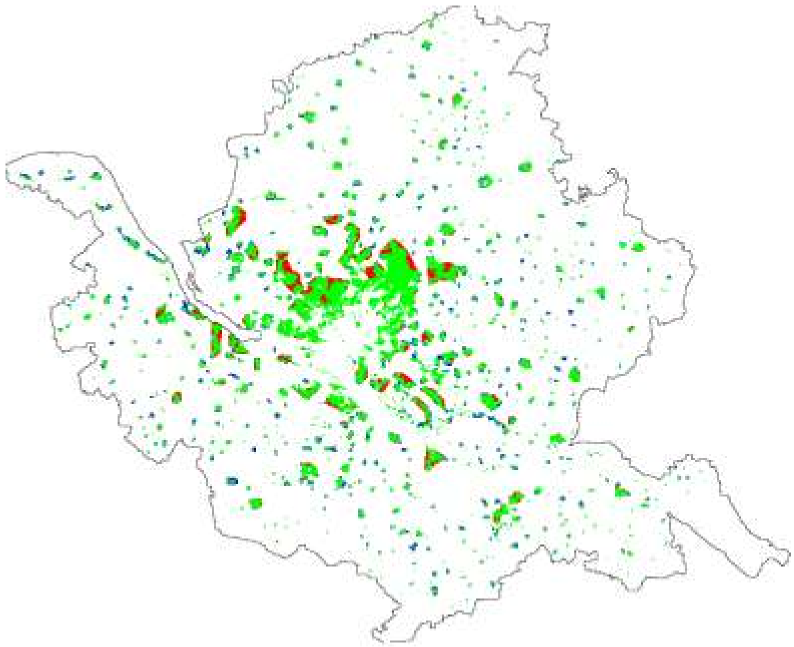


Figure 107: new development of dense open low rise with very high (blue color, alpha = 1) and no randomness (red color, alpha = 0).

As we observe in figure 107, if there is no randomness and the new development would strictly follow the neighborhood potential rules and would systematically occur around the higher concentrations of existing UVCZ. However, a high degree of randomness would distribute any new development around all existing areas in no particular pattern, with the lower influence from the neighborhood potential and other factors. By default the randomness coefficient (alpha) is set to 0,5. The common variation of the coefficient is within the range 0,3 – 0,7 (RIKS, 2013). For this study, I selected the default value of randomness coefficient – 0,5.

Zoning and suitability

Metronamica's model also contains two other variables. One of them is zoning. Zoning describes institutional suitability. It imposes spatial restrictions or active stimulation on the allocation of the new land. In other words the model can restrict or actively stimulate new development in a certain area. Another factor, which is not considered in this case study, is the physical suitability, or suitability. Suitability defines a degree to which the particular UVCZ cell can overcome the other UVCZ. For instance, a residential UVCZ cannot be built on a higher slope, but that is not necessarily the case for agriculture. The other characteristics of suitability could include soil type, altitude, wetness index and many other physical factors (RIKS, 2013).

Calibration assessment methods

It is very important to assess the quality of calibration. If the calibration is fine, it is appropriate to run the model further and generate future datasets. Metronamica has two methods that can be used to assess the quality of the calibration: visual and statistical. The visual method covers maps and graphs which show the spatial distribution of differences, produced using calibrated model. Because of the different visual interpretations, this method is quite subjective. However, it helps to identify the differences spatially. The second method is based on statistics. Statistics gives numbers, which can be easily compared. But statistics taken into account the entire area, and the spatial distribution of differences cannot be identified in this method. Although the statistical method gives better overall results of calibration, the specific areas, issues or anomalies can be observed only via the visual method. It is therefore recommended that both methods be used.

Visual

The visual calibration's assessment in Metronamica is done via a Map Comparison Kit (MCK). This tool is developed by the producers of Metronamica, the RIKS company. The visual assessment is done simply by combining the two grids of raster. In order to assess the quality of the calibration, one of the raster dataset has to be an actual data and another one is the modeled data. The MCK contains a number of algorithms for visual assessment. The essential ones are: per category", kappa and fuzzy kappa. The kappa comparison shows the differences between all cells, the fuzzy kappa shows the same difference, but uses the similarity matrix (see below), while the comparison per category shows the difference using only a specific category (in our case between a certain UVCZ). Moreover, the MCK has specific algorithms which calculate size of the patches, the clumpiness index and rank size. Based on the needs of the application, the selected algorithms can be applied. If results show the good correlation, the further steps can be taken. However, if the differences are not acceptable, it would be necessary to re-adjust parameters, run the model again and observe the changes. This would be repeated till the desired, or acceptable outcome, is reached.

Statistical

The MCK is able to produce not only the visual but also the statistical analysis. The statistical measures are the kappa, kappa simulation, fuzzy kappa and fuzzy kappa simulation. The coefficient k (kappa) was introduced by Cohen in 1960, and is also known as Cohen's kappa. Kappa measures the degree of agreement between two values (in this case – UVCZ datasets). It is a proportion of expected disagreements which do not occur. Mathematically it is expressed as:

$$K = \frac{p_0 - p_c}{1 - p_c} \tag{9}$$

p_0 is a proportion of units in which the judges agreed and p_c is a proportion of units for which the agreement is expected by chance. The negative values of kappa show less than chance of agreement. When kappa = 0, then the obtained agreement equals a chance of agreement. If kappa > 0, then the chance of agreement is greater. When the kappa = 1, it means the perfect agreement between the judges (Jacob Cohen, 1960). In a spatial context, the kappa shows agreement or disagreement between two datasets on a cell basis. Therefore, kappa analysis is common among the land use changes' comparison studies. However, the disadvantage of kappa is a lack of transition rules. This is where fuzzy kappa comes to the help.

The fuzzy kappa is the extension of kappa statistics. It uses the fuzzy set theory to identify the agreement or disagreement between two values. In addition to the standard kappa, it applies the fuzziness to the categories which are similar to each other. Fuzzy kappa is parameterized by the distance decay function between the cells and the similarity matrix between land classes (categories) (Hagen, 2003). The fuzzy kappa is much more appreciated where the changes of similar classes occur. An example of this might be in a ten cell comparison of a forest in which there is change from a coniferous to broad leaf forest within seven cells and the rest of the three cells are coniferous forest. The standard kappa would show a high disagreement. But if the type of forest does not matter, then the fuzziness can be applied to all types of forest cells, and the fuzzy kappa would show a very high agreement between two datasets.

The kappa simulation is another advancement of standard kappa. The standard kappa measures the agreement between datasets in all cells and probability of occurrence is equal to all cells. Meanwhile the kappa simulation considers probability of occurrence only to the cells which differ from initial map (van Vliet et al., 2013). The standard kappa usually shows good value, because there is a high agreement between most of the cells, no matter how different the changes were. On the other hand, the kappa simulation identifies the agreement between the actual changes which might not be as rewarding or useful, but would be much more accurate.

The fuzzy kappa simulation – it is a combination of fuzzy kappa and kappa simulation. It is based on land use transitions rather than land use classes for all cells and the fuzzy interpretation of land transitions enables us to identify a predictive capacity (van Vliet et al., 2013). Unfortunately, due to the technical MCK limitation, the fuzzy kappa simulation cannot be measured per category. It is measured for the whole area. Although the fuzzy kappa is an appropriate technique, the fuzzy kappa simulation is much more advanced and appreciated in order to deliver higher accuracy calibration results.

Similarity matrix

The similarity matrix presents the similarity between two specific UVCZ classes. It is used to contribute to the fuzziness set of rules and is useful when the properties between different UVCZ are quite similar. For instance, the harbor area contains warehouses and storage facilities but these could also be located in commercial areas. Another example would be the difference between the terraced open mid-rise and the perimeter open mid-rise, when considered primarily by the buildings' orientation. This is helpful when it doesn't make much difference if it's a harbor or a commercial area of a dense open low-rise or an open low-rise. Using the similarity matrix for these kinds of difference is very acceptable. This allows us to put our efforts toward the more serious differences in the study.

The similarity matrix is used in MCK in both a visual and statistical assessment for fuzzy kappa and fuzzy kappa simulation. Before doing the fuzzy kappa assessment, the similarity values should be defined for each UVCZ in a ration of 1 to N. "N" is the number of UVCZ to which a specific UVCZ is similar. The establishment of a similarity matrix for fuzzy kappa simulation is more complicated, due to its ability to consider the differences between the actual changes (transitions) of UVCZ and not all of the cells, as the standard kappa and fuzzy kappa do. The number of similarity values in fuzzy kappa simulation matrix is N^2. If the initial scenario contains many classes, this can be very time consuming. The size of the matrix is another reason I have not included it in this thesis. I have included the fuzzy kappa similarity matrix for similar function UVCZ (the potential housing, the harbor and commercial) below in table 7.

Table 7: similarity matrix of potential housing UVCZ for fuzzy kappa calculation.

	Compact mid rise	Dense compact mid rise	Terraced open mid rise	Perimeter open mid rise	Dense open low rise	Open low rise
Compact mid rise	1	0,5	0,3	0,3	0	0
Dense compact mid rise	0,5	1	0,3	0,3	0	0
Terraced open mid rise	0,3	0,3	1	0,5	0,2	0,2
Perimeter open mid rise	0,3	0,3	0,5	1	0,2	0,2
Dense open low rise	0	0	0,2	0,2	1	0,5
Open low rise	0	0	0,2	0,2	0,5	1

Table 8: similarity matrix of commercial and harbor UVCZ for fuzzy kappa calculation

	Harbor	Commercial
Harbor	1	0,3
Commercial	0,3	1

The tables 7 and 8 show the actual values of the fuzzy kappa similarity matrix. Values of 1 show highest similarity, while the values of 0 show the lowest similarity. In MCK the matrix is uploaded as a text file and there is no need to input the values each time a comparison analysis is run.

Calibration assessment results

The visual and statistical results of calibration assessment are presented for two time frames and by the most common UVCZ changes by category (class). I do not believe it is necessary to present results for all the classes, but I decided to present the three classes with the most changes. The MCK map with changes between actual and modeled datasets for each three UVCZ show a spatial mismatch and the statistics gives a great overview of the total disagreement in the whole study area. Moreover, the general map and statistics summarize the calibration assessment for all UVCZ classes. However, due to the large amount of UVCZ, the neighborhood potential and accessibility values, maps and graphs are not included in the results.

Time frame 1960 – 1990

Table 9 shows a significant new urban development between 1960 and 1990. This is seen from the changes between agricultural areas and the rise in dense open low rise UVCZ. Coming in second place was the terraced open mid-rise and in third place was the new development of commercial areas.

Table 9: most common UVCZ changes in 1960 - 1990

From	To	Number of cells
Agriculture	Dense open low rise	4764
Agriculture	Terraced open mid rise	766
Agriculture	Commercial	154

In the three most common UVCZ changes, the dense open low rise took the lead, with more than six times more cells than the terraced open mid-rise, which was five times higher than commercial development. It must be remembered, however, that this happened over the course of three decades. Averaging these statistics over a decade, the change would be lower: 1588 cells for dense open low rise, 225 cells for terraced open mid-rise and only 51 cells for commercial, per decade. The change of 51 cells is slightly more than twice the amount I considered to be an important UVCZ change. The actual minimal number of changes was 20 cells. In this research, any UVCZ change with a lower amount of 20 cells between two time periods was not reflected.

Dense open low rise

The dense open low rise is single dwelling housing and the most common potential housing UVCZ in Greater Hamburg. The average annual spread (considering 1960 – 1990 statistics) is 159 cells which is about 994 ha.

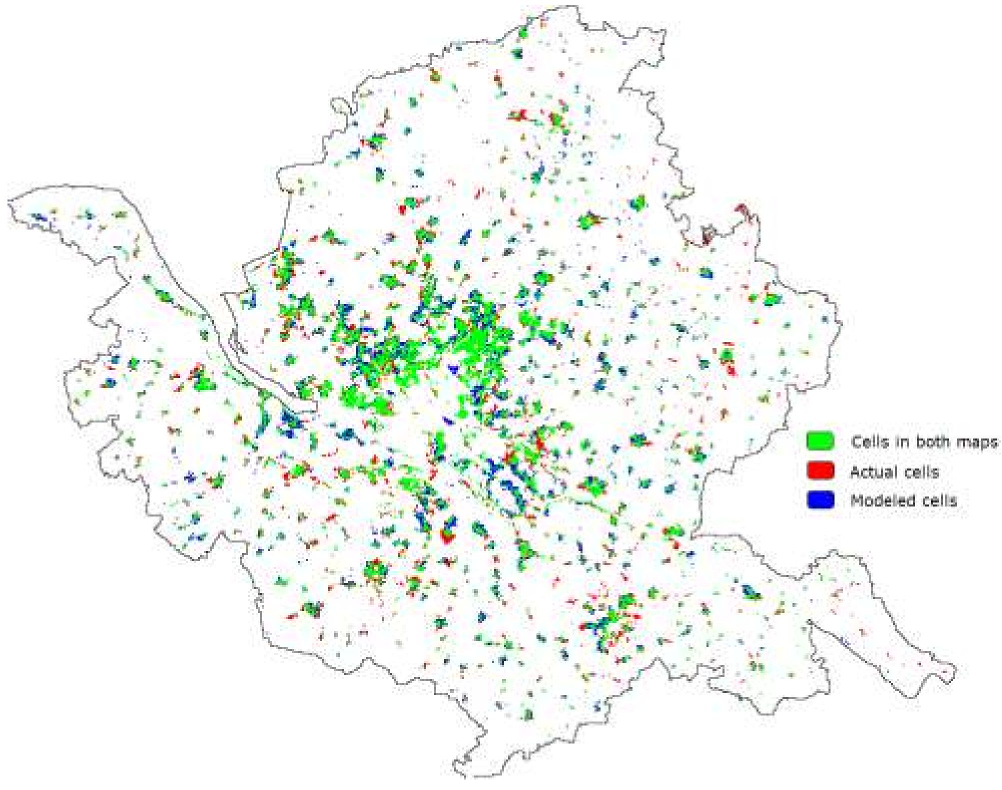


Figure 108: comparison of dense open low rise development between the actual and modeled data for 1960 – 1990.

Figure 108 presents the modeled and actual cells of dense open low rise UVCZ. As can be seen, the new development was more common in the surrounding districts than in the center of Hamburg city-state. The new development occurred in two ways: as small isolated clusters and as big clusters, adjacent to the existing dense open low rise UVCZ. The model represents both trends with some overestimation of a greater amount of new development within the Hamburg city-state area and with underestimation within the surrounding districts. It is noticeable that some bigger isolated clusters of actual development in the north and south are not represented correctly. However, these are only a few cases and in general the pattern of actual and modeled data looks quite similar.

Table 10: kappa statistics of dense open low rise and all UVCZ in 1960 – 1990.

Statistics type	Dense open low rise	All UVCZ
Kappa	0,684	0,867
Fuzzy kappa	0,818	0,916
Kappa simulation	0,256	0,306
Fuzzy kappa simulation	-	0,469

The statistical table (table 10) shows a lower disagreement between actual and modeled data for dense open low rise than all UVCZ, although the kappa and the fuzzy kappa values are fine. It means that, overall, the dense open low rise UVCZ was represented slightly worse than all of the UVCZ. Again, it must be remembered that kappa and fuzzy kappa represents the agreement between all cells within the study area and the simulation shows the agreement between the cells which actually have changed. According to RIKS (2013), the kappa simulation values between 0,2 – 0,4 is very good. Summarizing the good statistical values and good spatial match of the development trend, the calibration for the dense open low rise for time period of 1960 – 1990 is fine and accepted.

Terraced open mid rise

The Terraced open mid rise is a mid rise, average density housing UVCZ. It is the most common mid rise UVCZ in the Greater Hamburg. It is an open arrangement of 3 – 9 story buildings surrounded by vegetation. The houses are built irregularly as rows, usually clustered. The average annual spread (1960 – 1990 statistics) is 26 cells which is about 162 ha.

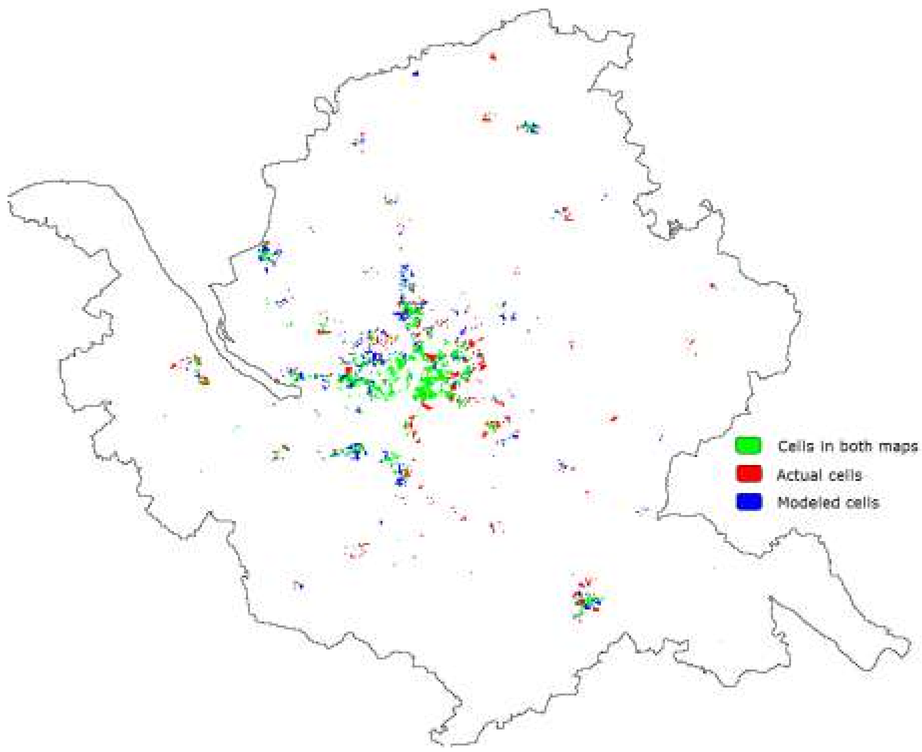


Figure 109: comparison of terraced open mid rise development between the actual and modeled data for 1960 – 1990.

In comparison to dense open low rise, the terraced open mid rise is much more localized (figure 109), but more dispersed within the clusters and there are large gaps between isolated cells. Most of the actual expansion occurred in the east and south east of Hamburg's suburbs, with some bigger isolated clusters around the towns in the adjacent districts having a higher concentration of population. The terraced open mid rise is well represented in the model. This can be seen especially well in the surrounding districts, with the exception of the overestimation in the South of Hamburg, which is the residential area of Harburg. However, the Southeastern (Lüneburg), Southernwestern (Stade) and Northeastern areas look fine. The model also overestimates the new development in the West, Northwest and North. Actual development occurred mostly in the East and Southeast, as well in North and Northwest. Visually, the modeled pattern matches the actual pattern quite well.

Table 11: kappa statistics of terraced open mid rise and all UVCZ in 1960 – 1990.

Statistics type	Terraced open mid rise	All UVCZ
Kappa	0,630	0,867
Fuzzy kappa	0,798	0,916
Kappa simulation	0,258	0,306
Fuzzy kappa simulation	-	0,469

The kappa statistics (table 11) shows good values of the terraced open mid rise. They are slightly lower than values of the dense open low rise. Considering that the new development of terraced open mid rise was almost six times lower than the development of dense open low rise, the results are quite good. The kappa simulation, however, value is lower in terraced open mid rise's case. It means that this UVCZ has a better representation in this model. Finally, the spatial comparison shows a good agreement between the actual and modeled data.

Commercial

The last, but not least, area is the commercial UVCZ. The growth of UVCZ is affected more by economical development than by growth in population. While the two previous UVCZ are areas used for housing people, the commercial UVCZ is used for business and work, the storage of goods, housing for various types of services and offices. Business skyscrapers and high rise commercial and office buildings are not considered as part of the commercial UVCZ. Instead, the Commercial UVCZ is a low rise zone with large, but not necessarily tall, buildings a large percentage of paved surfaces and limited vegetation around them. Such buildings can also be found in harbor, industrial parks and airport areas. The dominating building materials are steel, concrete and metal. Alignment is open and regular, often adjacent to the street with large open streets to accommodate trucks, equipment and materials. The average annual commercial expansion between 1960 and 1990 is 5 cells, which is slightly higher than 30 ha, about one large commercial park per year, on an average.

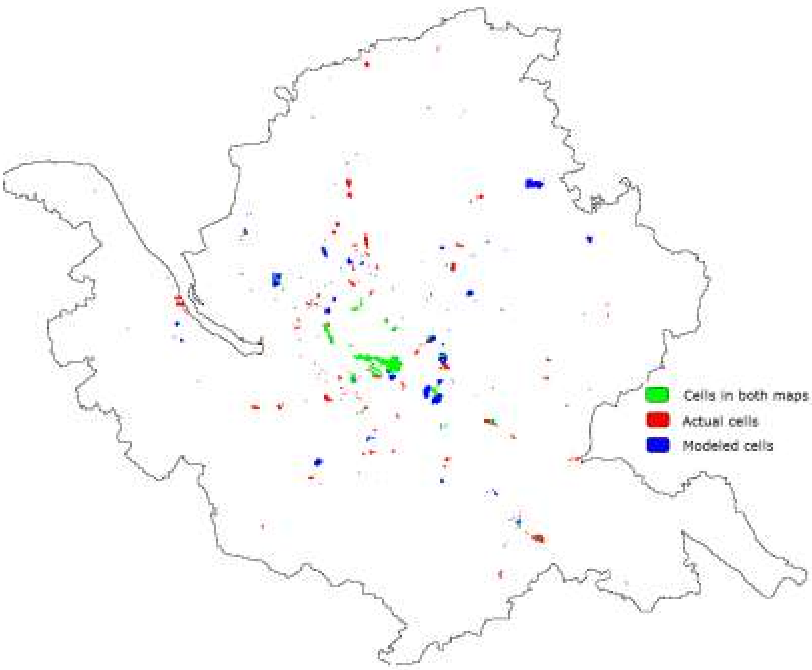


Figure 110: comparison of commercial development between actual and modeled data for 1960 – 1990.

It is more difficult to represent the commercial than the other two UVCZ in the model (figure 110) because the actual new development occurs randomly, as isolated larger clusters, located at a distance from already existing commercial zones. It's also difficult to find any systematic commercial areas in relation to other UVCZ. While it's known that new development occurs close to main roads and not necessarily far from the dense open low-rise and terraced open low-rise UVCZ, what is not obvious is the relationship between actual new commercial development and highways. The new commercial development has occurred mainly within the Hamburg city-state area, especially in the North and Southwest of Hamburg, and some of the neighboring districts. This development has usually been in clusters that are large and grouped together, rather than in isolation. The model overestimated the new development in

Eastern Hamburg, closer to the already existing commercial areas. Although this visual mismatch between the isolated clusters is significant, the pattern of commercial UVCZ looks correct. In many cases I see commercial areas being encouraged by special urban zoning plans, not by neighborhood functions or accessibility. If these plans are taken out of the model, it would have difficulties showing the actual outcome. I still contend that the calibration for commercial is acceptable because the modeled pattern is similar enough to the modeled trend.

Table 12: kappa statistics of commercial and all UVCZ in 1960 – 1990.

Statistics type	Commercial	All UVCZ
Kappa	0,448	0,867
Fuzzy kappa	0,562	0,916
Kappa simulation	0,232	0,306
Fuzzy kappa simulation	-	0,469

While the kappa and fuzzy kappa values are worse than above analyzed residential UVCZ, the kappa simulation is only slightly lower. Taking into account that there was much less development of commercial UVCZ, the calibration quality is quite good. This gives good credits to the commercial UVCZ's representation in the model.

Kappa statistics for all UVCZ 1960 – 1990

The following maps show the kappa statistics for all UVCZ. It shows the spatial disagreements between modeled and actual data.

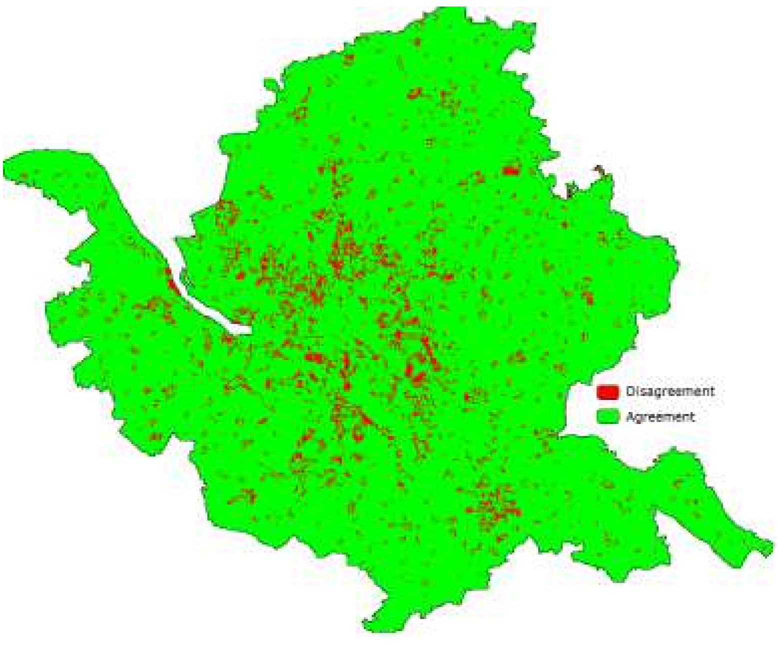


Figure 111: kappa of all UVCZ between actual and modeled data for 1960 – 1990 time period.

Figure 111 shows Boolean comparison between actual and modeled data for 1960 – 1990. The red color shows disagreement between the cells. The higher disagreement can be noticed around the suburbs of Hamburg city-state and the larger towns within the surrounding districts, as well as some clusters around. The kappa value for all UVCZ is 0,876 which mean a very good agreement.

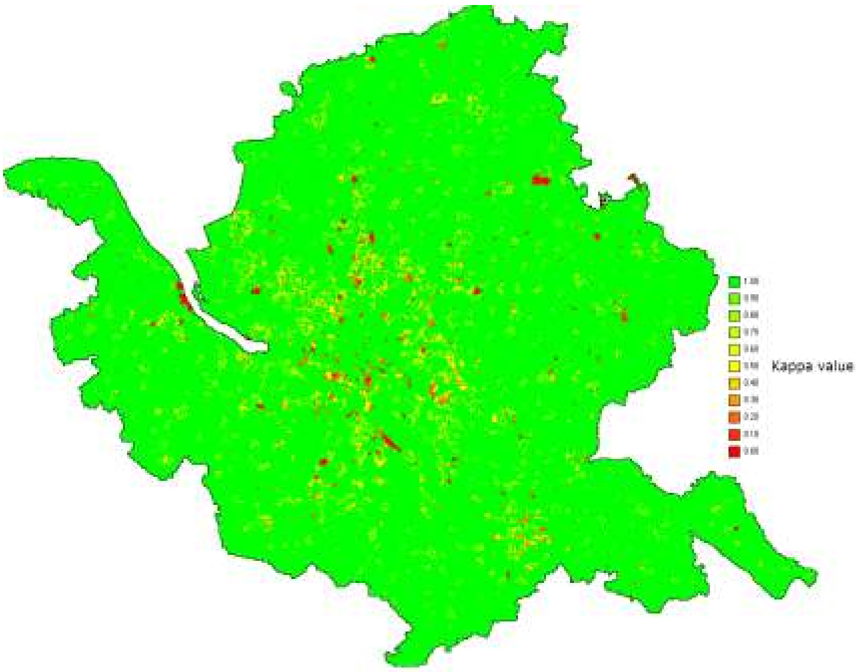


Figure 112: fuzzy kappa of all UVCZ between actual and modeled data for 1960 – 1990 time period using the similarity matrix.

The fuzzy kappa shows more positive results (figure 112) than the kappa. Based on kappa range, the red and orange values mean a lower disagreement. If comparing this map with the modeled commercial UVCZ (figure 110), you will notice that the blue clusters in figure 112 match with isolated red clusters in figure 110. In addition, the disagreements between road and rail infrastructure, bare rock or paved and airport's UVCZ can explain another reason for many low fuzzy kappa values. Unfortunately, the calibration results of such UVCZ as road and rail infrastructure, bare rock or paved, airports and other UVCZ classes are not presented in the results, because these classes are features which, as assumed, should not change over time.

The fuzzy kappa for all UVCZ and whole area is 0,916 which is a very good agreement between the actual and modeled data. The visualization and statistical value of the fuzzy kappa shows good results, therefore the model represents the historical 1960 – 1990 pattern quite well.

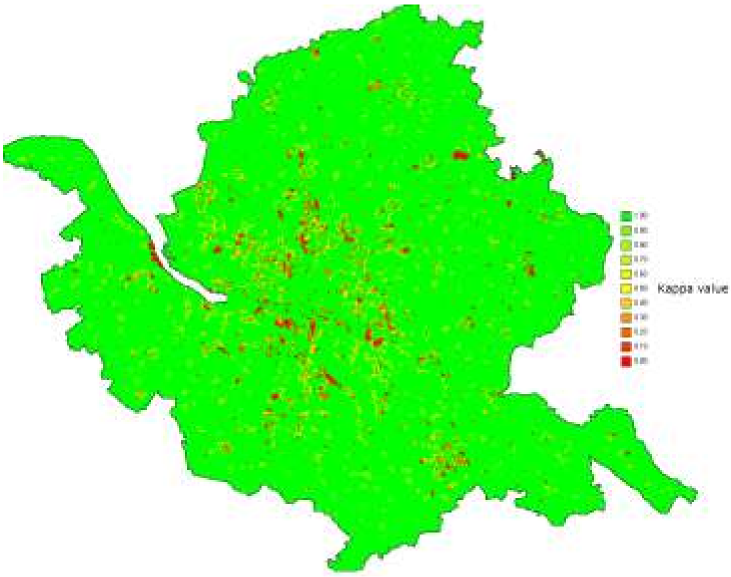


Figure 113: fuzzy kappa simulation of all UVCZ between actual and modeled land transition data for 1960 – 1990 time period using the fuzzy set.

Short reminder - the fuzzy kappa simulation is the measurement method between the fuzzy kappa and kappa simulation. Fuzzy kappa simulation is based on the land use transitions for all cells using the fuzzy set rules (similarity matrix). The spatial representation (figure 113) would be much more accurate if land which has not been affected by the changes, would be masked out. Only the fuzzy, the actual and modeled cells should be visualized for a better assessment. However, in comparison to the fuzzy kappa (figure 112), the fuzzy kappa simulation shows lower disagreement. But that is not surprising. According the RIKS calibration course (RIKS, 2013) the fuzzy kappa simulation is much more significant. And its value of 0,469 shows a very good agreement.

Urban cluster analysis

Urban cluster analysis is a specific analysis of MCK which helps to understand and compare the aggregation level of urban areas. In the GH case, I will apply two algorithms (clumpiness index and Zip's law) for the actual and modeled dense open low rise UVCZ, because this class has the most cells in GH.

Clumpiness Index

The clumpiness index shows the degree to which the cells of the same land type are adjacent to each other. Clumpiness is equal to 0 when the land (focal path type), or in GH case, the UVCZ, is totally disaggregated. When the index is equal to 1, then the patch type is maximally aggregated (RIKS, 2008). In other words it shows how compact (aggregated) or spread (disaggregated) UVCZ is from its class.

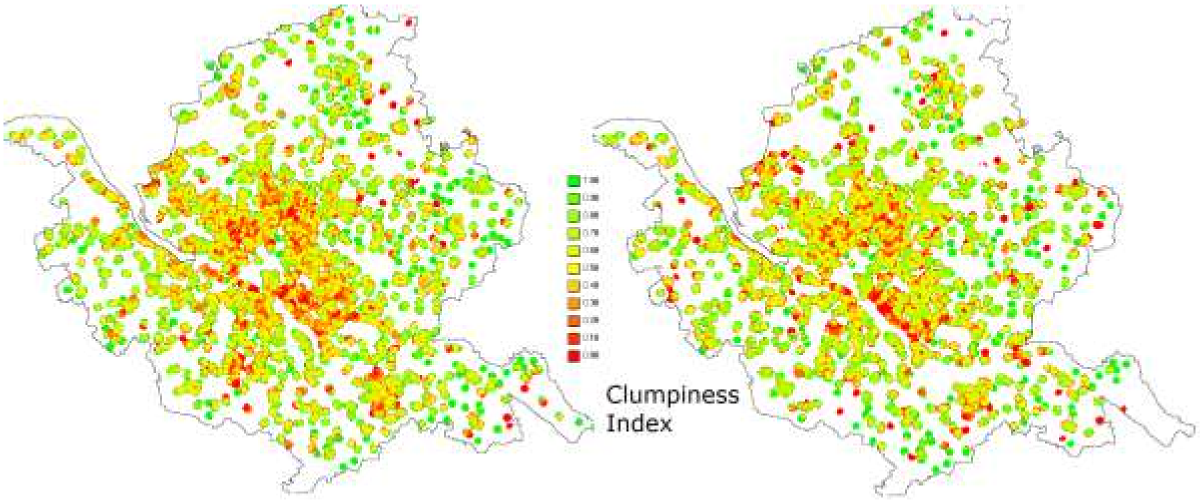


Figure 114: clumpiness index of the dense open low rise between actual (left) and modeled (right) data for 1960 – 1990 time period.

The green color in figure 114 shows the low and red shows the high disaggregation. In both maps, the actual and modeled high concentration of disaggregated cells is in the central part of Hamburg-city state and especially in Southeast and North. This may occur because of the limited area for new development of big dense open low rise clusters. The outskirts and surrounding districts, meanwhile, have more open space which is causes lower disaggregation. Although there are changes between the actual and modeled data, both maps look similar. The actual higher disaggregation is noticeable in south of Hamburg, but in general the trend is fine and acceptable.

Zip's law

Zip's law is an empirical law used for physical and social sciences. It states that the frequency of any word is inversely proportional to its rank in the frequency table (Zipf, 1949). The similar distribution of ranks by the size of the cities was noticed by Felix Auerbach (1913). In geography, Zipf's law for cities is an important concept which is valid in most countries. For most of the countries this law is valid. It means that the number of cities with populations greater than n is proportional to 1/n (Gabaix, 1999).

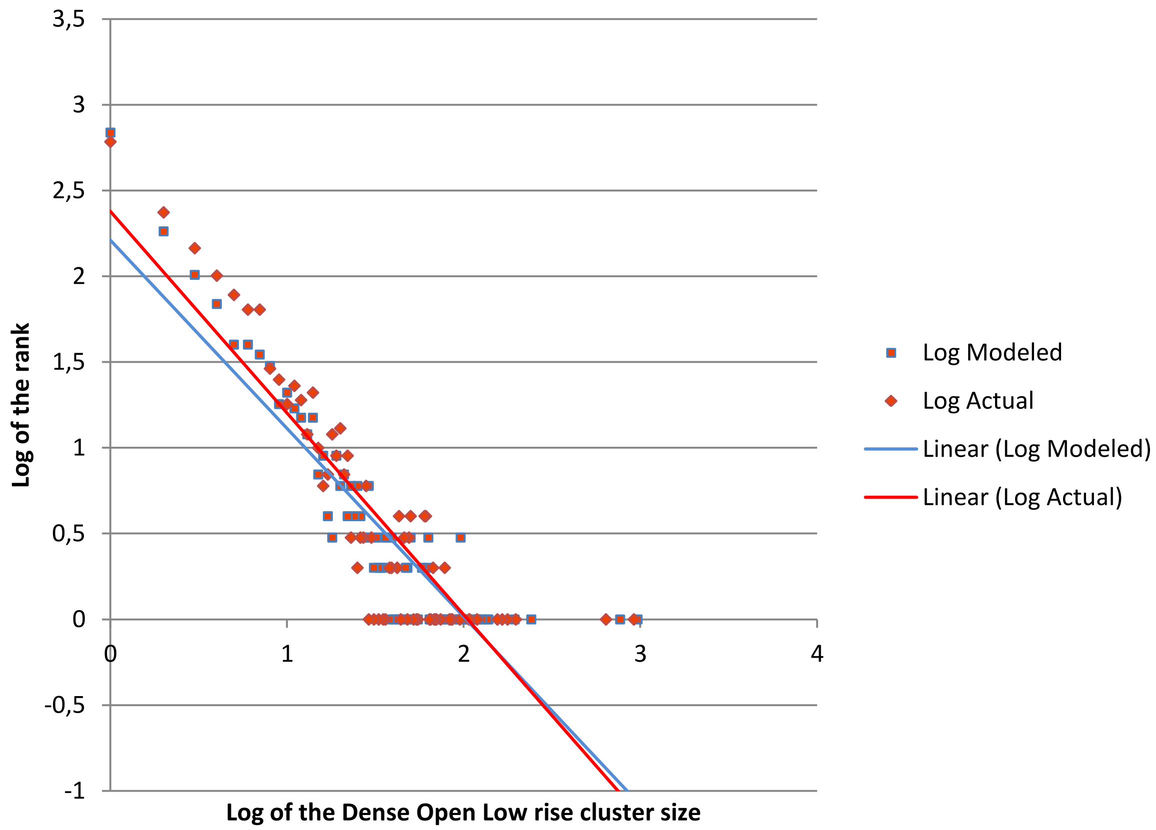


Figure 115: logaritmic rank and the size of the actual and modeled dense open low rise for 1990.

In order to verify the application of Zipf's law for the Greater Hamburg case study, I analyzed the cluster size and rank of the most common dense open low rise UVCZ. In total there were 609 actual and 689 modeled one cell size clusters (lonely cells) with the biggest cluster having 918 (actual) and 963 (modeled) cells. Figure 115 shows the logarithmic rank versus cluster size. It seems that the linear functions of the modeled and actual clusters show a good correlation. From 0 to 1 as a cluster size, the modeled data contained less small size clusters than the actual data, which caused a slight diversion in the linear function. In general, however, the trend seems fine, and both the actual and modeled data follow Zipf's law quite well.

Time frame 1990 – 2000

The UVCZ changes are somewhat similar when compared to 1960-1990. The most common UVCZ changes are the dense open low rise and commercial UVCZ (table 13). The dense open low rise leads with 896 cells during a decade and an average 90 cells per year (during 1960 – 1990 it was the 1588 cells in a decade and about 159 cells annually). This shows quite a significant decrease, almost 50% in 1990 – 2000. Commercial UVCZ takes second place this time, with 159 cells. The amount of changed cells was six time lower than dense open low rise, but almost the same amount of changed commercial cells in 1960 - 1990 (154 cells). I find this fact to be surprising, in that it shows commercial expansion to be three times higher during the period between 1960 and 1990. These numbers reflect only the conversion from agriculture, and not from other UVCZ.

Table 13: most common UVCZ changes in 1990 – 2000.

From	To	Number of cells
Agriculture	Dense Open Low rise	896
Agriculture	Commercial	159
Agriculture	Urban park (dense trees)	148

The third the most common UVCZ change was the development of urban park with dense trees (In 2011 Hamburg was named the European Green Capital). The development of urban park was slightly lower than commercial and considered about 148 cells (about 928 ha) while during the period of 1960 – 1990 the increase was only 6 cells (38 ha).

Dense open low rise

In total, counting the entire time period, the new development of dense open low rise during 1990 – 2000 is more than five times lower than in 1960 - 1990. The trend between 1990 and 2000 is different than was in previous years. This time there was less new development within the Hamburg city-state area, but more in the surrounding districts. This is seen especially in the Southeast area (Lüneburg). However, some of the new development occurred as isolated clusters, but there were much fewer of them, compared to 1960 – 1990. The common development trend of dense open low rise for both time periods was close to already existing dense open low-rise UVCZ as well as main and secondary roads. According to the spatial disagreement, seen in figure 116, the model overestimates the dense open low rise in the north and north west part of Hamburg and somewhat less in the South. The actual development was more common in the far Southeast (Lüneburg), far North and far West. Although the pattern seems correct, the clusters are concentrated in different locations, which might be caused by other factors, not by the neighborhood potential or transportation infrastructure.

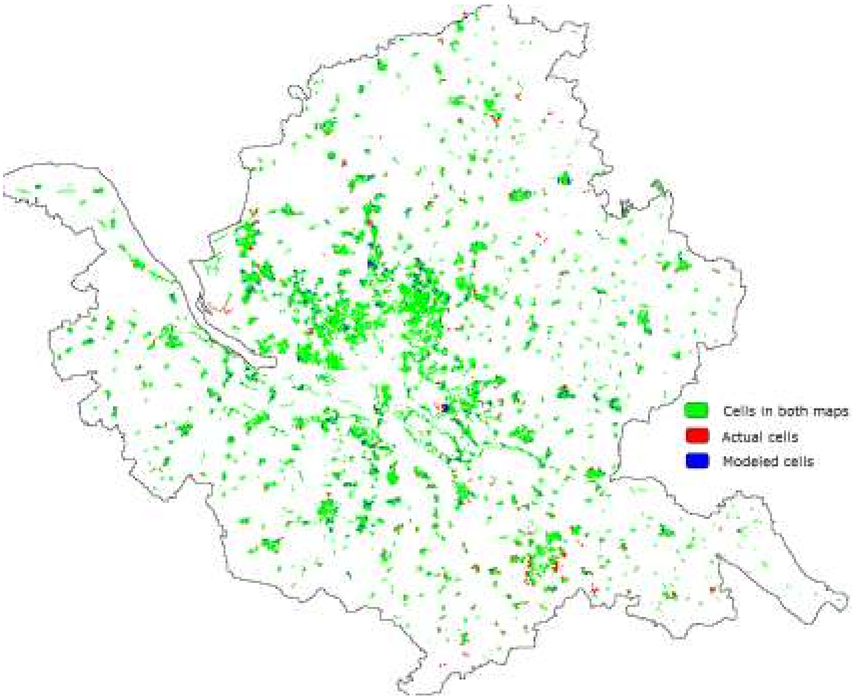


Figure 116: comparison of dense open low rise development between actual and modeled data for 1990 - 2000 time period.

The kappa statistics shows quite good results in both kappa and fuzzy kappa (table 14) with the values for the time period between 1960 and 1990 being even better (kappa=0,684, and fuzzy kappa =0.818). As was mentioned earlier, both parameters take into account all the cells. This results in the consideration that the fewer the general changes in UVCZ (which is obvious between 1990 and 2000), the higher the values for kappa and even greater value for fuzzy kappa.

Table 14: kappa statistics of dense open low rise and all UVCZ in 1990 – 2000.

Statistics type	Dense open low rise	All UVCZ
Kappa	0,921	0,956
Fuzzy kappa	0,960	0,972
Kappa simulation	0,097	0,113
Fuzzy kappa simulation	-	0,313

The kappa simulation gives the best value, with a value of 0,097, which is good. But it isn't as good as it was for the time period of 1960-1990 (0,256). The fact that during the same period there was five times less development occurring gives more randomness and the value is considered fair and acceptable.

Commercial

The development of new commercial UVCZ per decade during 1990 – 2000 was three times higher than during 1960 – 1990, even though the total number of changes is similar. According to figure 117, the pattern of 1990 - 2000 development did not change much.

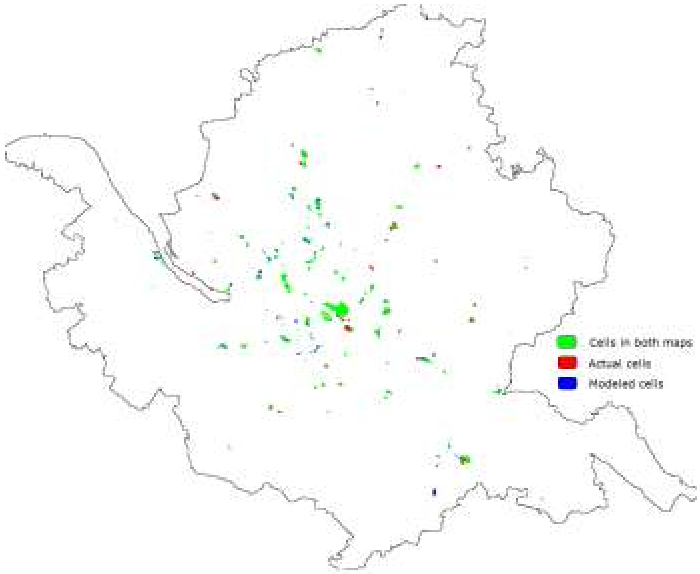


Figure 117: comparison of Commercial development between actual and modeled data for 1990 - 2000 time period.

The higher concentration is noticeable in the Northern part of Hamburg where expansion is close to the existing commercial areas. With the map containing a large portion of green, with less blue and red, we can say that there is a good agreement between actual and modeled data.

Table 15: kappa statistics of Commercial and all UVCZ in 1990 – 2000.

Statistics type	Commercial	All UVCZ
Kappa	0,819	0,956
Fuzzy kappa	0,903	0,972
Kappa simulation	0,254	0,113
Fuzzy kappa simulation	-	0,313

The kappa statistics (table 15) shows quite good results. However, it is still no match to the general kappa. In comparison to the time frame of 1960 – 1990, all the values, especially the fuzzy kappa (it was 0,562), have increased. However, the kappa simulation is slightly better than 1960 – 1990 (it is twice better than the kappa simulation). Meanwhile the fuzzy kappa simulation value of commercial for 1960 – 1990 is 25% lower than the fuzzy kappa simulation for 1960 – 1990. It means that compared to other UVCZ in 1990 – 2000, the commercial UVCZ is represented very well.

Urban park (dense trees)

The last analyzed UVCZ is the urban park with dense trees UVCZ. In comparison to the 1960 – 1990 changes, there was a huge increase of new urban park development between 1990 and 2000. Due to limited space, new developments occurred in the outskirts of the Hamburg city-state and its surrounding districts, rather than in the center. The new development was identified close to the forests, and not far from the dense open low-rise areas. There was no significant relationship found between urban park UVCZ and transportation infrastructure.

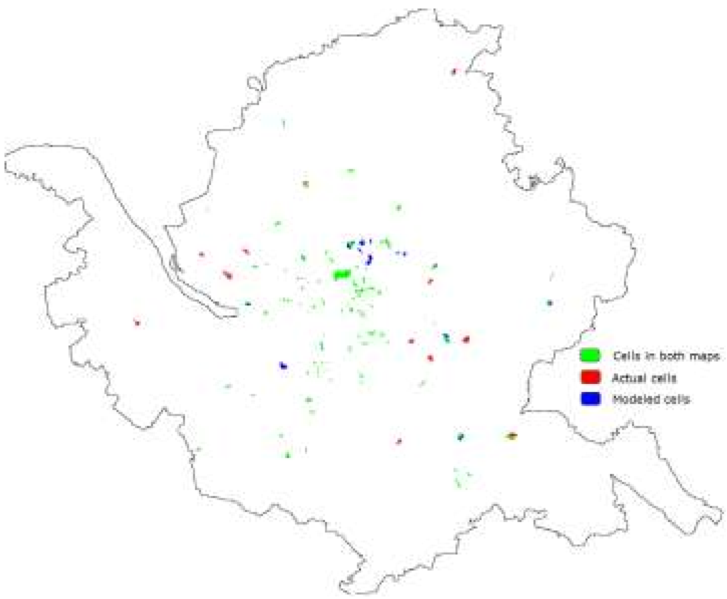


Figure 118: comparison of urban park (dense trees) development between actual and modeled data for 1990 - 2000 time period.

Although the pattern of large isolated clusters and some of the existing urban parks, the modeled urban park cells are significantly different from the actual cells (figure 118). There is a high overestimation to the North of Hamburg city-state, while the actual development occurred in the West and East.

The kappa and fuzzy kappa statistics present good values, while the kappa simulation value is not as good. It is very close to 0 because of the UVCZ random allocation. This shouldn't come as a surprise, because urban parks are a special zone which is heavily controlled by strict urban planning and therefore have no systematic relationship with other UVCZ or the transportation infrastructure.

Table 16: kappa statistics of urban park (dense trees) and all UVCZ in 1990 – 2000.

Statistics type	Urban park (dense trees)	All UVCZ
Kappa	0,773	0,956
Fuzzy kappa	0,810	0,972
Kappa simulation	0,013	0,113
Fuzzy kappa simulation	-	0,313

Although the kappa simulation is low, the pattern seems reasonable, especially because it's similar to the actual pattern. Because the urban park UVCZ is not a residential zone, the low kappa simulation value is also acceptable.

Kappa statistics for all UVCZ 1990 – 2000

The following maps show the kappa statistics for all UVCZ. It shows the spatial disagreements between the modeled and the actual data.

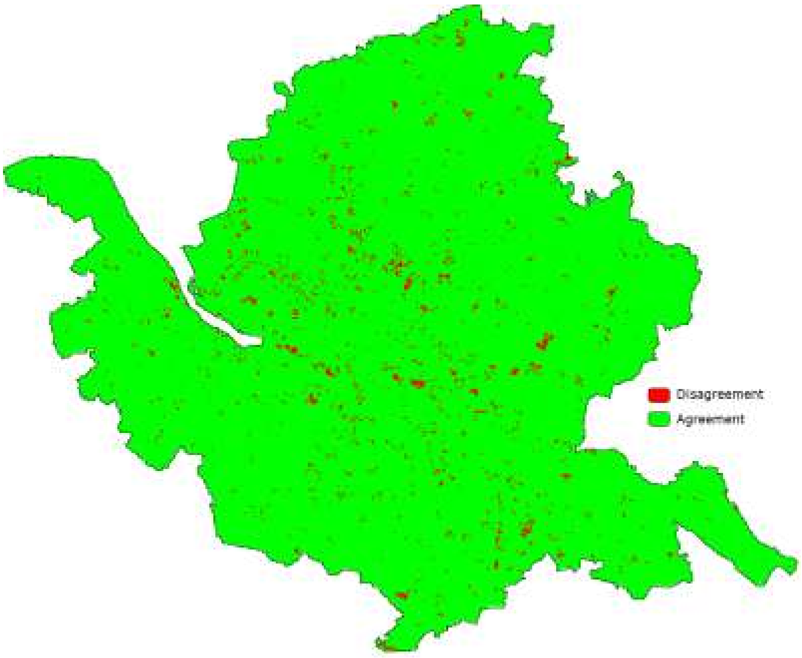


Figure 119: kappa of all UVCZ between actual and modeled data for 1990 – 2000 time period.

Figure 119 shows the agreement (green color) between the actual and modeled cells for 1990 – 2000 UVCZ. In comparison with the 1960 – 1990 UVCZ, there is much less disagreement. This would seem to be natural, because there were significantly fewer changes. The disagreement can be clearly observed more in the Northwest heading toward the Southeastern part of Hamburg city-state, as well as some larger clusters lining from West to East. These are the newly developed commercial areas, or converted for residential use, as well as bare rock or paved area conversion and development of urban parks. The kappa value for the whole map is 0,956. That is a very good agreement, and when compared to 1960-1990, it's even better (0,867 for 1960 – 1990).

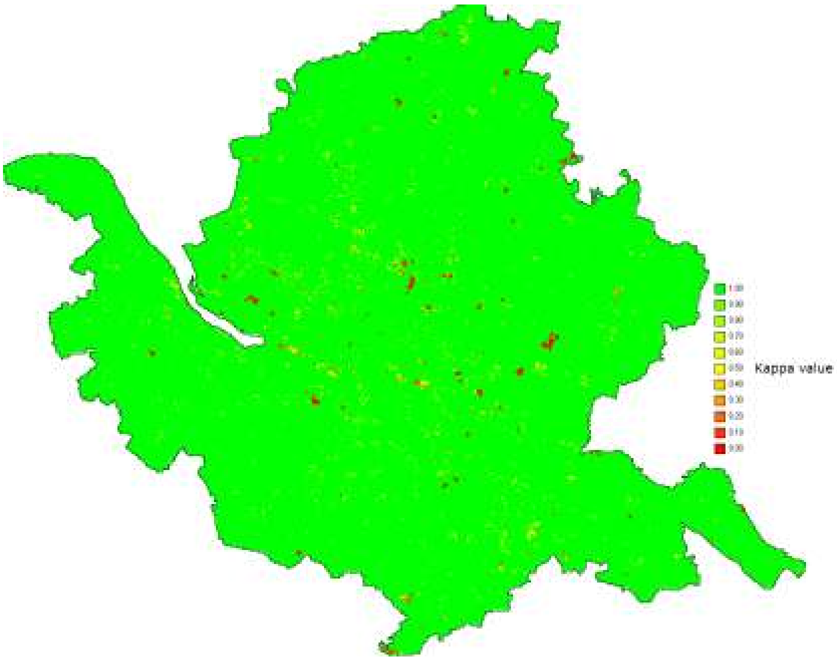


Figure 120: fuzzy kappa of all UVCZ between actual and modeled data for 1990 - 2000 time period using the fuzzy set (similarity matrix).

Figure 120 shows an even better perspective. The low fuzzy kappa values are for the conversion from quarries to agriculture areas and urban parks. In general, the fuzzy kappa visualization shows better results and neutralizes the disagreement with feature UVCZ, the issue for 1960 – 1990 data. The fuzzy kappa for the whole area is 0,972, which is only 0,016 higher than kappa, and therefore does not have a significant impact. The fuzziness can be observed with the limited yellow-orange color (average kappa) cells. Even though there are extreme high and low kappa values, the agreement in general is very good.

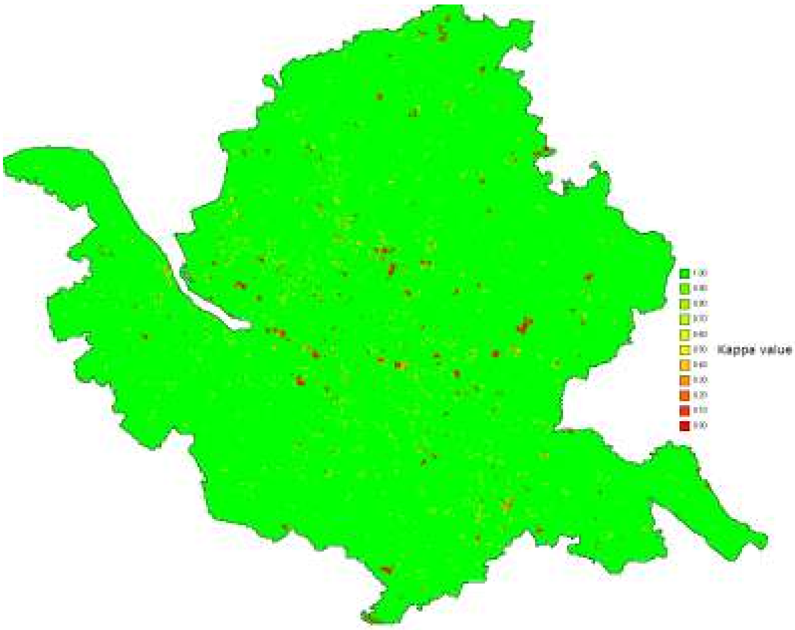


Figure 121: fuzzy kappa simulation of all UVCZ between actual and modeled land transition data for 1990 – 2000 time period using the fuzzy set (similarity matrix).

The fuzzy kappa simulation of 1990 – 2000 (figure 121) shows a higher disagreement than fuzzy kappa. However, it highlights the same issues – more disagreement of bigger clusters orientated from the Northwest to the Southeast and from West to East.. The fuzzy kappa simulation for the whole map is 0,313 which is quite lower than for the 1960 – 1990 time period. Meanwhile the kappa simulation is even three times lower – only 0,113 for the period of 1960-1990 it was 0,306. It is much lower, because, during that period, not as many changes occurred as between 1960 and 1990. Such results show the difference between the methods of the kappa and kappa simulation. However the kappa simulation result is not so bad, as it was with the urban parks, therefore it is adequate. However, the fuzzy kappa simulation showed quite good result – 0,313 which is a quite good value for calibration.

Urban cluster analysis

Urban cluster analysis is important in order to compare the properties of urban clustering. If the urban clustering of modeled data is close to the actual data, then the model is able to represent the correct urban clustering pattern which is important in urban development.

Clumpiness index

Figure 122 shows the clumpiness index of actual and modeled dense open low rise UVCZ for 1990 – 2000. Naturally, because there were fewer changes during a decade, the difference between aggregation levels in both datasets is lower and less noticeable.

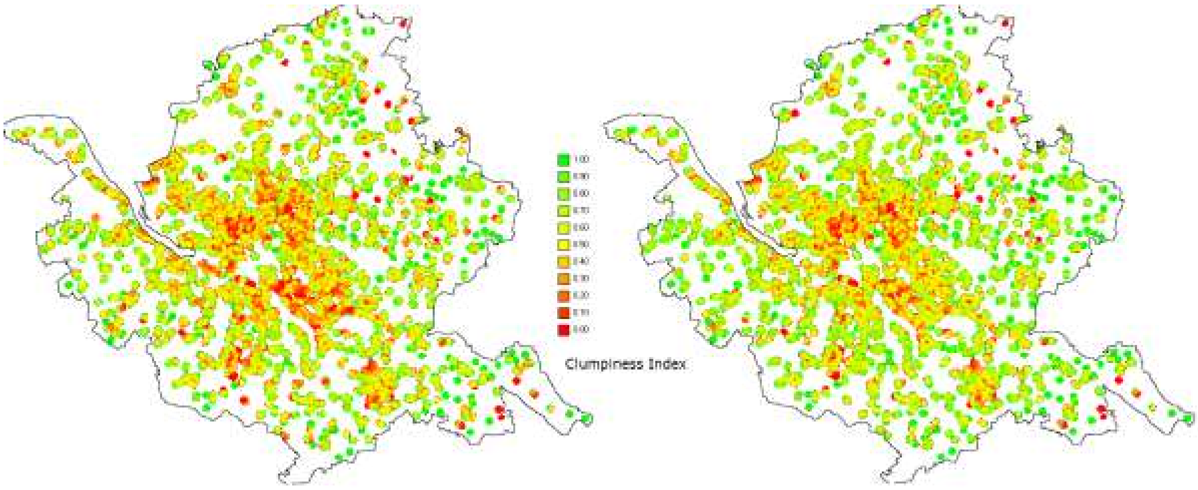


Figure 122: clumpiness index of dense open low rise between actual (left) and modeled (right) data for 1990 – 2000 time period.

However, the actual data seems to be more disaggregated, especially in Southern part of Hamburg city-state and slightly in the North. A similar trend was observed for the 1960 – 1990 time period (figure 114). The higher disaggregation in the center probably was caused by limited open space for new residential areas. There appears to be no major difference in disaggregation between the actual and modeled data.

Zipf's law

The Zipf's law was applied to the actual and modeled UVCZ (2000) as well.

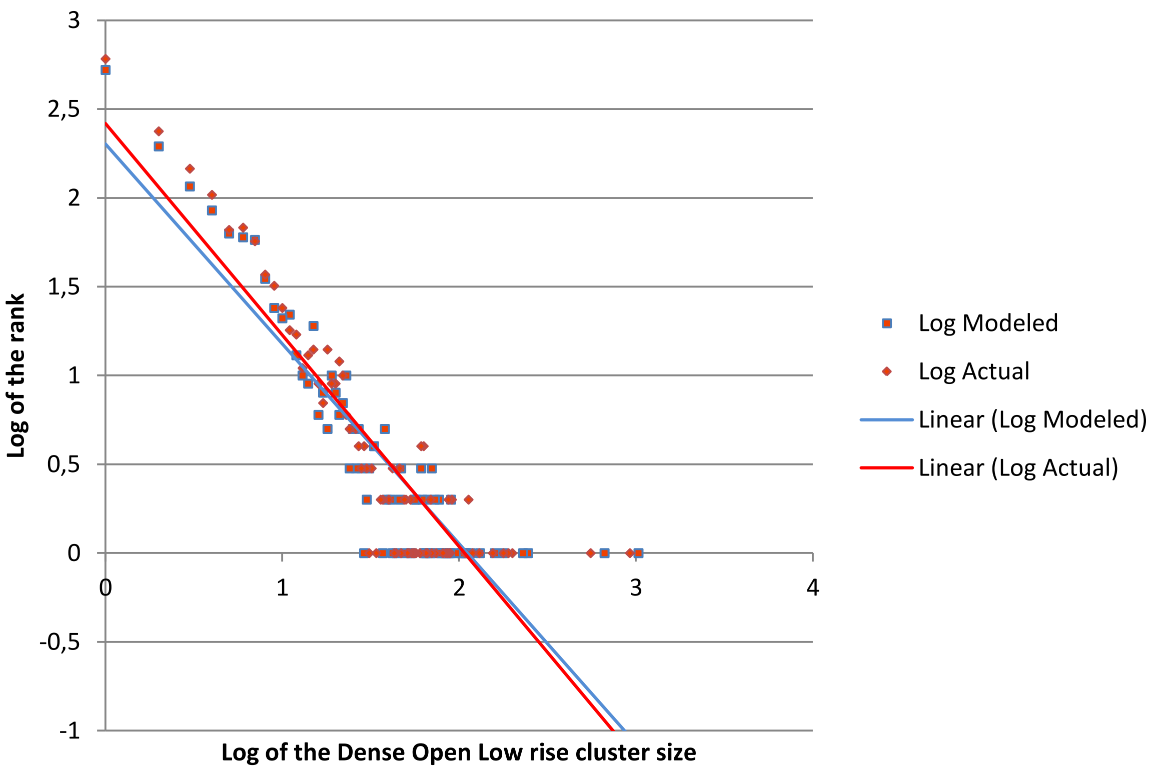


Figure 123: logaritmic rank and the size of the actual and modeled dense open low rise for 2000.

The actual data had 606 one cell clusters, while the modeled data had less, the 525. When compared to the decade between 1990 and 2000, the number of one size clusters decreased by only three clusters, in practicality meaning there was no change. While there was a slight change in the largest cluster (its size increased by six cells from 918 in 1990 to 924 in 2000), the modeled largest cluster increased by much more, namely to 1033. This is seen in the figure 123. The trend of the logarithmic ranking and cluster size seem to be similar, in 1990 between both the actual and modeled data (figure 115), this time with even smaller differences in the amount of small clusters. I confirm, therefore, that Zipf's law can be confidently applied to both the actual and modeled data of UVCZ in 2000. This proves that the calibration and modeling if fine and the urban clustering properties of the urban pattern did not significantly change.

Benchmarking the calibration assessment results

Benchmarking is used to answer the questions concerning the quality of the calibration of this study. It is obvious that the calibration should be a higher quality that the "standard." When looking at the kappa simulation values for certain UVCZ and the entire GH study area, as well as comparing the patterns seen, it can be stated that the quality of the calibration that was obtained is quite good.

According to the Oxford dictionary, (Oxford University Press, 2015), the benchmark means "*a standard or point of reference against which things may be compared*". Establishing a benchmark is the next important step in the process of a model calibration. There is a need, then, to verify how much better a calibrated model might perform over the non-calibrated model. The standard (or non-calibrated) model in Metronamica has a set of initial rules (IR). The initial rules are defined when the new Metronamica project is established. IR represents a default neighborhood potential with no influence from factors such as accessibility and zoning. The standard random coefficient is that alpha equals 0,5. At this point it is important to note that the default neighborhood potential if the IR set in Metronamica is adjust already quite well in representing standard neighborhood relationships. In order to reduce the user's efforts, the initial (default) values are based on average values from various case studies (RIKS, 2013). The IR neighborhood potential takes into consideration only the class influence on itself, not the influence of other classes. In most cases, the neighborhood potential by itself is not enough and the influence of other classes must be adjusted.

In order to see, how well the calibrated model performs, the modeled data had to be compared to the data modeled by IR (referred to as IR data in this thesis). In order to judge the calibration results, I compared the kappa statistics for the two time periods for all UVCZ. For the visual comparison, I used only the dense open low-rise UVCZ.

Time frame 1960 – 1990

To assess the quality of the 1960 – 1990 calibration I generated the map using the default IR. As it was stated earlier, IR considers only the single UVCZ neighborhood potential by itself. This is represented by figure 124. The red color is the IR modeled cells. All of them are close to the existing UVCZ, especially where their concentration is high. It occurs around the central part of Hamburg.

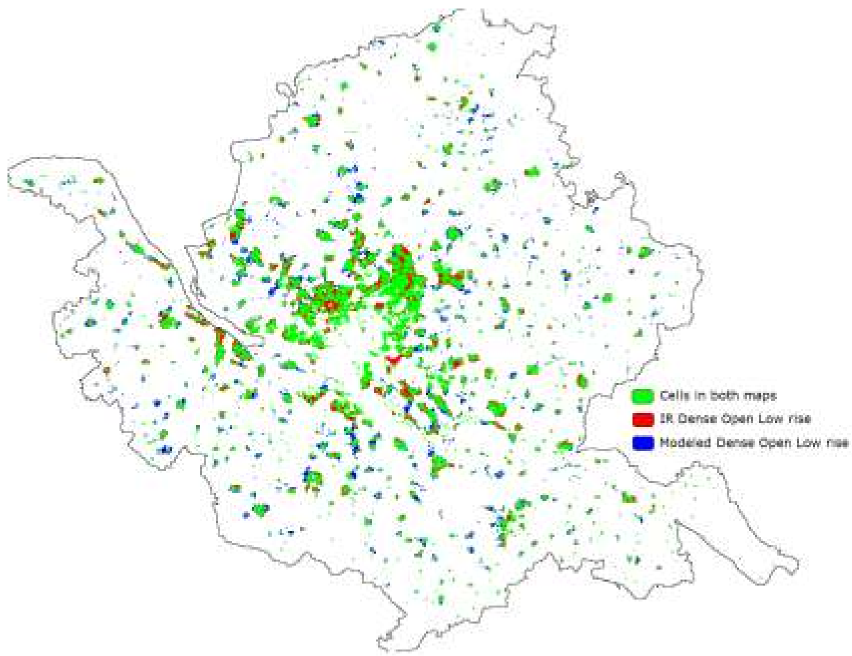


Figure 124: differences between IR and modeled dense open low use data for 1960 – 1990 time period.

Meanwhile the modeled data is not centrally focused, but distributed in the outskirts and neighboring districts. The actual dense open low rise development can be observed in figure 108. That figure shows that the modeled and actual development trends partially match. Table 17 shows the kappa statistics for IR and the modeled UVCZ.

Table 17: kappa statistics' comparison between IR and modeled UVCZ in 1960 – 1990.

Statistics type	IR UVCZ	Modeled UVCZ
Kappa	0,864	0,867
Fuzzy kappa	0,909	0,916
Kappa simulation	0,290	0,306
Fuzzy kappa simulation	0,442	0,469

The kappa of IR set is very slightly lower (by 0,003) than the modeled. The situation is a little bit better with the fuzzy kappa, but not much – the modeled shows a slight increase of 0,07 to 0,916. Even the kappa simulation shows an increase of only 0,016 to 0,306. The fuzzy kappa simulation gives better results with an increase of 0,027 to 0.468. These results were surprising, especially when observing a totally different trend in the development. This issue with kappa is described below. Despite the small difference of kappa statistics between IR and modeled data, the positive effect of calibration can be observed and identified.

Time frame 1990 – 2000

The changes between 1990 – 2000 are even less noticeable. Figure 125 shows a very small change between modeled and IR dense open low rise UVCZ. The actual trend can be seen in figure 116. In fact, the neighborhood potential function of modeled dense open low-rise is very similar to the standard rules (IR). This would explain why the new UVCZ allocation is so similar. Since the dense open low-rise is the most common UVCZ, it's easy to understand why the kappa values between all IR and modeled UVCZ are so similar.

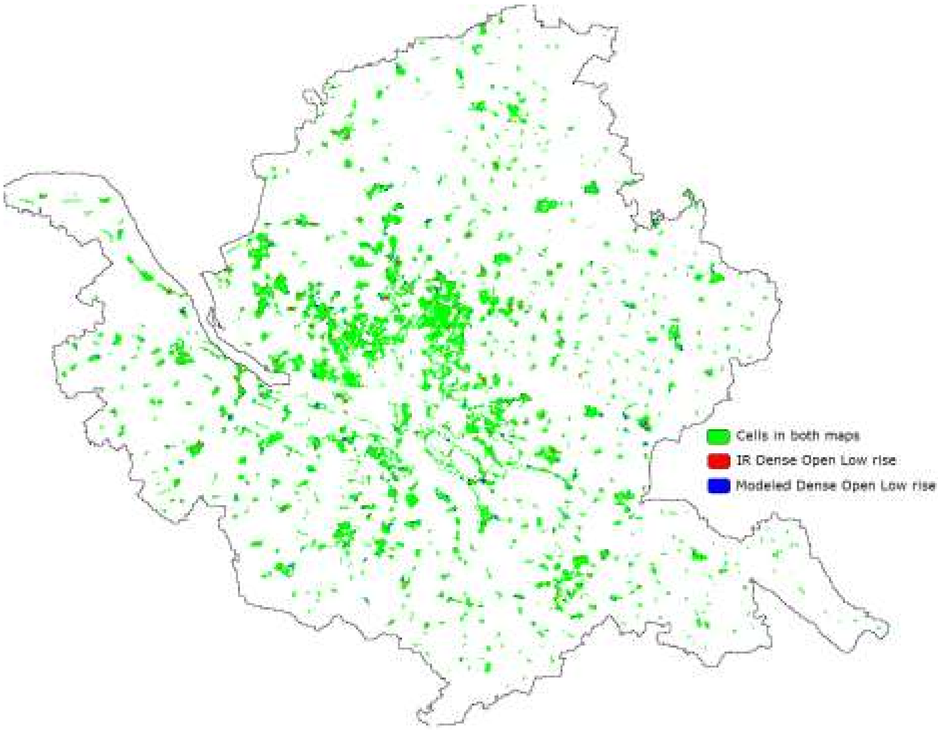


Figure 125: differences between IR and modeled dense open low use data for 1990 – 2000 time period.

The table 18 shows the kappa statistics for both, the IR and modeled UVCZ. The kappa is exactly the same. What is surprisingly, that fuzzy kappa for modeled data is even lower (by 0,001) than for IR data. But kappa simulation which shows the match between the changed cells, is much higher (considering the relative increase). But the fuzzy kappa and fuzzy kappa simulation are quite similar.

Table 18: kappa statistics' comparison between IR and modeled UVCZ in 1990 – 2000.

Statistics type	IR UVCZ	Modeled UVCZ
Kappa	0,956	0,956
Fuzzy kappa	0,973	0,972
Kappa simulation	0,072	0,113
Fuzzy kappa simulation	0,308	0,313

This proves the fact that fuzzy set in this case is much more favorable to the IR set. It means that newly IR generated cells are within the fuzzy set by category and distance. Meanwhile the modeled and calibrated dataset generates more disaggregated cells which cause lower fuzzy kappa values. Although the kappa statistics, the kappa simulation and the fuzzy kappa simulation is not as high as might be expected, the calibrated model results showed a better performance that the IR dataset. Thus, a final conclusion is that the 1990-2000 model was fairly calibrated and can be used for further modeling.

Issue of kappa

During the process of benchmarking the issue with kappa was identified. This issue was observed during the adjustment of the IR. As it was discussed before, the IR neighborhood potential focuses on the existing UVCZ and most of the development occurring close to it where the concentration is higher. This pattern is not correct for the Greater Hamburg case study. After comparing the benchmarking results, and seeing that the kappa of the calibrated data was slightly better than, or at time equal to IR, questions were raised concerning the applicability of this method.

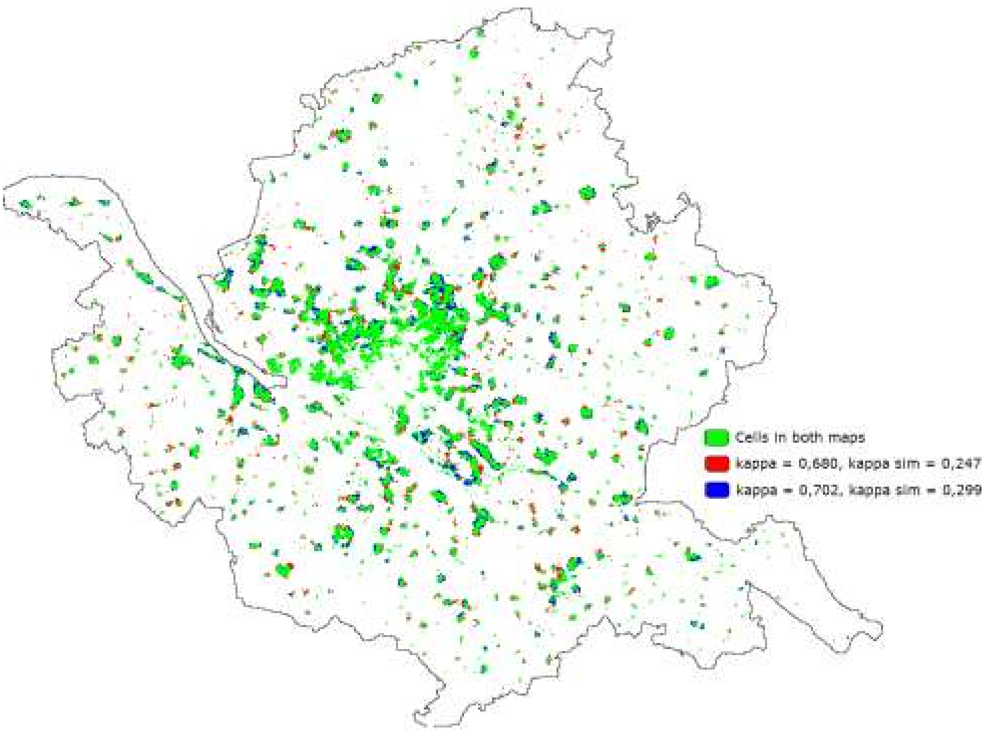


Figure 126: the differences between neighborhood potentials of dense open low rise data for 1960 – 1990 time period.

Surprisingly, extending the IR trend and increasing the neighborhood potential to itself caused more new development around the existing UVCZ - which was not the case for an actual development. Even though the trend was false, the kappa statists showed better results.

Figure 126 shows the differences in between the neighborhood potentials of dense open low rise. The blue color represents the extended IR and the red represents the development, which is closer to the actual and modeled one. The blue colored cells develop around a few, heavily aggregated clusters leaving fewer cells clusters with no development. Meanwhile the red colored cells are equally allocated close to already any existing clusters of dense open low rise, despite their aggregation level. Although the "red" trend is more realistic, it received the lower kappa and kappa simulation values.

A possible reason for the higher kappa is that the calibrated and modeled dense open low-rise is more dispersed. The trend, then, is more random, which lowers the possibility to actually populate the cell. Such cases are then measured by kappa statistics. The extended IR, meanwhile, produces larger aggregated clusters and causes less randomness, which gives greater possibility of populating a cell. This, in the end, would show better kappa statistics results.

Conclusions

This sub-chapter presented the analysis of calibration results and compared the actual and modeled data. The comparison was done visually and statistically. The visual approach via MCK gave a good spatial view of the data mismatch and identification of trends in urban development. Meanwhile the statistical approach quantified and justified the quality of the calibrated data over the actual and standardized datasets.

The kappa statistics in general showed good agreement between modeled and actual data with the exception of urban parks (with dense trees) in 1990 – 2000.The kappa simulation of 1960-1990 was 0,306 which, based on RIKS (2013), is a very good result . Meanwhile the 1990 – 2000 dataset has only 0,113 which is not perfect, but is an outcome coming from a fair calibration. Despite the low or no improvements of kappa statistics between IR and calibrated and modeled data, the fact that the higher kappa does not always represent the correct urban development trend (which is the focus of this study), it was decided to accept the existing calibration results and use the modeled parameters for the baseline scenario in the future.

6 Vulnerability indicators

The successful calibration of the UVCZ model enables us to model future UVCZ which can be used to model (unpack) vulnerability indicators which could become future vulnerability indicators (also identified as future conditions). However, first it is necessary to discrete/relate (pack) the vulnerability indicators to the UVCZ classes. In this study, the discretization was based on the aggregation and disaggregation of UVCZ 2000 and various datasets containing population's vulnerability indicators which quantify the vulnerability elements that are presented in the vulnerability assessment framework (figure 55). This chapter covers in detail these indicators, it justifies the selection of these certain indicators, and presents their allocation and statistics in Greater Hamburg. The statistics are used afterwards to model future population's vulnerability indicators.

Based on the conceptual setting presented in Part II, available data and common population's vulnerability to heat wave assessment studies, I selected eight population vulnerability indicators for Greater Hamburg (excluding the UVCZ as a proxy parameter): the monthly average minimum and maximum temperatures, degree of soil sealing, the population density, the relative population over 65 years of age old, the relative number of welfare recipients and the distance to the nearest hospital. The future monthly average minimum and maximum temperatures and distance to the nearest hospital indicators are spatial indicators which do not depend on UVCZ. They were modeled in other studies and were available at the local scale, therefore no additional processing was required. I called these population's vulnerability indicators the "auxiliary indicators". Because the other future population's vulnerability indicators were not available, they had to be modeled via the UVCZ proxy. I called these indicators "modeled indicators".

6.1 Modeled indicators

The modeled indicators are the ones which must to be modeled in order to assess future vulnerability successfully. The purpose of this research is to relate UVCZ to vulnerability indicators (modeled), model the UVCZ and populate them with the vulnerability indicators (modeled). In other words, the task is to pack the vulnerability indicators into the proxy by transferring the continuous data into discrete mean values and then to model the future UVCZ out to 2050 and unpack the indicators by transferring the data from the discrete to the continuous range (mean +- 0,5 of standard deviation) via randomization.

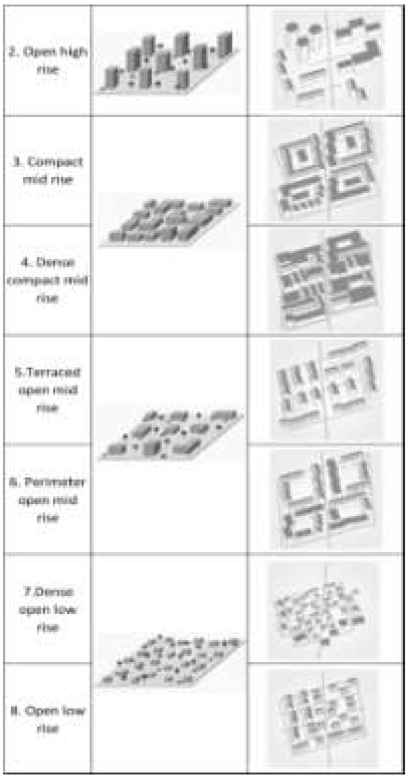


Figure 127: UVCZ classes, suitable for housing in the Greater Hamburg area (Kaveckis et al., 2017).

This sub-chapter presents the spatial and statistical analysis of the vulnerability indicators (year 2000) which is called the basis data. The analysis of basis data is very important in order to find the statistical relationships between the vulnerability indicators and UVCZ. Assuming that these relationships will not change over time, the future indicators can be reproduced from future UVCZ. Because most of the vulnerability indicators are related to the population, the focus of the analysis is to look at potential housing UVCZ classes. It is not necessary, therefore, to process statistical information on UVCZ classes which are not suitable for housing, such as harbor, agriculture, forest, and commercial because they will have little or no population which could be vulnerable. While all UVCZ classes affect each other and need to be modeled with the CA model, not all of them need to be populated by vulnerability indicators. The proxy parameter, therefore, will use the statistical data from seven potential housing UVCZ classes typical for Greater Hamburg area (figure 127). The statistical data is calculated for all modeled vulnerability indicators which are assembled into two groups: population and heat exposure.

Heat exposure

A person can experience the same heat in various ways, because of different urban areas and different local urban climates. The local urban climate is greatly affected by surface structure (height and spacing of buildings and trees) and surface cover (the coverage of pervious and impervious surfaces which modify the effects of albedo, the availability of moisture and the ground’s heating and cooling potential (Steward and Oke, 2012).

A pervious surface is the opposite of an impervious surface, which is also known as sealed soil. The sealing of soil or surface is the permanent covering with impermeable (impervious) materials such as concrete, asphalt and stone. Typically, the sealing of soil comes from building construction, roads, parking lots and other private and public spaces. Sealed soil is unable to perform natural soil functions and provide ecosystem services, such as water infiltration and evaporation and temperature regulation. For instance, the green urban areas with no or very low degree of soil sealing are much cooler than the heavily sealed urbanized areas (EEA, 2016). According to Bojariu et al. (2014), from all the impacts of land cover change, the increase of soil sealing is the most predominant effect contributing to natural hazards. It means that the soil sealing is strongly related to the environment and affects heat susceptibility. The greater degree of soil sealing causes higher heat susceptibility and contributes to UHI effect (Kropp et al., 2009; Lissner et al., 2012; Schauser et al., 2010). In matter of the UVCZ, the greater degree of soil sealing a UVCZ class has, the greater the heat susceptibility people staying in that zone will experience. If it is possible, therefore, to model future UVCZ, it should be possible to model the heat susceptibility of the area as well. Soil sealing is not the only factor affecting heat susceptibility, but it is the major factor and is easily measured. Assuming that the degree of soil sealing for each potential housing UVCZ will not change over the years, the future heat susceptibility can be modeled using UVCZ as a proxy. But a most important step is to find the degree of soil sealing for each potential housing UVCZ class within the Greater Hamburg study area.

Soil sealing aggregation

In order to find a soil degree for each potential housing UVCZ class, I need to match (overlay) both datasets - degree of soil sealing and UVCZ. If the resolution of the datasets differs, the statistical aggregation or disaggregation must to be used. In order for these datasets to be trustworthy, both (satellite acquired soil sealing and the digitized UVCZ from topographical maps) must be done over similar time frames. These datasets are large and were collected and processed over several time frames so it was necessary to establish requirements for each dataset, in an effort to make them as similar as possible. Requirements for the soil sealing database were as follows:

- Dataset should be dated closer to the year 2000 as possible, in order to match the latest UVCZ data;
- Dataset should contain degree of soil sealing (0 – 100);
- Dataset should have resolution close to the UVCZ grid (250 x 250 meters).

The dataset closest to the defined requirements was disposed by the European Environmental Agency (EEA) which produced the European degree of soil sealing map in 2009. The spatial resolution of the dataset is 100 x 100 meters for the reference year 2006. The satellite imagery was delivered by the European Space Agency (ESA) and classified by EEA to degree of soil sealing classes from 0 to 100. The 100 value means totally sealed soil with impervious surfaces, while the 0 value means the non-built up areas and bodies of water.

Concerning the time frame, I was not able to find any 2000 year soil sealing data, except the CORINE 2000 layer with land use and land cover classes which does not represent the degree of soil sealing. According to the analysis, the changes between 1990 and 2000 UVCZ were minor, compared to 1960 - 1990. I assume, therefore, that the changes between 2000 and 2006 should be even less in number. Moreover, the degree of soil sealing data will be overlaid (matched) not with the whole Greater Hamburg area, but with residential, potential housing UVCZ. In other words the soil sealing will be clipped (masked out) by potential housing

UVCZ 2000. The changes, therefore, should be even fewer. I made decision to use the EEA degree of soil sealing data with the reference year 2006, assuming that the degree of soil sealing did not change much from the 2000 data. The 2006 degree of soil sealing data will be clipped by the potential housing UVCZ 2000 data and the average degree of soil sealing for each potential housing UVCZ class will be calculated.

Because the soil sealing data spatial resolution was higher than the UVCZ data, I was required to use the spatial aggregation approach. Figure 128 shows how the soil sealing cells are aggregated into the coarser resolution cells, matched with potential housing UVCZ.

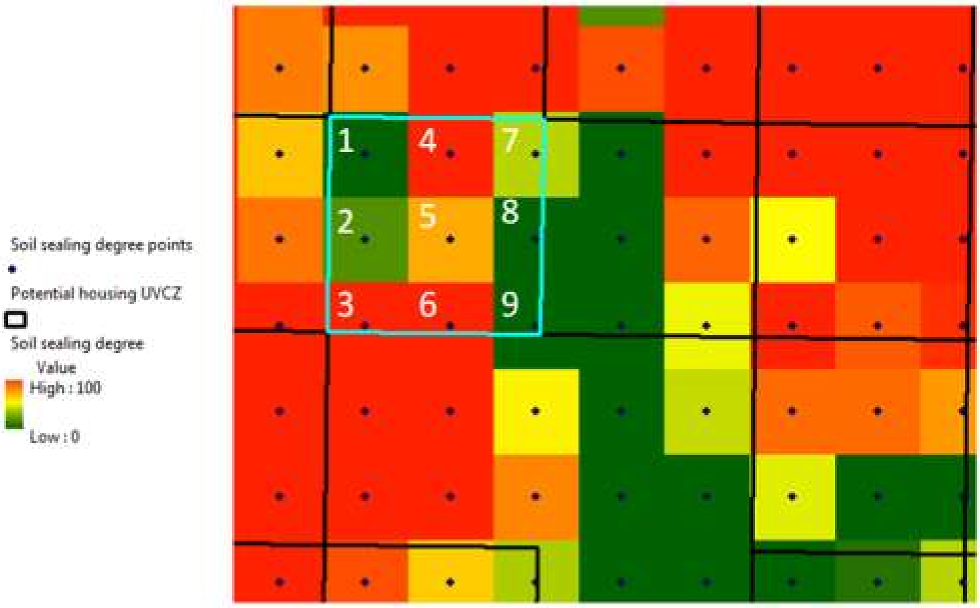


Figure 128: aggregation of degree of soil sealing. The light blue UVCZ cell receives the average degree of soil sealing value of nine degree of soil sealing cells/centroids.

The numbered (1-9) degree of soil sealing cells' centroids with their values are aggregated in the cyan colored UVCZ cell. The procedure of aggregation sums all centroids of the cells within the UVCZ cell and divides by the number of centroids. The result will be the average (mean) degree of soil sealing of the certain UVCZ cell. The means of the specific potential housing UVCZ classes will be compared and statistically processed. The soil sealing is the only indicator, available for the whole Greater Hamburg area. Meanwhile the population data is available only for the Hamburg city-state area. The larger set of data means more samples and better representation of the modeled data, but it can also cause a higher variance as well. It was decided to use the entire Greater Hamburg area for the statistical analysis, because it was assumed that there would be a high variance in either case.

Results

The centroids of the original soil sealing data were aggregated into 16567 potential housing UVCZ cells. The distribution of the aggregated degree of soil sealing is normal with a higher frequency of cells in the lower extreme corner of figure 129, in an area that has no built up area and no soil sealing. The low degree of soil sealing values are typical for cells with no impervious surfaces and a high percentage of vegetation, such as parks or water sources, which are plentiful in Hamburg. Therefore the high number of zero soil sealing cells within the case study area is not surprising. The high number of sealed surfaces is typical for cities.

Although Greater Hamburg is a Metropolitan area, 9940 out of 16567 (60%) cells have a degree of soil sealing that is lower than 50%. It may be difficult to say that Greater Hamburg could be called a “green city” but it would be interesting to compare the degree of soil sealing in other European cities to see which one would have the lowest degree of soil sealing.

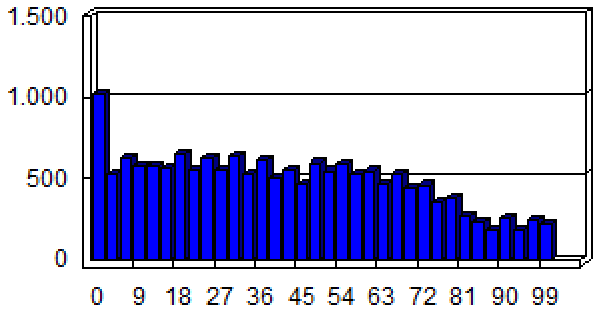


Figure 129: frequency distribution of the degree of soil sealing by aggregated potential housing UVCZ cells.

The other soil sealing values are distributed quite evenly along the range and start to decrease around the degree of soil sealing of 70%. This shows a smaller amount of totally sealed surfaces in Greater Hamburg. Figure 130 below shows the spatial representation of degree of soil sealing aggregation on the basis of the potential housing UVCZ cells. The notable high degree of soil sealing is located in the city center and its surroundings. Some clusters in the South (Harburg) Southeast (Bergedorf) are the sub-centers with the higher density structures and high degree of soil sealing. The small populated clusters in the far Southeast are the low density urban areas along the roads. The far West side also has a low degree of soil sealing. These are the settlements of wealthier Hamburg’s residents with more green spaces around. The far North (Volksdorf) has a low degree of soil sealing as well, because it has plenty of forests and is sparsely populated (in comparison to other areas in Hamburg) despite the fact that it’s located within the city limits. The small hamlets and villages in the surrounding areas have a high amount of greenery and, therefore a low degree of soil sealing.

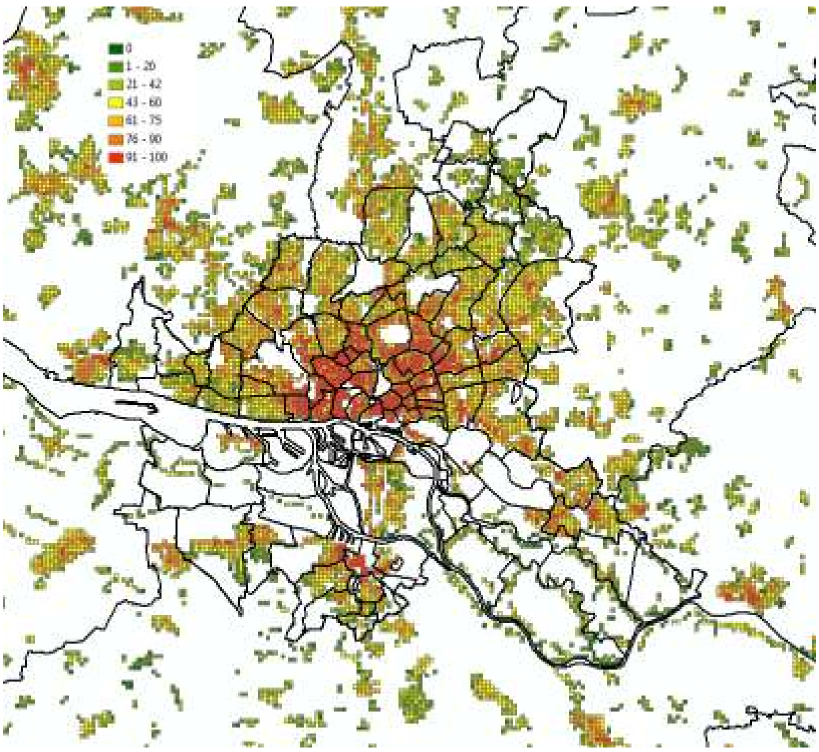


Figure 130: results of aggregation: degree of soil sealing distribution on the potential housing UVCZ cell basis in Greater Hamburg (zoomed to Hamburg city-state). The outlines are the Hamburg's neighborhoods and surrounding districts.

Statistical analysis of degree of soil sealing

The modeling of future heat susceptibility requires the statistical analysis of the aggregated degree of soil sealing. The statistical analysis presents the distribution of the values and how they differ from each other within and between the potential housing UVCZ classes. An analysis shows the variation as well as heterogeneity. In order to get a more accurate soil sealing representation for each UVCZ class, I excluded the cells with office buildings, since they usually have a high degree of soil sealing and low population. Three types of statistical analysis were done for the soil sealing: box plot, variance and variability.

The box plot is a great graphical way to visualize the statistical information of various classes into quartiles. Additionally, box plot shows the minimum and maximum values, the outliers, medians and the range of values. The variance analysis presents the variance between the values in the class and between the classes. And the last, but not least is the coefficient of variation. Compared to the variance, the coefficient of variation is more accurate in that it describes the heterogeneity of the values because it is normalized by mean.

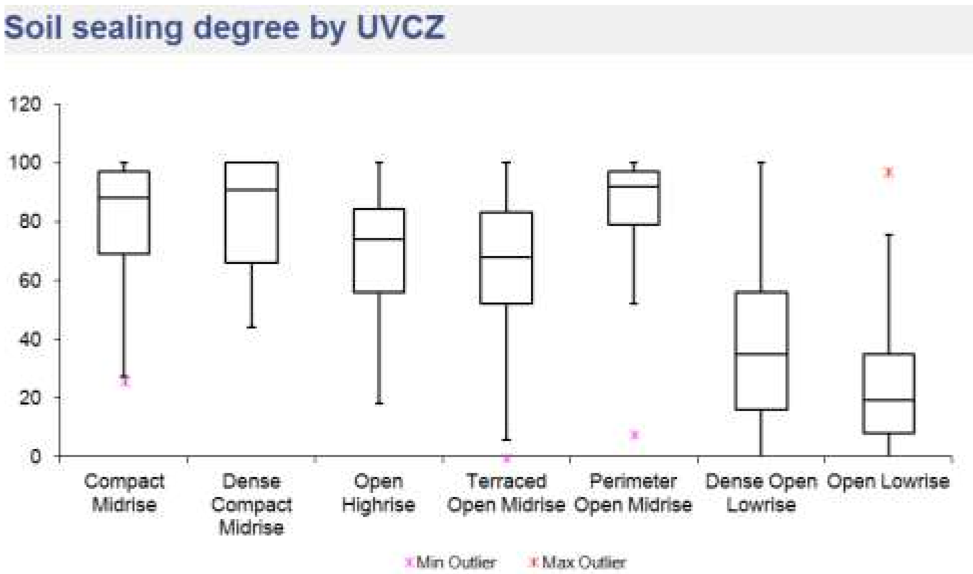


Figure 131: box plot of the degree of soil sealing among the potential housing UVCZ in Greater Hamburg.

The box plot (figure 131) shows the median, 1st and 3rd quartiles, and the minimum and maximum outliers. The highest median degree of soil sealing has the perimeter open mid rise UVCZ. The medians of compact mid rise and dense compact mid rise are close. The typical perimeter open mid rise housing consists of a green area surrounded by housing blocks, building a perimeter along the streets. The reason there is a high level of soil sealing in perimeter open mid-rise could be that the green area in the middle is too small to be identified as an area with a low degree of soil sealing. Conceptually, the compact mid-rise and dense compact mid-rise UVCZ have a similar, but more chaotic structure with less green area and more inside build area.

The perimeter open mid rise has a highest 1st quartile, showing that 75% of all cells have values higher than 79% of soil sealing. However, its minimum outlier is quite below the minimum outlier of compact mid rise and dense compact mid rise. This means that from all high degree soil sealing mid rise UVCZ classes, the cell with the lowest soil sealing value is in the perimeter open mid rise. Meanwhile the highest minimum value belongs to the dense compact mid rise UVCZ class which, according to the morphology, should have the highest soil degree by average.

The terraced open mid rise class contains a cell with a zero degree of soil sealing which is more typical for the dense open low rise and open low rise UVCZ classes. In this case, the cell of the zero degree of soil sealing can be an error, or simply an area of a meadow, park or a water channel close to the actual terraced open mid rise housing. When the pervious area is large enough (250 x 250 m), the remote sensing and aggregation identifies it as a zero soil sealing cell. The values of terraced open mid rise are similar to open high rise UVCZ. Both have similar medians, 1st and 3rd quartiles. In general, both UVCZ seem to have similar amounts of sealed areas and vegetation with only the height of the buildings differing. The dense open low rise and open low rise are potential housing UVCZ classes with the lowest soil sealing values. However, still, their maximum values can still reach 100 and 97, but there are not that many cells with such high degree of soil sealing. The possible reason for the high degree of soil sealing possibly could be because of the low vegetation cover and a higher than usual density of buildings. Since the soil sealing number does not define the building height, but the sealed area, even a large parking lot with no building could be identified as a 100% sealed area.

Anova: Einfaktorielle Varianzanalyse

ZUSAMMENFASSUNG

Gruppen	Anzahl	Summe	Mittelwert	Varianz	STDEV	Mean	Coef. Of variation
Compact mid rise	55	4484	81,52727273	348,8094276	18,6764404	81,52727273	0,22908212
Dense Compact Midrise	37	3040	82,16216216	357,1396396	18,8981385	82,16216216	0,230010239
Open Highrise	63	4356	69,14285714	381,1889401	19,5240605	69,14285714	0,282372776
Terraced Open Midrise	2130	140203	65,82394366	515,6199995	22,7072675	65,82394366	0,344969722
Perimeter Open Midrise	456	38965	85,4495614	286,1425053	16,9157473	85,4495614	0,19796178
Dense Open Lowrise	12907	480147	37,20051135	606,0656343	24,6184003	37,20051135	0,661775858
Open Lowrise	919	22206	24,16322089	422,6944628	20,5595346	24,16322089	0,850860682

ANOVA

Streuungsursache	Quadratsummen (SS)	Freiheitsgrade (df)	Mittlere Quadratsumme (MS)	Prüfgröße (F)	P-Wert	kritischer F-Wert
Unterschiede zwischen den Gruppen	2851183,264	6	475197,2106	828,937737	0	2,099142333
Innerhalb der Gruppen	9493192,863	16560	573,2604386			
Gesamt	12344376,13	16566				

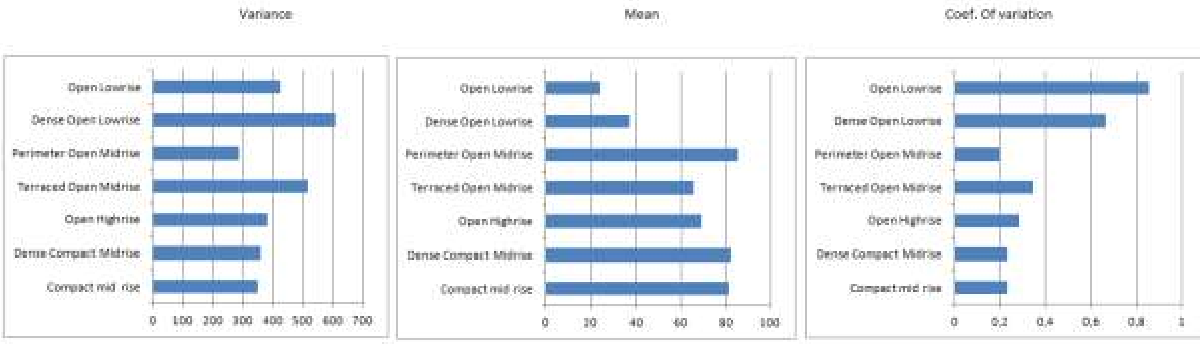


Figure 132: heterogeneity of degree of soil sealing among the potential housing UVCZ in Greater Hamburg.

Figure 132 presents the differences of degree of soil sealing among the potential housing UVCZ classes in Hamburg in the year 2000. The results were developed using the MS Excel add-on "ANOVA". The upper tables show the number ("Anzahl" in German) of cells, used for analysis, their sum ("Summe" in German), average/mean ("Mittelwert" in German), variance ("Varianz" in German), standard deviation ("STDEV") and coefficient of variation. The variance, mean and coefficient of variation are plotted in the bottom as bar graphs. The variance is the square of standard deviation. A very low standard deviation gives a very low variance. The lower is the variance, the lower is the difference between the values. Because the standard deviation is squared, the variance overestimates the dispersion. The smaller value should give a smaller dispersion but this is not the case with variance. The difference between the values could be better represented by the coefficient of variation, which shows the ratio between the standard deviation and the mean.

The variance, as it had to be expected from the box plot graphs, is very high. The variance is higher within the group than between the groups. It means that the degree of soil sealing within a specific potential housing UVCZ are quite heterogeneous. Although the dense open low rise and open low rise have the smallest degree of soil sealing by average, they have the highest variance and highest coefficient of variation. The absolute leader of "heterogeneity" is the open low rise. Meanwhile the dense compact mid rise has five times lower coefficient of variation. The low rise UVCZ has a low degree of soil sealing on the average and the low rise cells with high degree of soil sealing increases the coefficient of variation. In general all the other UVCZ classes, except the low rise, have a fairly low coefficient of variation. The possible reason for this has been already mentioned previously – the presence of sealed parking lots and roads with low or no vegetation around low rise zones gives a significantly high degree of soil sealing. Another possible reason for this could be a false reading on soil sealing or a UVCZ vectorization error or a generalization and/or aggregation error. .

Table 19: min, max, mean and standard deviation values of the soil sealing for each potential housing UVCZ within Greater Hamburg.

	Compact mid rise	Dense compact mid rise	Open High rise	Terraced open mid rise	Perimeter open mid rise	Dense open low rise	Open low rise
Min	26	44	18	0	8	0	0
Max	100	100	100	100	100	100	69
Mean	82	82	69	66	85	37	21
ST deviation	19	19	20	23	17	25	20
+0,5ST	91	92	79	77	94	50	31
-0,5ST	72	73	59	54	77	25	10

Table 19 shows the statistics of the aggregated soil sealing for each potential housing UVCZ. The statistics will be used to model future soil sealing using the different future UVCZ scenarios. In order to represent more realistic future patterns, I decided to randomize the soil sealing values for the new cells in the range +/- 0,5 of the standard deviation (SD) from the means of the historical aggregate year 2000 data. The +0,5SD marks the top and the -0,5SD marks the bottom of the range of soil sealing values which will be randomly assigned to the modeled UVCZ cells for all future scenarios. For instance, all new future open low rise UVCZ cells will receive the random soil sealing value ranging from 10 to 31. Because of the high variance within the classes, it can happen that an open low rise UVCZ cell will get a value of 31 and a nearby created dense open low rise will get a 25, which is lower than 31, although, conceptually, the degree of soil sealing should be lower in the open low rise, than in the dense open low rise. This issue exists due to the heterogeneity of the surface and housing properties within the same UVCZ zone. The housing and surface properties are not the only ones which have a high variance. The population living within the same UVCZ zone can be even more diverse.

Population

All people, more or less, are sensitive to natural hazards. Their sensitivity to hazards varies because of differences in age, gender, race, ethnicity, employment and income, education, housing conditions, disease, use of medication, special needs, and other factors (Blaikie, 2004; Cutter et al., 2001, 2003; H. John Heinz III Center for Science Econ and White, 2000; Tan, 2008). But the dominant characteristic which is also easily measurable, is age— the elderly and young children often need physical and psychological assistance during and after disasters, and they are more prone to diseases. During the summer of 2003, 82 percent of the fatalities in France caused by heat wave were over 75 years old (Poumadère et al., 2005). In addition to age, the type of hazard has much to do with the sensitivity of a certain population group, e.g. physically disabled people may be able to withstand beat, but are severely restricted during an evacuation during a flood. Specific socio-demographic characteristics of a population can also play a major role during certain disasters. Even with these considerations, some characteristics, such as age and gender, affect a population's behavior more strongly during all types of disasters. However, for this heat-wave focused case study, age is the dominant indicator of the population. It is a "predictable" indicator, in that knowing how many people of certain age group are currently living within the area today allows us to project how many people of certain age groups will live in that area in 30 years from now, considering the birth and death rates, as well as migration and other population influencing factors. Of course, it may be difficult to project that future population because of increased mobility and unpredictable political decisions, but the scenarios-based approaches with certain assumptions are plausible.

Figure 133: the pregnant women are extremely vulnerable to heat stress.

The most heat-sensitive group may well be pregnant women and their unborn fetus - the heat impact can increase fetus and maternal mortality, cause birth complications and lower reproductive health (Rylander et al., 2013). It was decided not to address this most heat-hazard sensitive population group for the following reasons: future modeling of pregnant women and their fetus would be very difficult because there is limited statistical information; healthcare for pregnant women generally is increased, as is supervision, especially during heat waves. Therefore it was decided do not address this most heat hazard-sensitive population group.

As mentioned above, studies have shown that the other two groups most sensitive to heat hazard are the young and elderly. Children require assistance during disasters, but their physical health and mobility is much better than elderly people. Because of this, the social group of people over 65 years of age was selected as the most suitable sensitivity to heat waves indicator of this study. The threshold of 65 years was selected because it is a common threshold in disaster-related studies to describe old people (elderly) and is often the average age of retirement. This indicator is often called "elderly" as the social group, usually in their retirement age. Other indicators defining a population's sensitivity to heat were considered not suitable for this study due to a lack of available data, lack of projections, weak relations with heat-mortality and modeling issues. It was decided to use the elderly indicator as the only indicator in defining the future population's sensitivity to heat waves in Greater Hamburg.

Sensitivity is not the only vulnerability feature. It becomes necessary to identify a population's capacity to adapt to the heat hazard. The capacity to adapt to heat waves means that even when people are sensitive to heat waves they are able to avoid heat stress. The capacity, or adaptation, is often misinterpreted and confused with sensitivity. Previously identified indicators, such as employment and income, education and housing conditions are not sensitivity but rather the ability to adapt. For instance, if an elderly couple is sensitive to heat stress, and they do not do anything, they will be affected. However, if they have enough money to install air condition, pleasant temperatures in the house will lower, or completely eliminate the heat hazard. Klinenbert (2015) identified income level as the main adaptive capacity indicator which influences the individual heat-related mortality. Because poorer households may have lower building standards in their flats than the housing of wealthier people, wealthier people tend to have better housing conditions. This gives one explanation for higher mortality rates in lower social status areas (Moshammer et al., 2009). Income and employment are practically the same thing, since an unemployed person will not receive enough income to be able to adapt appropriately. With enough income, housing conditions can be improved. But income cannot buy knowledge and these two indicators measure different properties in the population. According to studies (Harvy, 2009; Preston and Smith, 2008; Schauser et al., 2010), higher education and knowledge enable people to make better decisions to achieve a better capacity to adapt. Logically speaking, though, higher educated people generally make higher incomes than uneducated. It can be concluded that the capacity to adapt can be measured by income. The plausible population's indicator of adaptive capacity is the income which can be expressed as wealth, or the inversed form of poverty. In reviewing all the available population data in Greater Hamburg, the most plausible capacity indicator is the relative number of people living in poverty, or the number of people living on welfare.

Although the population count (density) is not one of the heat hazard sensitivities or one of the adaptive capacity indicators, areas with a higher population density with a higher concentration of old and poor people are particularly vulnerable to natural disasters (EEA, 2008). Just the higher amount of vulnerable people does not necessarily represent their relative vulnerability, but it would be very valuable in showing the absolute vulnerability and in identifying the pressure on the health care and emergency services during heat wave events. Therefore, the population density as a socio-exposure indicator is included as a part of the vulnerability indicators in Greater Hamburg.

Population disaggregation

Population density, sensitivity and adaptive capacity are the set of a social population's characteristics. It is already known that the population sensitive to heat can be described by many indicators, but not all of them are possible to model or can be easily projected. In order to model a future social population's characteristics, it is necessary to have a basis, or proxy, of today’s social characteristics which can be used to model their further changes. I also want to verify the hypothesis: if the UVCZ classes represent not only land use, land cover and urban morphology, but also different classes of population density, elderly and economically poor population. In order to obtain good quality data, the following requirements for the baseline social data were defined:

- The dataset should be dated as close to the year 2000 as possible, in order to match the latest UVCZ data;
- The dataset should contain the population count/density, share of population aged over 65 years of age, and the share of the population with a low income or welfare received;
- The dataset should have a resolution close to the UVCZ grid (250 x 250 meters).

The best information I could receive for Greater Hamburg was the Census’ statistical information of the year 2000. I found the statistical tracts within Hamburg city-state and the statistical municipalities for the neighboring districts as the most suitable census data for this study. Unfortunately, none of them fully met the requirements. One of the main issues was the scale. The Hamburg city-state area is much more populated in comparison to the neighboring districts. Therefore, the area representing one census unit in Hamburg-state is smaller than in surrounding districts (figure 134). But even the census units within Hamburg differ in size, because of the different population distribution. In the central part of Hamburg where the population density is high, the statistical units are quite small. Their size is close to the UVCZ cells. However, in other areas, the size of the census unit is quite large, close to the size of a district.

Figure 134: available social characteristics data census tracts (blue) for Hamburg city-state and statistical municipalities (green) for neighboring districts.

The other issue is the attributes of the census data. The census tracts for Hamburg city-state contain all required data: including, but not limited to, the population density/count, people over 65 years of age and people receiving welfare. Municipalities in the surrounding districts collected such data only after 2004, when new regulations were implemented. Unfortunately, for the year 2000, the data from the municipalities contained only the population count and density. The number of people over 65 was only available at the higher district level. At this point, this is the best data that I can find.

As mentioned in chapter 3.4, disaggregation is a dispersion of data from larger to smaller areas. Census data, discussed above, are larger areas which are known as source zones. The aim of disaggregation is to assign the social characteristics to the smaller, so called “target zones” (figure 135) which in this case is the UVCZ grid.

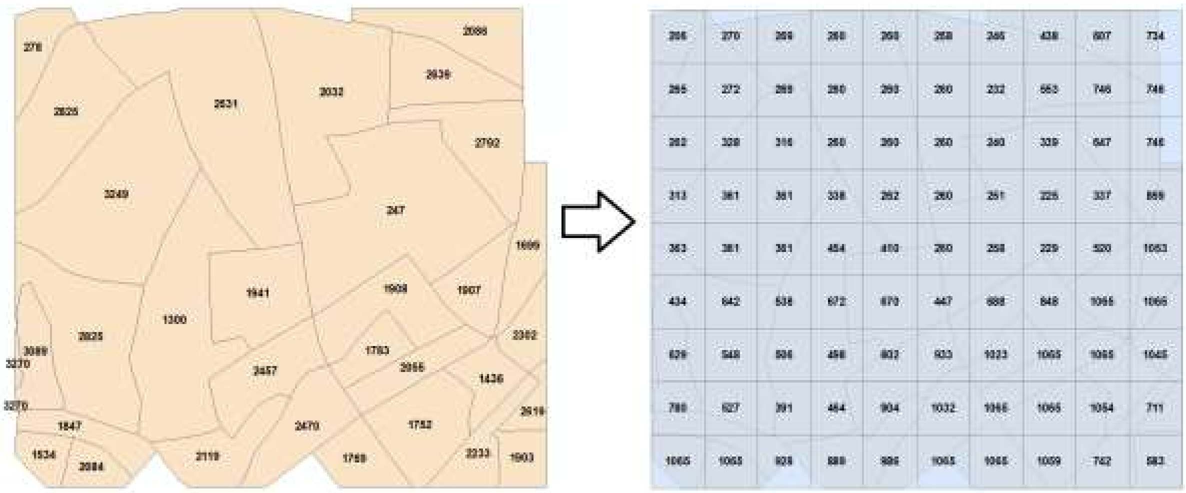


Figure 135: disaggregation of the census data from the census units (left, brown color) to the UVCZ grid cells – target zones (right, blue color).

The common disaggregation methods are the simple area weighted, binary dasymetric mapping and classified dasymetric mapping methods. The simple area weighted is the basic area-based disaggregation which equally distributes the values along the area. The classified dasymetric mapping masks out only the specific areas, where the values are distributed equally. And the classified dasymetric mapping method not only masks out specific areas, but also specifies them by density. More details about disaggregation methods can be found in chapter 3.4.

Based on available data, the most suitable and comprehensive method is the classified dasymetric mapping method. However, this method requires auxiliary data, which often is the density. And in this case, I do not have any density information of the target zones (UVCZ). The UVCZ is distinguished by land use, land cover and urban morphology, as well as housing type. While the average ratio of impervious surface, or the density of buildings, can be calculated statistically, that might not be very accurate (the variance of degree of soil sealing is unusually high within one UVCZ class). The task, however is to find the population density and the other social characteristics for each UVCZ in order to model them in the future. Because this information is not available, the dasymetric mapping method cannot be used for this case study. An alternative method is the binary dasymetric mapping in which the data is dispersed along a specific masked area. In GH the masked area was selected as potential housing UVCZ, assuming that most of the population lives within this type of UVCZ.

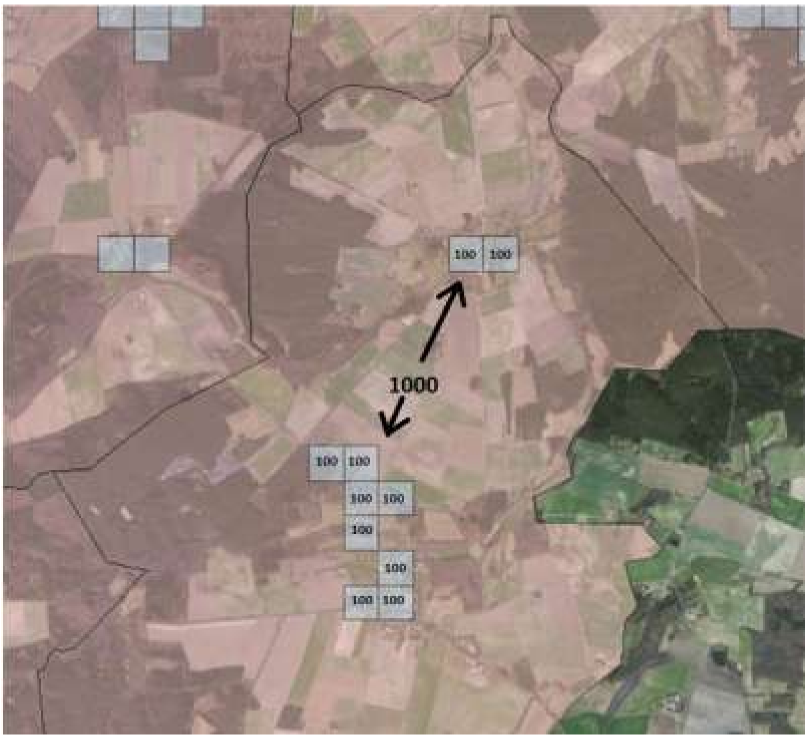


Figure 136: binary dasymetric mapping disaggregation. The data is transferred from the municipality census units (red transparent) to potential housing UVCZ (blue transparent) (sources: imagery by ArcGIS Imagery WMS Service, accessed on 2015.12.04).

The binary dasymetric mapping approach is quite simple. Assuming that people are living only within a certain area, we can state, that the population attributes of the whole municipality belongs to that certain area (figure 136). In figure 136 the social characteristics of source zone (municipality census unit) is distributed among the 10 UVCZ cells. Let's assume that 1000 people are living within this municipality. The task is to disaggregate the attributes to the potential housing UVCZ. If the use of simple area weighting method is used, the 1000 will be distributed within 315 cells, for about 3,17 persons per cell. Meanwhile, if the binary dasymetric method is be used, the 1000 people will be distributed only within 10 cells (shown in figure 136), with 100 people per cell. If I could know which areas of potential housing UVCZ are more or less populated, I could get even more accurate data. Additionally, the smaller is the source zone, the smaller is the error and the accuracy of disaggregation is higher. The technical procedure of disaggregation was performed using various GIS operations, mainly based on ESRI ArcMap, such as Clip, Identify, Dissolve and Field Calculator operations.

Results

From the surrounding districts, the 458 municipalities with 1530477 people were disaggregated into 11103 cells of potential housing UVCZ. In the Hamburg city-state area, the 944 statistical units with population of 1706833 were disaggregated into 5379 cells of potential housing UVCZ. The frequency distribution of population density for both regions can be seen in figure 137.

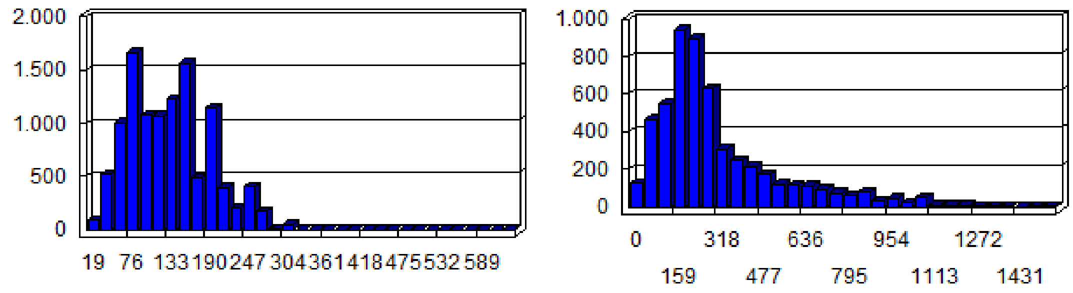


Figure 137: frequency distribution of population density by cells in Hamburg city-state area (right) and surrounding districts (left).

Both distributions are normal with some spikes and extending to the right because of a few cells with a highly dense population. The overall population density is higher in Hamburg city-state area which is represented in the frequency distribution of population density.

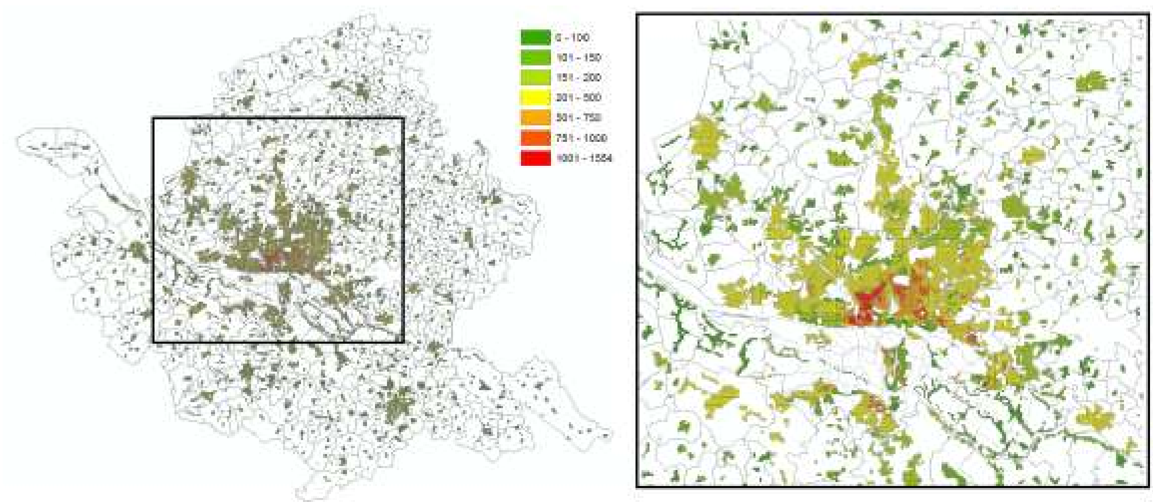


Figure 138: results of disaggregation: population density distribution on the UVCZ cell basis the Greater Hamburg area (left) and zoomed Hamburg city-state area (right) in year 2000.

Figure 138 shows the spatial distribution of population density on the UVCZ cell basis. It is notable that the highest density of population is in the Hamburg city-state area and the Northern side of the Elbe River's bank. The old town is less populated due to a high amount of business and offices, while the largest clusters of densely populated areas are located in West of Alster lake.

In addition to the population density, the number of people over 65 years old and number of welfare recipients was disaggregated. However, these characteristics were available only for the Hamburg city-state area, but not for the surrounding districts. The absolute numbers of elderly and welfare recipients were transformed into relative numbers (figure 139 and 140) in order to better identify the more vulnerable groups.

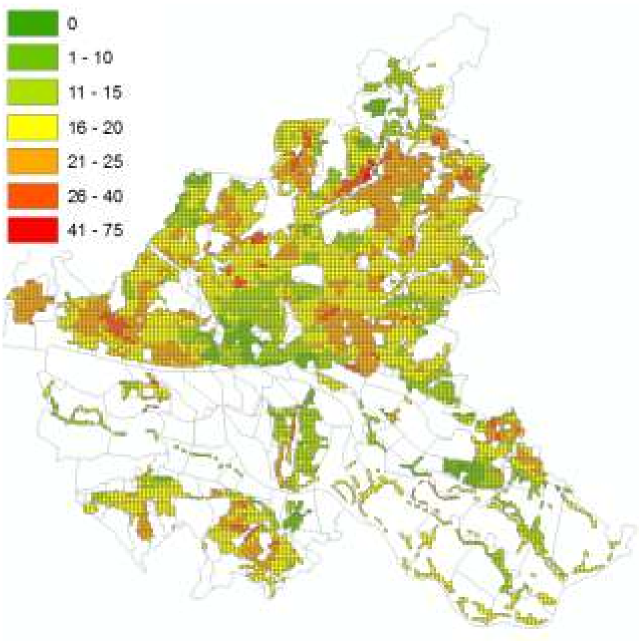


Figure 139: disaggregated distribution of relative number of population over 65 years in Hamburg city-state in year 2000.

The distribution of percentage of population over 65 years old differs greatly from the population density (figure 139). The highest percentage of people over 65 years old is 75%. This high concentration of elderly has been found in the Northeast area where the homes of the elderly are located. The lowest value of the elderly population (0) was found in the central parts of Hamburg, indicating that no elderly people live there at all. The heavily populated Western center part of the city has a relatively young population, while there are some hot spots of an elderly population in the far Northwest. The situation in the central Eastern part of the city partially matches the population density. There are high concentrations of elderly population that are noticeable in the far West and far Northeast, where they are the majority of the population. In general, I can conclude that the elderly area distributed within the circle of the city center, with a radius of 6-10 km, with some hot spots outside the area.

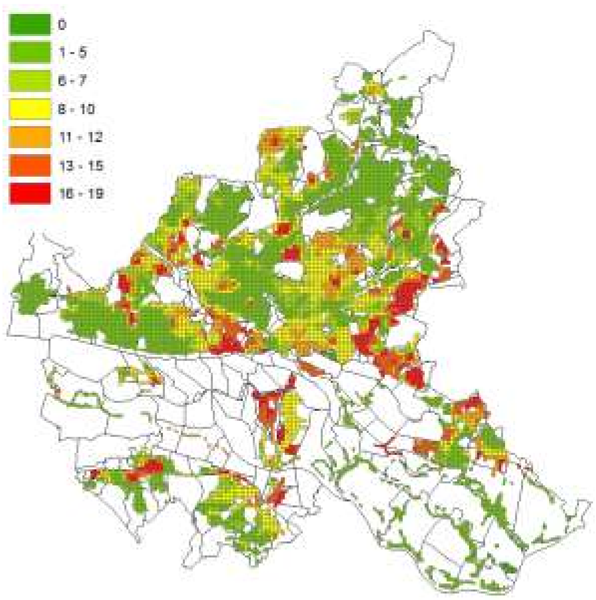


Figure 140: disaggregated distribution of relative number of welfare receivers in Hamburg city-state in 2000.

Although the concentration of welfare recipients is lower than´the elderly, the more clustered concentration of welfare recipients can be spotted. While many areas in Hamburg city-state are not poor, having zero percentage of welfare recipients, other areas have a fairly high number (19% maximum) of welfare recipients. Such poor areas are located in the East, Southeast side of Hamburg as well as Wilhelmsburg in the South, St. Pauli in the West center and Lurup in the Northwest.

Disaggregation problems

Although, disaggregation was successful, many issues still exist. One of them is that the disaggregation was based on masked potential housing UVCZ. The direct misinterpretation of UVCZ class can dramatically change the outcome of the results. Even if the interpretation was right, the generalization through conversion from vector to raster and back to vector has a very high impact.

Ideally, the population in source zones should be equal to the population in target zones. However in this case, I rounded up for the final stage of population calculation after the densities were developed. This caused a loss of some of the population. In surrounding districts the number of people "lost" was 6019, which is 0.39% of the total population in those surrounding districts. Meanwhile the in Hamburg area the missing number of people after disaggregation is 5942, which is 0.35% of total population in Hamburg.

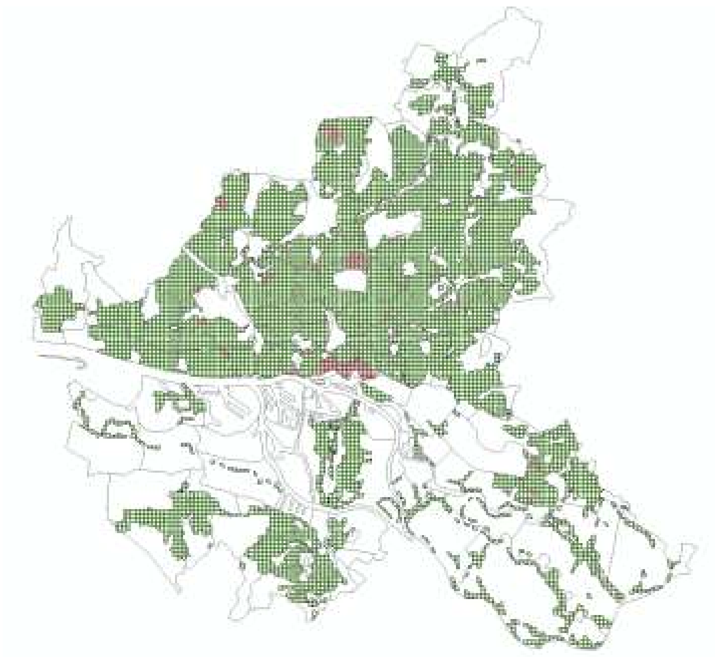


Figure 141: office spaces and public buildings (both in red color) and potential housing UVCZ identified as non-offices and public buildings (green) in Hamburg area in year 2000.

Another issue is the offices and public buildings (figure 141). The land cover and urban morphology of the office and public occupied areas can be exactly like the potential housing UVCZ, but with no or very limited population. For the general vulnerability assessment it is not a problem. However, if we want to model future population social characteristics, the offices should be excluded from the statistical analysis, in order to acquire more accurate results. Many cells of the dense compact mid rise contain offices and public bureaus as well.

But because of the limited number of cells and the unique urban morphology, it was decided not to exclude this UVCZ class from the statistical analysis.

Statistical analysis of population's social characteristics

The statistical analysis of the social population characteristics is very important in order to model the future social characteristics – the vulnerability indicators. The statistical analysis shows the distribution of the values, their differences, variation and heterogeneity. The dataset, used for statistical analysis, was the updated non-office dataset, developed from the outcome of the disaggregation process. Because of the above mentioned issue with the office space in potential housing UVCZ, the suspected areas of offices were masked out. In total three types of statistical analysis for each social characteristic and for each class of potential housing UVCZ were performed: variance analysis, box plot and variability. The analysis used the same methods as were used for the degree of soil sealing.

Population density

The population is a very important social characteristic. It is an absolute value of the population living within one cell (250 x 250 meters) of the potential housing UVCZ. Because each cell has the same size, it would not be a mistake to name this value as "population density".

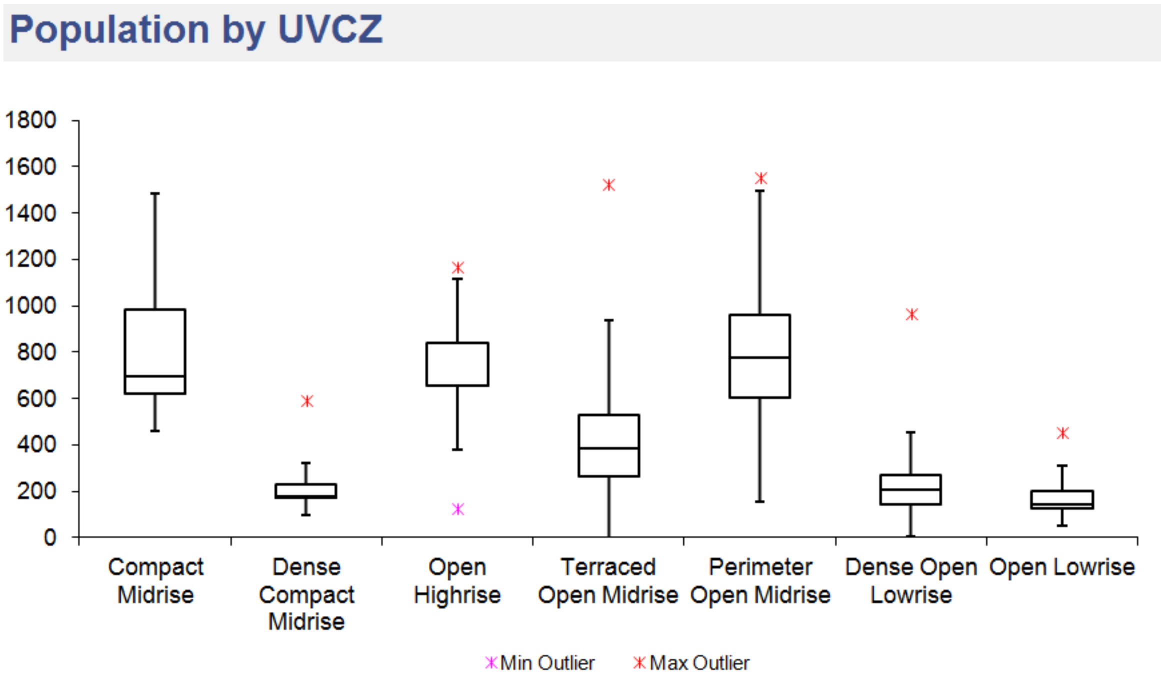


Figure 142: box plot of population density among the potential housing UVCZ in Hamburg city-state in year 2000.

Figure 142 shows the population distribution by potential housing UVCZ in Hamburg city-state area in the year 2000. The compact mid rise, open high rise and perimeter open mid rise classes have the highest population densities on average. The dense compact mid rise, dense open and open low rise have significantly lower densities. The terraced open mid rise class stays in the middle. The low population density of dense compact mid rise could be justified because of the commercial spaces in the ground floors within the central area of Hamburg. However, despite the name of the class, the compact mid rise has a much higher population density. It can be stated, therefore, that the name of the UVCZ class represents the building, but not the population density. And, in the case of the dense compact mid rise class even part of the buildings aren't used for housing people.

Surprisingly, the class of perimeter open mid rise showed an unusually high population density - even higher than open high rise. The outliers of terraced open mid rise showed a similar maximum population count, around 1600 people per cell, although the median is lower. The dense open low rise class, which is the most common UVCZ in Hamburg, represents fairly low population densities, close to 200 by average. The open low rise, as expected, had the lowest population count.

Anova: Einfaktorielle Varianzanalyse

ZUSAMMENFASSUNG

Gruppen	*Anzahl*	*Summe*	*Mittelwert*	*Varianz*	*STDEV*	*Mean*	*Coef. Of variation*
Compact Midrise	21	16871	803,3809524	78074,14762	279,417515	803,3809524	0,347802016
Dense Compact Midrise	16	3615	225,9375	15304,32917	123,710667	225,9375	0,547543755
Open Highrise	47	32919	700,4042553	33995,41998	184,378469	700,4042553	0,263245787
Terraced Open Midrise	1322	555895	420,4954614	47333,82322	217,563377	420,4954614	0,517397683
Perimeter Open Midrise	426	326966	767,5258216	58664,49911	242,207554	767,5258216	0,315569258
Dense Open Lowrise	3322	725065	218,2615894	13074,94363	114,345282	218,2615894	0,523891001
Open Lowrise	76	12165	160,0657895	4064,862281	63,7562725	160,0657895	0,398312923

ANOVA

Streuungsursache	*Quadratsummen (SS)*	*Freiheitsgrade (df)*	*Mittlere Quadratsumme (MS)*	*Prüfgröße (F)*	*P-Wert*	*kritischer F-Wert*
Unterschiede zwischen den Gr.	146848981,7	6	24474830,28	950,1298544	0	2,100124588
Innerhalb der Gruppen	134541650,2	5223	25759,45823			
Gesamt	281390631,9	5229				

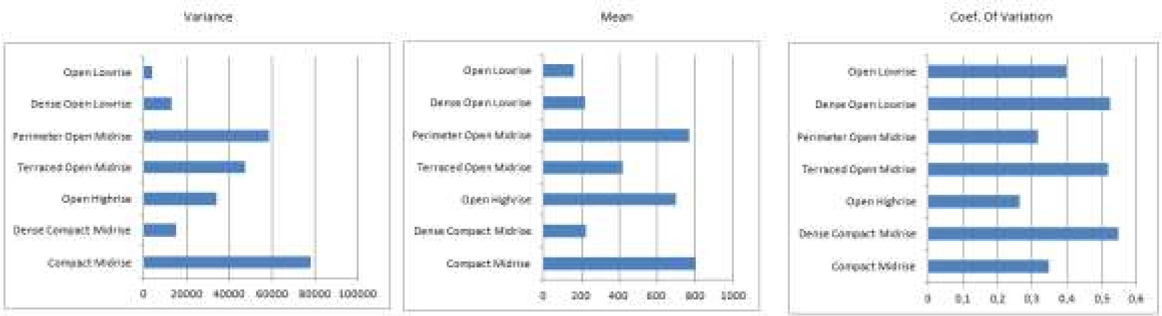


Figure 143: heterogeneity of population among the potential housing UVCZ in Hamburg in year 2000.

The variance of population density (figure 143) is the highest among the compact mid rise cells which is not surprising considering that the mean of the compact mid-rise has the highest value and variance is a function of the mean. Meanwhile the coefficient of variation is lower than average. The most common UVCZ, the dense open low rise has a significantly low variance, but because it has a lower mean of population density than other UVCZ, the coefficient of variation is still quite high. As I discussed previously, the dense compact mid rise is a special class. But one wonders why the higher building density does not represent a higher population density. The answer is that the dense compact mid-rise is a unique class occupying a large part of the old town and has housing as well as commercial and public function. Because it has this unique urban morphology it was not assigned to offices and was excluded from the analysis.

Elderly

Age is the second, and most important social characteristic. The elderly are defined as the population over 65 years of age. Originally, the dataset contains the absolute values of elderly, but I transferred them to the relative number (percentage) in order to avoid the effect of population density.

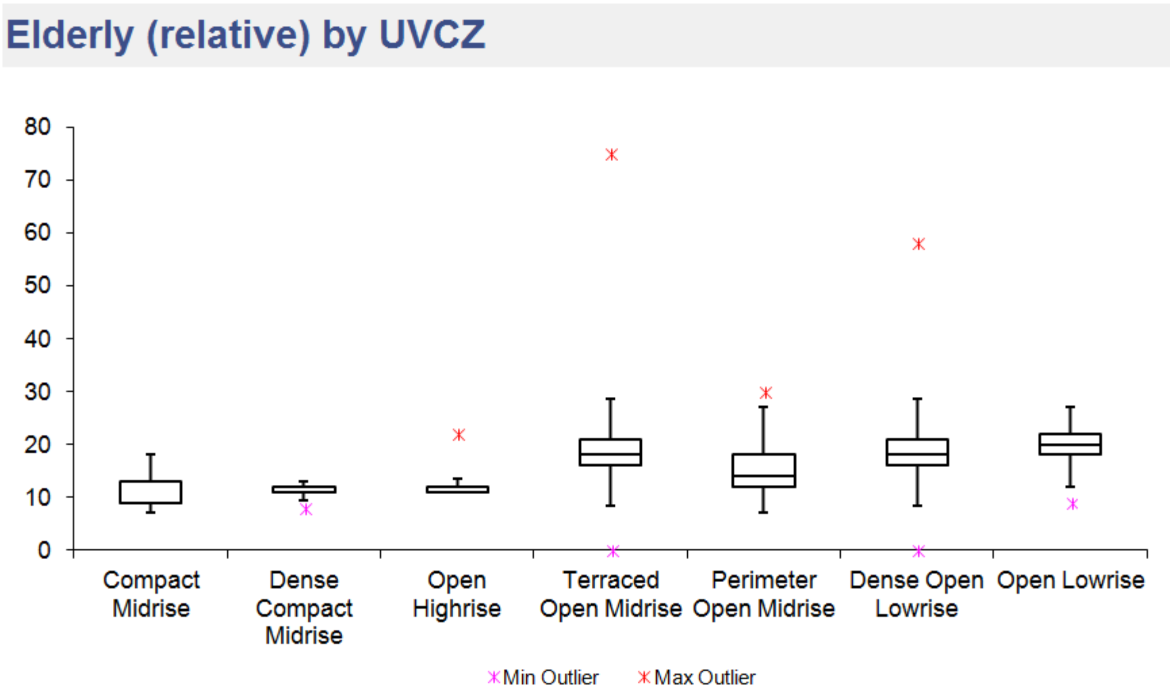


Figure 144: box plot of relative elderly (over 65 years old) among the potential housing UVCZ in Hamburg city-state in year 2000.

Figure 144 shows the distribution of the potential housing UVCZ for the elderly population. The variation is much lower than the population density because the numbers are relative. Although the quartiles and medians are similar for all classes, the max outlier, identifying the max percentage of elderly within a class, differs significantly a lot. This can be seen especially in the terraced open mid-rise class, where just a few cells contain more than 70% of the population over 65 years of age. A similar tendency is seen in the dense open low rise, with a lower percentage. The percentage of elderly in compact mid-rise, dense compact mid-rise and open high-rise classes if low. It is, however, higher in the open mid-rise and low-rise classes. This pattern is typical for elderly people who prefer the quiet of suburbs with a low to average housing density, or even single dwelling homes over the dense, and often noisy areas such as city centers and shopping districts.

Anova: Einfaktorielle Varianzanalyse

ZUSAMMENFASSUNG

Gruppen	Anzahl	Summe	Mittelwert	Varianz	STDEV	Mean	Coef. Of variation
Compact Midrise	21	250	11,9047619	12,59047619	3,5483061	11,9047619	0,298057713
Dense Compact Midrise	16	179	11,1875	1,495833333	1,22304265	11,1875	0,109322248
Open Highrise	47	581	12,36170213	5,975023127	2,44438604	12,36170213	0,19773863
Terraced Open Midrise	1322	24227	18,32602118	28,26683185	5,31665608	18,32602118	0,290115133
Perimeter Open Midrise	426	6315	14,82394366	15,52422535	3,94007936	14,82394366	0,265791577
Dense Open Lowrise	3322	60222	18,128236	16,85798599	4,10584778	18,128236	0,226489096
Open Lowrise	76	1523	20,03947368	10,97175439	3,31236387	20,03947368	0,165291959

ANOVA

Streuungsursache	Quadratsummen (SS)	Freiheitsgrade (df)	Mittlere Quadratsumme (MS)	Prüfgröße (F)	P-Wert	kritischer F-Wert
Unterschiede zwischen den Gruppen	7689,488874	6	1281,581479	66,08083634	1,7798E-79	2,100324588
Innerhalb der Gruppen	101295,6318	5223	19,39414738			
Gesamt	108985,1207	5229				

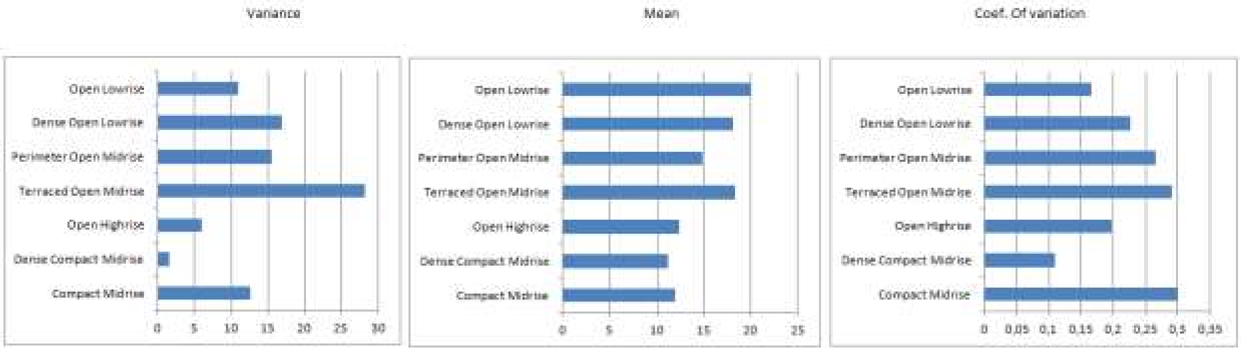


Figure 145: heterogeneity of relative elderly (over 65 years old) among the potential housing UVCZ in Hamburg in year 2000.

The variance, as well as the coefficient of variation, is the highest among the terraced open mid rise class, while the lowest value belongs to the dense compact mid rise class. The highest concentration of an average percentage of elderly is within the open low rise and the lowest concentration is in the dense compact mid-rise. Generally speaking, there are no classes in which the majority of the people are over 65 years old. However, as noticed in the box-plot, the higher concentrations of the elderly at one time lived in terraced open mid-rise and low-rise classes. The open high rise, the dense compact and compact mid-rise appear to be for younger people and the perimeter open mid-rise is for the middle aged people. There are no extreme values for any specific class by average, as all average values range from 11 to 20. It would be obvious that no housing type can be occupied by one age class alone, but the fact is that the terraced open mid-rise and dense open low-rise are the “oldest” housing types in the UVCZ classes in Greater Hamburg.

Welfare recipients

Welfare recipients is an adaptive capacity indicator and says how many people receive welfare. Indirectly, this indicator is related to income and unemployment, poverty. It would be fair to say that if a person is receiving welfare, they are probably unemployed or underemployed, so that the number of people receiving welfare could be an indicator of poverty. As we see more people receive welfare we also see their adaptive capacity is lowered.

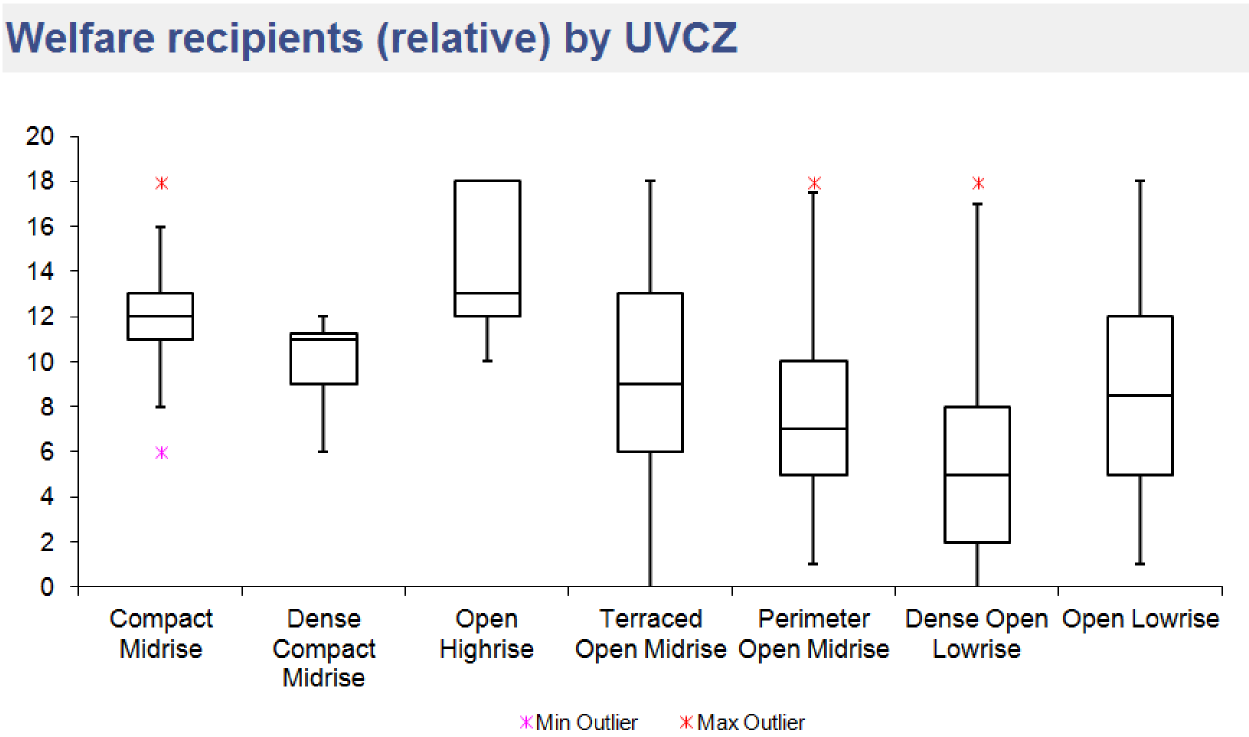


Figure 146: box plot of relative welfare recipients among the potential housing UVCZ in Hamburg city-state in year 2000.

Figure 146 presents the box-plot of the relative number (percentage) of welfare recipients in each potential housing UVCZ class. A clear difference can be observed between the two sets of classes (similar to the elderly case, discussed previously). The compact mid rise and open high rise have a higher number of welfare recipients, by average. These two classes (except the perimeter open mid rise) have the greatest population density, while the lowest number of welfare recipients, on average, is in the dense open low rise. This class is very diverse with a wide range of outliers. Some cells have as low as 18% of welfare recipients. The outliers for compact mid-rise and open high rise are narrower. This means that these classes have lower variance which can be seen in figure 147.

Anova: Einfaktorielle Varianzanalyse

ZUSAMMENFASSUNG

Gruppen	Anzahl	Summe	Mittelwert	Varianz	STDEV	Mean	Coef. Of variation
Compact Midrise	21	258	12,28571429	9,314285714	3,05193147	12,28571429	0,248413027
Dense Compact Midrise	16	163	10,1875	3,095833333	1,75949803	10,1875	0,172711464
Open Highrise	47	688	14,63829787	8,757631822	2,95932962	14,63829787	0,202163506
Terraced Open Midrise	1322	12718	9,620272315	21,71792332	4,66024928	9,620272315	0,484419684
Perimeter Open Midrise	426	3301	7,748826291	15,42617509	3,92761697	7,748826291	0,50686605
Dense Open Lowrise	3322	18572	5,590608067	15,75767148	3,96959336	5,590608067	0,710046799
Open Lowrise	76	642	8,447368421	18,62385965	4,31553701	8,447368421	0,51087354

ANOVA

Streuungsursache	Quadratsummen (SS)	Freiheitsgrade (df)	Mittlere Quadratsumme (MS)	Prüfgröße (F)	P-Wert	kritischer F-Wert
Unterschiede zwischen den Gruppen	19551,17508	6	3258,52918	189,928249	1,595E-219	2,100324588
Innerhalb der Gruppen	89609,09184	5223	17,15663256			
Gesamt	109160,2669	5229				

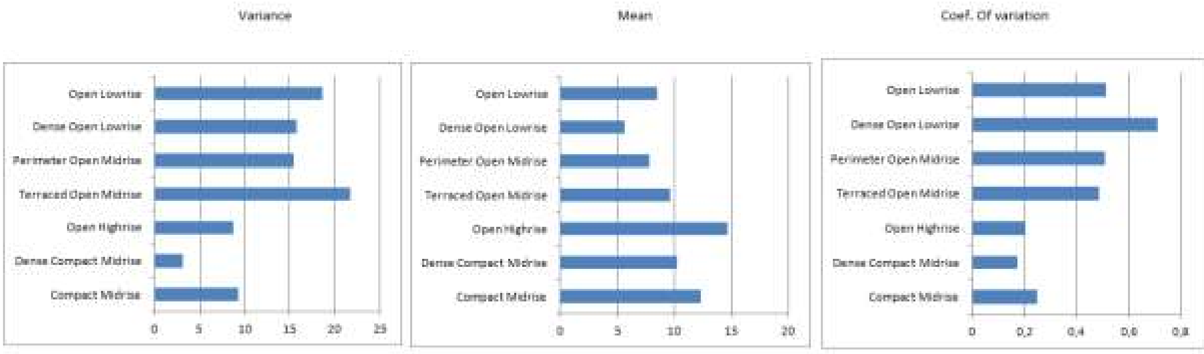


Figure 147: heterogeneity of relative welfare recipients among the potential housing UVCZ in Hamburg in year 2000.

While it can be observed from the box plot, figure 147 also makes even more clear that the heterogeneity of the relative number of welfare recipients is much higher in the classes of open low-rise and open mid-rise UVCZ, even though their means are lower. Statistics clearly show that the more financially sensitive groups (welfare recipients) live in open high rise, dense compact mid-rise and compact mid-rise classes, with a low coefficient of variation.

The statistical analysis presents the comprehensive results of the social population's characteristics, their distribution and their average values by potential housing UVCZ classes. The characteristics differ not between the individual, but between the groups of classes. It is obvious, however, that no certain social group (elderly, young, poor or rich) can live within one type of potential housing UVCZ class.

The table 20 shows population's statistics. In order to model the future population density, the relative number of elderly and the number of welfare recipients, I decided to use not the means, but the values within the range of +/- 0,5 standard deviation from the mean. For instance, if statistically there were an average of 803 people per cell of compact mid-rise in 2000, all new compact mid rise cells will have a random value of population density from 664 to 943. It is possible that one new open low rise cell will have 190 people and the other dense open low rise cell nearby will have 162 people. This may happen because of the high variance of the population density between historical cells.

Table 20: min, max, mean and standard deviation values of the population density, elderly and welfare recipients for each potential housing UVCZ within Hamburg city-state.

Population density

	Compact mid rise	Dense compact mid rise	Open high rise	Terraced open mid rise	Perimeter open mid rise	Dense open low rise	Open low rise
Min	462	99	123	0	153	2	48
Max	1485	595	1168	1523	1554	967	454
Mean	803	226	700	420	768	218	160
SD	279	124	184	218	242	114	64
+0,5SD	943	288	793	529	889	275	192
-0,5SD	664	164	608	312	646	161	128

Welfare recipients (relative)

	Compact mid rise	Dense compact mid rise	Open high rise	Terraced open mid rise	Perimeter open mid rise	Dense open low rise	Open low rise
Min	6	6	10	0	1	0	1
Max	18	12	18	18	18	18	18
Mean	12	10	15	10	8	6	8
SD	3	2	3	5	4	4	4
+0,5SD	14	11	16	12	10	8	11
-0,5SD	11	9	13	7	6	4	6

Elderly (relative)

	Compact mid rise	Dense compact mid rise	Open high rise	Terraced open mid rise	Perimeter open mid rise	Dense open low rise	Open low rise
Min	7	8	11	0	7	0	9
Max	18	13	22	75	30	58	27
Mean	12	11	12	18	15	18	20
SD	4	1	2	5	4	14	3
+0,5SD	14	12	14	21	17	25	22
-0,5SD	10	11	11	16	13	11	18

The variance and variation might be high for some of classes, but it is not clear what would be an acceptable homogeneity. Therefore, I approved and accepted the variance and variation of the social characteristics. Those statistics give a broad understanding and distribution among the potential housing UVCZ classes. The ranges of half of the standard deviation of the characteristics will be used for the modeling the new emerging cells in the Metronamica CA model. It is highly possible that the new datasets will be developed in future and a more comprehensive statistical analysis of the social characteristics could be done. But at this moment, the most comprehensive way to model future vulnerability indicators is to use statistics.

6.2 Auxiliary indicators

The auxiliary indicators are the vulnerability indicators, not modeled in this study, but supplied by other models. Technically, they were modeled in other studies, scientifically or methodologically approved and published in open access sources. I used these studies to provide more auxiliary indicators while conserving resources and time spent on modeling. This case study uses two auxiliary indicators at the local scale - the monthly average minimum and maximum temperatures and the distance to the nearest hospital. Both indicators were obtained and processed before they were able to be integrated into the vulnerability assessment.

Monthly average minimum and maximum temperatures

Temperature is the key indicator used to define the severity of a heat hazard effect. In my vulnerability concept it is one of the exposure indicators - the physical exposure. After analyzing a number of heat impact and vulnerability to heat waves studies (DG Environment, European Commission, 2007, 2011; Hunt and Watkiss, 2013; Kazmierczak, 2012; Kropp et al., 2009; Murphy et al., 2011; Preston and Smith, 2008; Rinner et al., 2010; Schauser et al., 2010), I concluded that the temperature is the most commonly used heat hazard indicator. For heat-related mortality studies, temperature is the best predictor of the mortality (Huang et al., 2011). But there exist many types of temperatures. According to the Barnett et al., (2010), who examined seven temperature types (minimum, mean, maximum and minimum, mean, maximum apparent temperatures and humidity index) on a daily basis for 107 US cities between 1987 – 2000, none of the temperature types had an advantage, because all types had a strong correlation between themselves. Therefore, for the projection based research, Huang et al., (2011) recommends to choose the mean temperature as the most available and commonly used indicator from the climate models.

For most vulnerability assessment studies, the dominant factor in choosing an indicator is its availability. This study is not an exception. Unfortunately, I could not find any local Hamburg studies providing future temperature data on a local scale. Therefore, I searched for any downscaled data which would have a good correlation with future temperatures in Greater Hamburg. I found a downscaled global model temperature data for the years 2041 – 2060. These were the monthly average minimum and maximum temperatures with the spatial resolution of 30 arc seconds. In general the minimum and maximum temperatures are quite the good measures to identifying a heat hazard, which is the consequence of a heat wave. The German Environmental Ministry defines a heat wave as a prolonged period of time in which the average daily maximum temperature is over 30°C and stays longer than five consecutive days in the row (German Environmental Ministry, 2016). A minimum nighttime temperature of higher than 20 °C is identified as a tropical night (DWD, 2016) and can cause a serious threat to a population which is looking for relief after an extremely hot day. With these definitions, the future monthly average minimum and maximum temperatures seem to be a good selection for this study. But it is not enough to select appropriate indicators. The next important step is to identify which monthly average minimum and maximum temperature values are the threat to the people.

Mortality and the temperature

A number of epidemiological studies (Baccini et al., 2008; Bell et al., 2008; Goodman et al., 2004; Hajat et al., 2005; Stafoggia et al., 2009; Yu et al., 2011) have found a strong correlation between mortality and the maximum, average apparent and diurnal temperatures.

A few studies (Anderson and Bell, 2009; Hajat et al., 2002; Yu et al., 2010) compared the mean temperature with other temperature measures using statistical methods and concluded that the mean temperature had strongest correlation to the heat-related mortality. Additionally, the average temperature is the easiest to assess and compare within the policy context (Anderson and Bell, 2009). The relationship between temperature and mortality is often represented as log-linear model and described as a "V", "U" or "V" shape (Armstrong, 2006; Braga et al., 2002; Curriero et al., 2002; Hajat et al., 2007; McMichael et al., 2008).The mortality increases when the temperature passes a certain threshold which varies from place to place and from time to time (Souch and Grimmond, 2004). The heat threshold is known as the minimum mortality temperature (MMT) and is defined as an optimum temperature corresponding to the minimum level of mortality (Kalkstein and Davis, 1989). The

Hajat and Kosatky (2010) analyzed the relationship between daily mortality and summertime daily mean temperature in London between 1976 – 2006. The risk of mortality drastically increased when the average temperature passed the MMT which was defined as 20 °C for the London City. Another study by Hajat et al. (2007) discussed the heat-related deaths in England and Wales. That threshold was derived from the 95th percentile of mean temperature and varied from 17,7 to 20,4 °C. The heat effects were more visible once the mean temperature reached the value of 17 - 18°C and the most of the affected people were, of course, the elderly. Ishigami et al. (2008) analyzed the mortality in three European cities: Budapest, London and Milan, with thresholds of 24,4, 20,4 and 23,0 °C which were the 95th percentiles of daily mean temperatures. In that study the thresholds were called as "heat cut-points" and the highest impact of heat occurred to people above 65 years old as well. The research done by Keatinge et al. (2000) compared the annual heat and cold mortalities in northern and southern Finland, Netherlands, London, southern Germany, northern Italy and Athens. The thresholds in these areas were not fixed, but were stated in 3°C bands associated with the mean summer temperature. The bands of 3°C in southern Germany ranged from 19,0 to 22,0 °C, in London from 19,3 to 22,3 °C and in Netherlands from 17,3 – 20,3 °C. However, the study in Netherlands (Kunst et al., 1993) identified a significantly lower threshold. Based on the observed data, the lowest mortality occurred when the average daily temperature was only 16,5 °C. The further systematic reviews (Hajat and Kosatky, 2010; Yu et al., 2010) present the long list of thresholds mostly related to the daily mean, mean apparent and maximum apparent temperatures, all around the world. Of the highest interest for the Greater Hamburg case study are the thresholds in London, Netherlands and southern Germany, which have similar climates to Greater Hamburg. I assume that the average daily temperature should correlate will with the minimum mortality temperature of 20,0 °C in Greater Hamburg as well. Ignoring the factor of acclimatization, it should be able to be said that daily average temperatures in Greater Hamburg higher than 20,0 °C should cause an increase in heat-related mortality. Later on in the text, I will call the days with the daily average temperatures over 20 °C as the heat days not to be confused with the common definition of summer, or hot, days.

Thresholds in Greater Hamburg

Although the threshold of average daily temperature is assumed, the only data I have for future temperatures for Greater Hamburg is the monthly average minimum and maximum temperatures. The daily average temperature is not the same as the monthly average temperature, which is the sum of the daily average temperatures divided by the number of days. The result of this is that the monthly average temperature has a much lower variation and the temperature extremes are much difficult to identify. The task, then, is to review the historical Hamburg climate data to ascertain if there is any correlation between the monthly average minimum and maximum temperatures and the daily average temperature. For the analysis I selected the hottest month of the year in Greater Hamburg – July.

The historical monthly minimum and maximum temperatures in Hamburg show a great correlation and linear relation (figure 148). This means that, based on monthly averages, the days with a high maximum temperature also experience higher minimum temperatures during the night as well. Although the monthly minimum and maximum temperatures have a good correlation, I decided to use both of them in order to identify a stronger relationship between the monthly average minimum/maximum temperature and the occurrence of the heat days (when the daily average temperature is higher than 20°C).

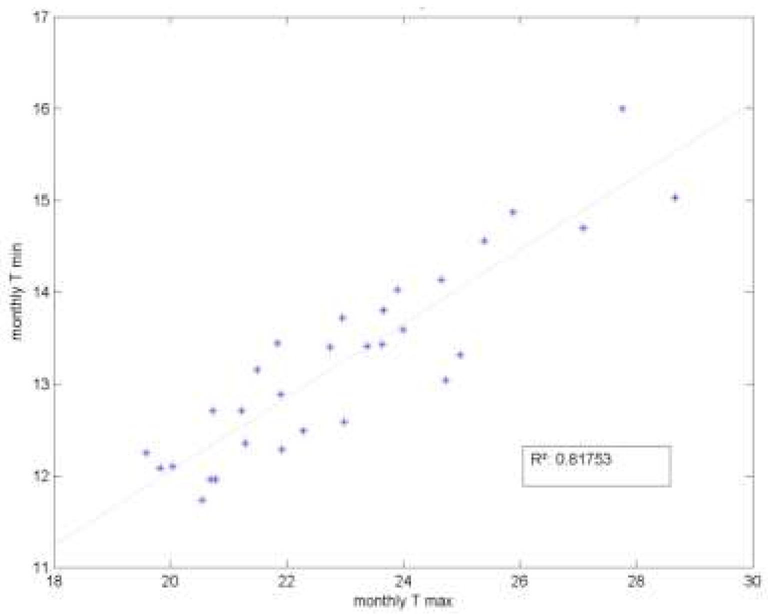


Figure 148: correlation between monthly average minimum and monthly maximum temperatures in Hamburg in July months in 1986 – 2015 (source: DWD).

Figure below (149) shows the positive correlation between the monthly average minimum (left) and the maximum temperatures (right) with the number of heat days (daily average temperature over 20 °C) in one of the weather stations in Hamburg in 1986 – 2015. The x axis shows the number of heat days and the y axis shows the monthly average minimum (left) and maximum (right) temperature of that month. The lowest monthly average minimum temperature (left) causing the appearance of a heat day is about 12°C. It means that the number of heat days starts to appear when the monthly average minimum temperature is higher than 12°C (on average). For instance, there is one instance in which the month of July, with a monthly average minimum temperature of ~14,7 °C experienced about 20 heat days. The lowest monthly average maximum temperature (right) causing the appearance of a heat day on average is about 20°C. There are two times that the month of July, with a monthly average maximum temperature of ~ 25°C, experienced about 14 heat days.

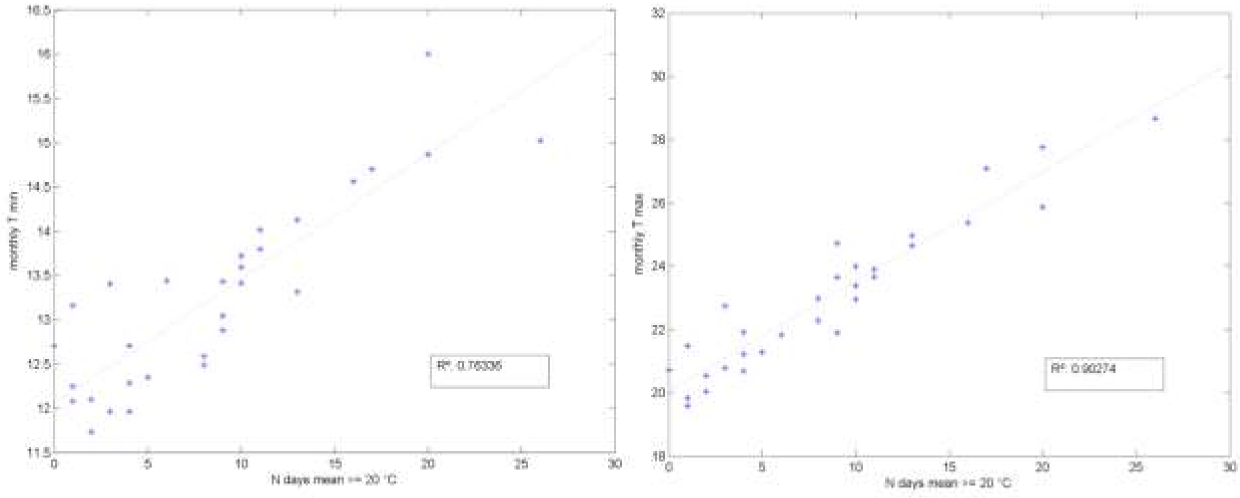


Figure 149: correlation between monthly average minimum (left) and maximum (right) temperatures with the heat days in Hamburg in July months in 1986-2015 (source: DWD).

Lowest monthly average minimum and maximum temperatures causing the appearance of heat days can be identified as thresholds for future monthly average minimum and maximum datasets. Such an approach transfers the MMT from the average daily mean (based on literature analyzed previously) to the monthly average minimum and maximum temperatures and the future data available for the Greater Hamburg. If the spatial distribution of historical temperatures is available, the areas with a potential appearance of days with the daily mean over 20,0°C can be identified. The only available historical spatial distribution of monthly average minimum and maximum temperatures for Greater Hamburg was available in the WorldClim database (WorldClim, 2016). This data is observational and was interpolated from the time period 1960 - 1990. Although the time period of the correlated data and the WorldClim datasets does not exactly match, it would be a good idea to investigate which areas experience/experienced heat days. Figure 150 presents the spatially distributed historical monthly average minimum and maximum temperatures for Greater Hamburg. The monthly average minimum temperature (left) for Greater Hamburg ranges from 11,0 to 12,9°C and the maximum temperatures (right) ranges from 20,9 to 23,2 °C. This data is observed data and interpolated from a period that is longer than three decades. If some of the year had extreme temperatures, it cannot be shown, because of the average values. From the perspective of the minimum temperature, the lowest temperatures are dominant in the West and in the South of GH, with some limited clusters in the North and Northwest. The temperatures are higher in the central part and to Southeast, most probably caused by the effects of the Elbe River. The greater difference is located in the East and the far Southeast which are the mostly agricultural areas. A similar trend is identified with the maximum temperatures, except, that the temperatures in the North are similar to the temperatures in the West. The temperatures in the East are not as high as the temperatures in the central Southern areas. The climate of the North Sea affects the North, West and South, while the East and Southeast areas are affected by the continental climate.

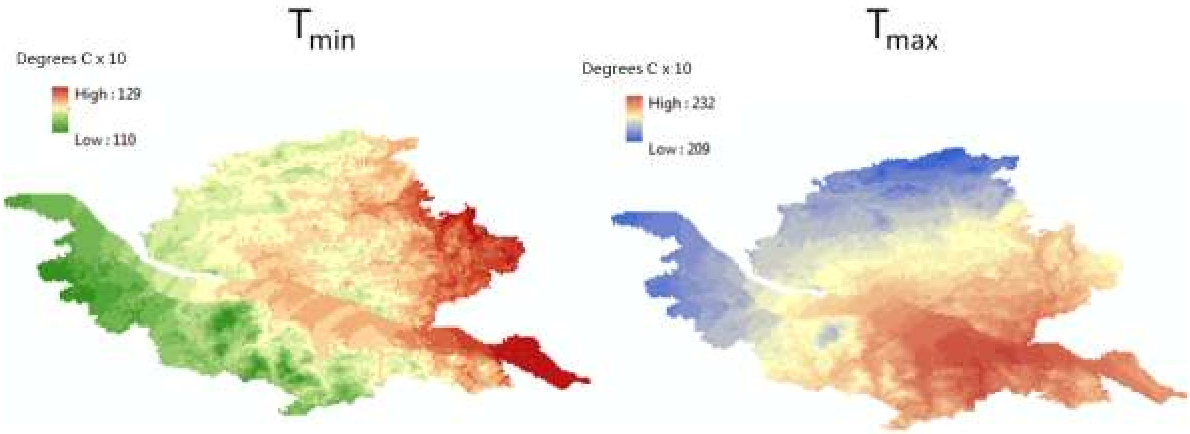


Figure 150: historical (1960-1990) interpolated monthly average minimum (left) and maximum (right) temperatures (source: WorldClim, 2016).

Previously I discussed the developed MMT thresholds for monthly average minimum and maximum temperatures. Figure 151 shows these thresholds would be applied for the current data. If we would consider only the maximum temperature (right), the entire Greater Hamburg area would experience (hatched area) the appearance of heat days (daily mean higher than 20,0°C), because the lowest maximum temperature is 20,9°C which is above the threshold of 20,0°C. It means that the entire case study area experienced more than one heat day in 1960 – 1990.

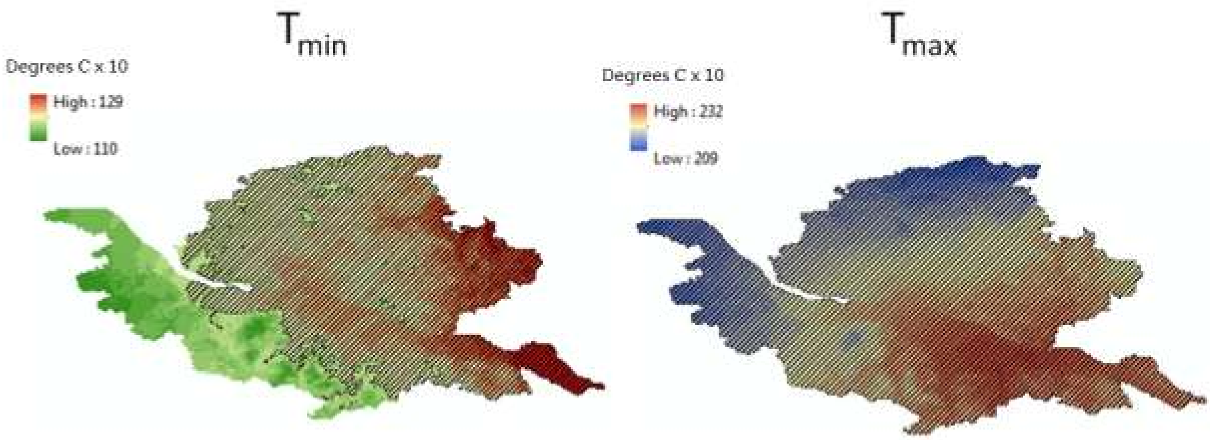


Figure 151: historical (1960-1990) interpolated monthly average minimum (left) and maximum (right) temperatures. The hatched areas mark the temperatures causing appearance of the heat days (source: WorldClim, 2016).

Meanwhile, if we consider the minimum temperature (left), the areas in the West, Southwest, South and some clusters in the North did not experience (hatched area) the appearance of heat days, because these are the areas with a monthly average temperature below the threshold (12,0°C). However, in the reality, I cannot state that these areas surely did not experience the days with the daily mean over the 20,0°C. These data are only the monthly averages, which have been observed and interpolated over a long period of time and do not exactly represent the discrete climatic events of extreme temperatures.

Distance to the nearest hospital

The distance to the nearest hospital is another auxiliary indicator which was available to use for a vulnerability assessment. The word “hospitals” includes not only hospitals but also private and public clinics which provide healthcare services. This indicator is the only vulnerability indicator proximity and is employed as one of the adaptive capacity indicators. The distance to certain healthcare facilities gives different values. In this case the shorter the distance to a hospital, the greater the adaptive capacity.

According to the World Health Organization (2009), the availability of healthcare services is one of the heat mortality-related factors. During the heat events, the people seek for assistance, and the closer the hospital or other health care facility is, the shorter the required time period is to reach it. When the distance to the healthcare facility is too long, and requires too much time to reach a healthcare facility, some people do not even bother to go to seek assistance thinking that their health will get better. Another topic altogether is the affordability of healthcare for people, as well as the availability of healthcare. There is no doubt that the availability of the healthcare infrastructure gives significant boost to the adaptation to the heat hazard events. Because of these considerations, this indicator must be included in the vulnerability framework.

Unfortunately, the UVCZ classes do not contain any information about healthcare infrastructure or its facilities. Therefore it was decided not to relate it to the UVCZ proxy, as many other indicators have been, but to have it a separate indicator. What is not clear is whether the distance to the facilities should be measured according to the Manhattan or the Euclidian method. The Manhattan distance measures the accessibility in a more realistic way by considering different speeds of movements over different surface types, surface types, and obstacles such as rivers and building blocks. It would require additional processing of the road network, which would require a significant amount of time and resources. One more consideration concerning this Manhattan method is that healthcare facilities can be reached not only by private car but also by metro and surface trains and/or buses, all of which have their own transportation networks.

Because the focus of this research is on methods to do the research, and not on obtaining the best quality of data, it was decided to keep it simple and use the Euclidian method. This method measures/evaluates the direct distance to the healthcare facility for each potential housing UVCZ in Greater Hamburg. Figure 152 shows the distance to all cells including facilities both inside and outside Great Hamburg because the boundaries of the study area not “impenetrable”, meaning the people living far from healthcare facilities within Greater Hamburg can also access facilities outside Greater Hamburg, and vice versa. The green colored areas in figure 152 have a closer proximity to the healthcare facilities than the yellow or the red colored areas. Some parts are very isolated and are at a significant distance away from the healthcare infrastructure. Hence the population living within these areas would have limited adaptive capacity during the heat events.

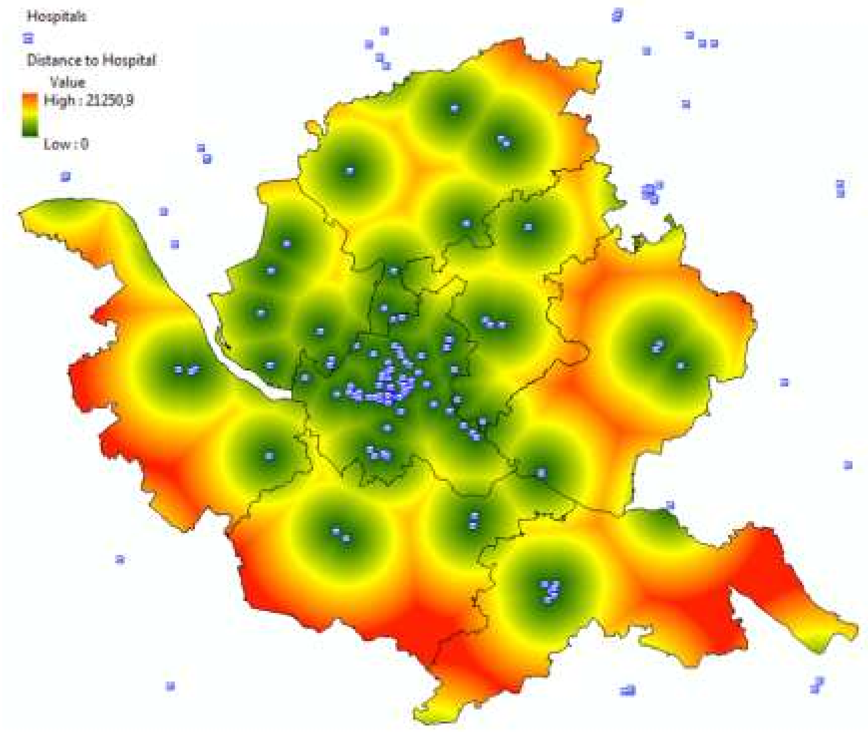


Figure 152: Euclidian distance to the healthcare facilities for each cell within Greater Hamburg.

There is certainly an interest in the future, and the question about healthcare facilities in the future is certainly valid. What can we know about healthcare facilities in 2050? The ability to model locations where the future healthcare facilities will stay, is very limited or does not exist at this moment. The development of certain UVCZ classes cannot be related to the construction of the new facilities either. In general, the role of adaptive capacity and adaption was always questionable, as well as indicators representing them. The theory and the practice are very are unclear and difficult to determine. Therefore it was decided to use the current distance to the nearest hospital as a suitable adaptive capacity data, assuming that it will not change over time.

7 Scenarios, projections and future vulnerability indicators

The discretized vulnerability indicators give a green light to model future vulnerability via future UVCZ. However, the future UVCZ is not known yet. The calibrated UVCZ model allows us to use the historical UVCZ development pattern to produce future UVCZ. However, the future is affected by more than just the historical UVCZ development. This chapter covers the list of climate change, population, socio-economic, zoning and urban development scenarios, selected and applied in the Greater Hamburg case study. These scenarios give a greater possibility to see how certain processes could affect future UVCZ and future vulnerability. Based on these scenarios, future vulnerability indicators are modeled.

The "future" in general is a very abstract word. According to the Online Dictionary of Oxford, the future is "*a period of time following the moment of speaking or writing*" (Oxford University Press, 2015). However, the future can be the next 5 seconds, as well as next 5 centuries or millenniums. When we are saying the "future" it means the occurrence of future events which would occur in the following time. The projected future events are based on the scenarios, the possibilities of consequences which would occur in a certain sequence of events. Scenarios are not projections or predictions, but rather credible and coherent stories defining different paths of future events (Davis, 2002). Scenarios are nothing more than our defined sequence of specific events. Creating scenarios helps to understand not only the sequence of events, but also the consequences of these events. They also can be very helpful in making decisions.

The processes and the time frame we are dealing with today are so complex, and are so far into the future that the science of today cannot really predict how thing will happen in the next 50 years. Scenarios help us to speculate on future actions and reactions and outcomes. The use of scenarios is often helpful in describing the sequence of events and their consequences in the case of extreme events. By identifying the most favorable consequence, a specific scenario can be chosen and decisions can be made to affect the actions that would, as closely as possible, result in the best possible outcome.

The IPCC is an active actor by developing future climate, social and economical scenarios. The following figure shows previously and recently used IPCC scenarios. The previously used Special Report on Emissions Scenarios (SRES) on the left side of the image represent the global surface warning in degrees of Celsius during a specific year, based on the global emissions of the greenhouse gasses as expressed in letters and numbers (i.e. B1, A1T etc.). The far left image (in figure 153) shows the allocation of the aggregated emissions scenarios by being environmentally or economically friendly, from a global or regional focus.

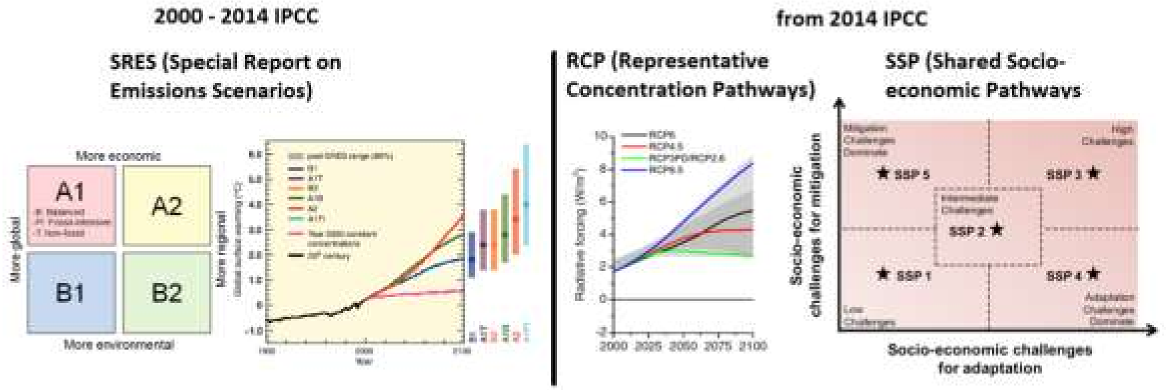


Figure 153: previously and recently used IPCC global greenhouse gas emissions, radiative forcing scenarios and their allocation by social, economical and environmental focus (O'Neill et al., 2015; Susan, 2007).

The right side shows the RCP which represent the four greenhouse gas emissions scenarios by the radiative forcing during the time period, up to 2100. On the far right side is the shared socioeconomic pathways (SSP), related to the integrated assessment scenarios. The SSP are the part of the climate change framework, developed by the climate change research community, in order to facilitate the integrated analysis of the future climate impacts, vulnerabilities, mitigation and adaptation (O'Neill et al., 2015). These scenarios are developed by experts, who used knowledge and various models to identify how the specific greenhouse gas emissions would affect the world and what the consequences would be. Based on the consequences, decision makers can decide which path should be taken to achieve the desired results (possible consequence).

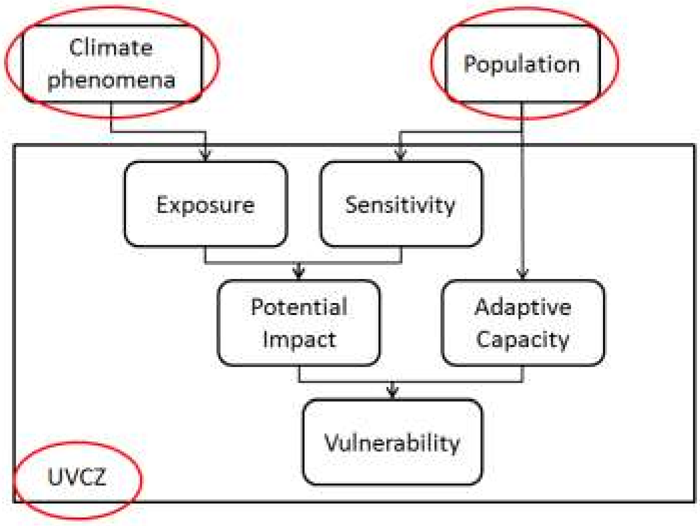


Figure 154: IPCC vulnerability assessment framework and affecting factors (circled in red).

The scenarios of the case study for Greater Hamburg should represent a high specter of plausible, but abstract pathways which would affect future vulnerability. It is important, therefore, to develop a concept of what these scenarios should represent. The scenarios should be logical and related to the input data (indicators) and should be able to affect the model. As I discussed previously, I use the IPCC vulnerability assessment framework (figure 55) which takes into account the elements of exposure, sensitivity, potential impact and adaptive capacity. All of these elements are affected by UVCZ - the urban landscape, climate and population. The different UVCZ scenarios would mean different UVCZ allocation within the Greater Hamburg study area. In summary, the future population's vulnerability to heat waves is based on three types of scenarios: climate, population and environment (zoning and urban development).

7.1 Climate change

In this study, the scenarios of the climate phenomena represent the monthly average minimum and maximum temperatures under the specific greenhouse emissions' scenarios which are also known as representative concentration pathways (RCP) introduced in the Fifth Assessment Report (AR5) by the IPCC (2014b).

Representative Concentration Pathways (RCP)

In total, four RCP scenarios exist: RCP2.6, RCP4.5, RCP6, and RCP8.5. All of them are named after the possible range of radiative forcing values in the year 2100 relative to the pre-industrial values. The number (i.e. "2.6", "4.5") means the watts per square meter (Weyant et al., 2009). For instance, the radiative forcing in the RCP2.6 scenario in 2100 will be 2,6 W/m^2 higher than in pre-industrial times and in the RCP8.5 scenario it will be even 8,5 W/m^2 higher. Meanwhile the radiative forcing is calculated using the scenarios of greenhouse gas emissions. The scenarios of greenhouse emissions are based on current countries' gas emissions, industries' influence on the GDP, the usage of the fossil fuels, perspective of renewable energy, recycling ratio and many other aspects (Bjornas, 2015). The following table shows a detailed overview of each RCP scenario.

Table 21: RCP scenarios used in AR5 and listed by emissions, developer, radiative forcing, comparison to SRES and additional features (after Bjornas, 2015).

Name	Emissions	Developed by	Radiative forcing	Comparable to SRES	Features
RCP 2.6	Low	PBL Netherlands Environmental Assessment Agency	2.6 W/m2 by 2100	None	Declining use of oil
					Low energy intensity
					World's population of 9 billion by year 2100
					Use of croplands increase due to bio energy production
					More intensive animal husbandry
					Reduction of methane emissions by 40%
					CO2 emissions stay at today's level till 2020, then declines and negative in 2100
					CO2 concentrations peak around 2050, then modest decline to 400 ppm by 2100
RCP 4.5	Intermediate	Pacific Northwest National Laboratory in US	4.5 W/m2 by 2100	B1	Lower energy intensity
					Strong deforestration programmes
					Decreasing use of croplands and grassland due to yield increases and dietary changes
					Stringent climate policies
					Stable methane emissions
					CO2 emissions increase only slightly before decline starts around 2040
RCP 6.0	Intermediate	National Institute for Environmental Studies in Japan	6.0 W/m2 by 2100	B2	Heavy reliance on fossil fuels
					Intermediate energy intensity
					Increasing use of croplands and declining use of grasslands
					Stable methane emissions
					CO2 emissions peak in 2060 at 75% above today's level, then decline to 25% above today
RCP 8.5	High	Applied System Analysis in Austria	8.5 W/m2 by 2100	A1F1	Three times today's CO2 emissions by 2100
					Rapid increase in methane emissions
					Increased use of croplands and grassland, driven by an increase in population
					A world population of 12 billion by 2100
					Lower rate of technology development
					Heavy reliance on fossil fuels
					High energy intensity
					No implementation of climate policies

The RCP scenarios are used to calculate global climatic phenomena in the advanced and complicated climate models. The table below (22) shows the global mean and likely range of the global surface temperature based on the RCP scenario. However, these are the global values and they cannot be applied for the Greater Hamburg case study. The other issue is that the research teams around the world use different global climate models (GCM). These models include specific region-based features and often generate different outputs. Therefore it is important to select the most suitable GCM for Greater Hamburg case study and downscale it to the required resolution (scale).

Table 22: global mean surface air temperature for the mid and late 21st century relative to the reference period of 1986 – 2005. Based on CHIMP5 model (Field et al., 2014).

		2046–2065		2081–2100	
	Scenario	Mean	*Likely* range[c]	Mean	*Likely* range[c]
Global Mean Surface Temperature Change (°C)[a]	RCP2.6	1.0	0.4 to 1.6	1.0	0.3 to 1.7
	RCP4.5	1.4	0.9 to 2.0	1.8	1.1 to 2.6
	RCP6.0	1.3	0.8 to 1.8	2.2	1.4 to 3.1
	RCP8.5	2.0	1.4 to 2.6	3.7	2.6 to 4.8

The most suitable model for this case study is the Max Planck Institute Earth System Model (MPI-ESM). The model is developed by my colleagues from Hamburg, University of Hamburg, Institute of Meteorology. This model combines the exchange of energy between the atmosphere, ocean and land surface. Fortunately I found the auxiliary future climate data, downscaled from the MPI-ESM model for three RCP scenarios on the website of WorldClim (WorldClim, 2016) in the resolution of 30 arc seconds. The data is in the GeoTIFF format, downscaled and calibrated using the WordClim 1.4 as baseline 'current' climate. The available time period is 2050 (average for 2041-2060) and the variables of the data are the monthly average minimum temperature in °C multiplied by 10, monthly average maximum temperature in °C multiplied by 10, monthly total precipitation in milimeters and other annual average bioclimatic variables. Based on previous knowledge (chapter 6.2) the monthly average minimum and maximum temperatures are suitable climatic indicators for the heat hazard study.

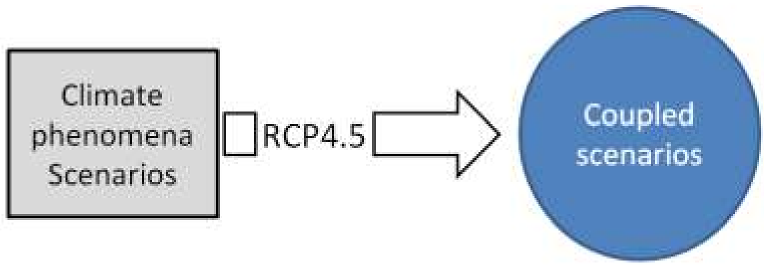


Figure 155: the RCP4.5 scenario is the only scenario used for the Great Hamburg case study. In the end it will be coupled with other scenario types.

In order to reduce the number of results and focus on the recent ones, it was decided to use only one future climate scenario. The main reason for this decision is that the high number of scenarios would cause greater complexity and multiple results which would be difficult to compare and analyze in details. Therefore, from three available RCP scenarios, I selected the RCP4.5 which is the average, business as usual (BaU) scenario. This scenario is the most probable pathway if the influence of the factors affecting climate today would remain constant or close to constant. I think this scenario is the middle ground of all three scenarios. This RCP 4.5 climate scenario must be coupled with other, environmental and population scenarios.

7.2 Population

The population scenarios are very important to this research, when addressing the population's vulnerability. Vulnerability can change dramatically between now and 2050, caused by different patterns in population growth and changes in population characteristics (aging, increased poverty, etc.). But the population is not environment or the climate. It is more dynamic and more complex to project, especially today when people are so mobile and can travel and reside without visas. It is obvious, that it is not possible to model the future for each individual living in Hamburg, although some computers in the world would be able to. Therefore the high degree of abstraction has to be maintained. The idea is to use the population development (population growth) and population aging scenario which would be based on the local Greater Hamburg population projections, considering births, deaths, migration and aging process. But the prime step is to be aware of available local population projections.

Available population projections

The Greater Hamburg case study covers the federal state of Hamburg (city-state) and the adjacent districts of Lower Saxony and Schleswig-Holstein (figure 156). The service providing the population statistic for Greater Hamburg is divided into two regional statistical offices. For Hamburg city-state and Schleswig-Holstein the Statistikamt-Nord is responsible while statistics for Lower Saxony are found in the statistical office of Lower Saxony ("Landesamt fur Statistik Niedersachsen" in German). The population development trends also differ not only among the federal states but also among the districts within the federal state, causing differences between the population projections.

Figure 156: The Greater Hamburg, the federal state of Hamburg (green) and surrounding districts (red – Lower Saxony, yellow – Schleswig-Holstein).

The first analyzed population's projection is for the city-state Hamburg. The projection is developed by the Statistical Department of Hamburg and Schleswig-Holstein (Statistikamt-Nord) and published on 7th of September in 2015 and titled "*Population's Development in 2015 – 2035 in Hamburg. The result of the 13th coordinated population's projection*" (Statistisches Amt für Hamburg und Schleswig-Holstein, 2015a). This report contains two scenarios (W1 and W2) in which population is grouped by age groups for every 5 years (starting in 2015) till 2035. Additionally it has annual information of births, deaths, migration from foreign countries and federal states and total population. The scenarios W1 and W2 represent different immigration policies in Germany. The W1 assumes that the migration balance plus 500,000 migrants currently coming to Germany will continue until 2021. This number then will decrease to 100,000 and will maintain that level. The W2 scenario assumes that the migration balance plus an unknown number of migrants will continue to come until 2021 and this number will reach 200,000 and will remain at that level.

After consulting with social and population experts, it was determined that with today's immigration policies in Germany, the W1 scenario is not plausible. Because of the high number of people immigrating currently, it is hardly possible to limit the immigration to a migration balance of 100,000. I have chosen, therefore, the W2 scenario as the only plausible scenario to use. In addition to the W2 scenario, I also know the population's migration tendencies in Hamburg. With those two considerations, it was decided that there should be no migration from the federal states to Hamburg and all positive migration, as defined in the W2 scenario, was converted to zero. The outcome was integrated into the final calculations of population projection for the entire Greater Hamburg area.

The second dataset was for the surrounding districts of Schleswig-Holstein (Segeberg, Pinneberg, Herzogtum Lauenburg and Stormarn). This projection is developed using data from the same statistical department that was used to obtain the data for Hamburg city-state was. The report was published on 7th of September in 2015 and titled "*Population's Development in 2015 – 2035 in Schleswig-Holstein. The result of the 13th coordinated population's projection*" (Statistisches Amt für Hamburg und Schleswig-Holstein, 2015b). This report contains two scenarios (W1 and W2) as well, with the population grouped by age groups for every 5 years (starting in 2015) till 2035. Additionally it has annual information of births, deaths, migration from foreign countries, federal states and total population. In order to remain consistent, I decided to use the W2 scenario as well. While the dataset was valid for the entire federal state of Schleswig-Holstein, it was not valid for the different districts which were required for the projections. I was able to find such district level information in the previously published statistical report (April 21, 2011) titled "*Population's development in districts of Schleswig-Holstein till 2025*" (Statistisches Amt für Hamburg und Schleswig-Holstein, 2011). This report contains only one scenario (W1) with annual information on total population for each district and city in Schleswig-Holstein from 2009 till 2025. In order to produce the W2 from this data, the additional processing was required.

The third dataset covers by the districts of the Lower Saxony (Niedersachsen). The newest projection, developed in 2015 by the Statistical Department of Lower Saxony and titled "*Births, deaths and migrations balance from 2014 till 2060 the 13th coordinated Population's projection in Niedersachsen*" (Landesamt für Statistik Niedersachsen, 2015). It contains two scenarios (W1 and W2) with annual births, deaths, age groups and migration balance from 2014 till the 2060. For all the reasons stated above, it was decided to use only the W2 scenario for the Greater Hamburg case study.

Because the most current projection did not contain any district level data, I had to search other sources for that information. I found a report, issued on 9th of May in 2011by the Statistical Department of Lower Saxony named as "*Population's movements during the projection period in the cities and districts of the Lower*" (Landesamt für Statistik Niedersachsen, 2011) which contained the W1 scenario with annual births and deaths, migrations balance and total population from 2009 till 2030 at the district level. Additional processing was again necessary in order to produce data to use in the W2 scenario from this data.

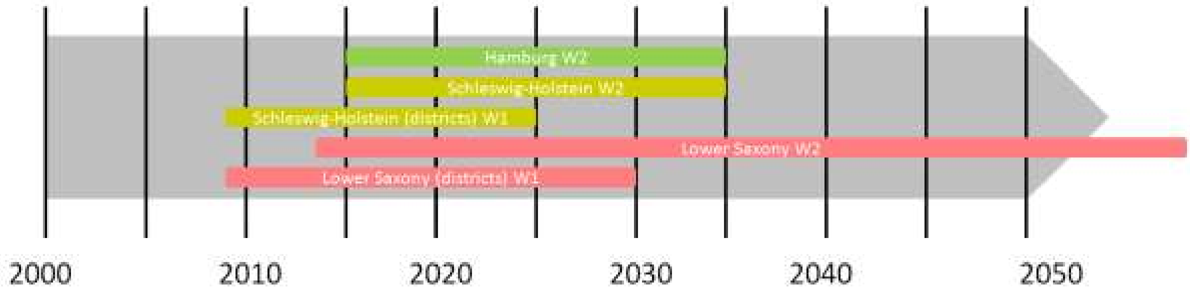


Figure 157: visualization of the projections' coverage over time frame of Greater Hamburg study.

So, in the end I obtained four population projections: the W2 scenario for whole Lower Saxony, W1 for districts of Lower Saxony, W2 for whole Schleswig-Holstein, W1 for districts of Schleswig-Holstein and W2 for Hamburg city-state. Figure 157 (above) represents the graphical visualization of the projections' covered timeframes. The colors of the projections correspond to the colors of the areas in figure 156. The objective is to obtain the W2 scenario for Hamburg city-state and the districts of Schleswig-Holstein and districts of Lower Saxony from today (2015) till 2050. Figure 157 clearly shows a data gap that exists and that must be filled.

Data extrapolation and results

Greater Hamburg case study requires the population projections' data, covered from the initial year 2000 till 2050. Figure 157 shows that none of the projections at the district or city-state level satisfies this requirement. Additional processing is again required.

The first step required was to normalize all scenarios to the W2 type. Since the data for districts in Saxony and Schleswig-Holstein is available on the W1 level only, it was necessary to identify the difference (ratio) between the W1 and W2 scenarios for the common time period. Knowing the ratio would allow the transformation and extrapolation of the data. This procedure would be required for both the federal states of Lower Saxony and Schleswig-Holstein. The common time period for both scenarios for Lower Saxony is sixteen, while the common time period for both scenarios for Schleswig-Holstein is only ten years (figure 157), which was still enough to identify the ratio.

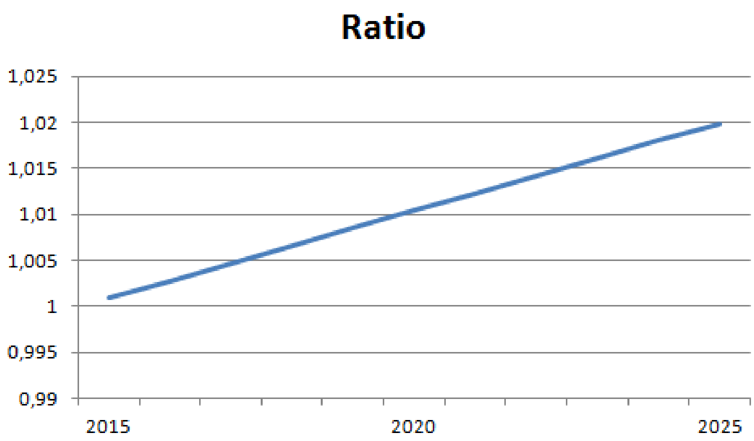


Figure 158: ratio between the W1 and W2 scenario for the federal state of Schleswig-Holstein and selected districts.

Figure 158 shows the linear dependency between the W1 and W2 scenarios for Schleswig-Holstein for the year 2015-2025. Assuming that the ratio will not change in the future, the scenario W2 can be extrapolated till the year 2050.

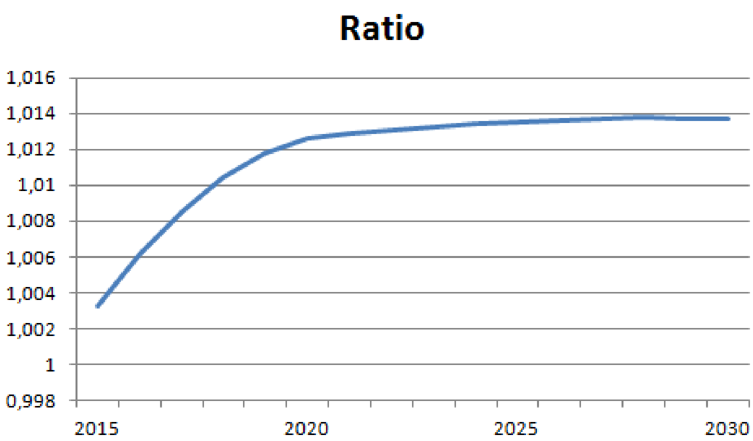


Figure 159: ratio between the W1 and W2 projections for the federal state of Lower Saxony and selected districts.

The other graph (figure 159) shows the logarithmic dependency between the W1 and W2 scenarios for Lower Saxony for 2015-2030. Assuming that the ratio will not change in the future, the scenario W2 can be extrapolated till the year 2050.

After the ratio was applied, all the projections contained the W2 scenario at the district level. The next task was the extrapolation which was done via Microsoft Excel software by plotting the dots of the actual (historical) and projected data. The dots were connected into a function which was simply extended and the values were extrapolated till the year 2050. The following graphs present the final population projections for districts grouped by federal state and its districts.

Federal state of Lower Saxony

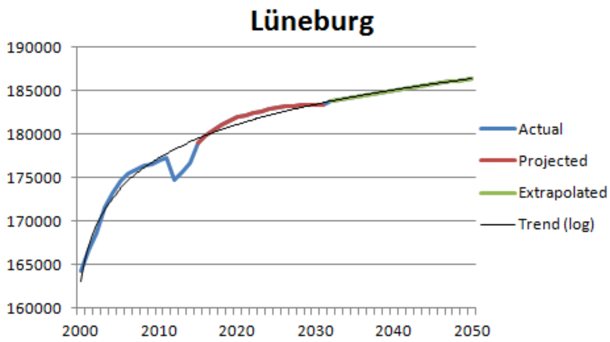


Figure 160: population's development in Lüneburg district.

The first district of Lower Saxony is Lüneburg. Using the actual-historical data and projection I was able to identify the logarithmic trend of the population development in Lüneburg. If the trend remains constant, the number of population should exceed 185,000 by around 2040. The steep decline and incline of the graph after 2010 is caused by a difference between Census data and actual registered population in 2011.

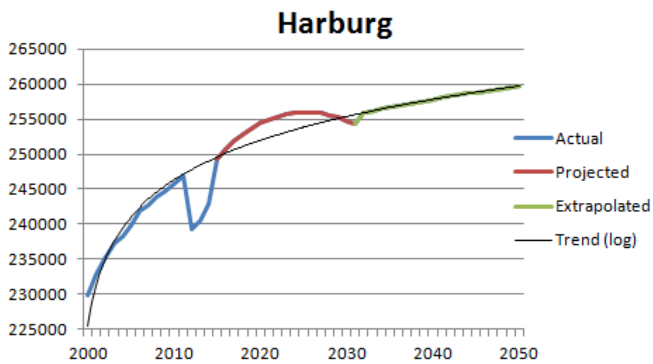


Figure 161: population's development in Harburg district.

The population's development in Harburg is represented by logarithmic function as well. The actual data shows the data error in 2011 and the projection slightly overestimates the general function. Around year 2050 the total population in Harburg is projected to be around 260 000.

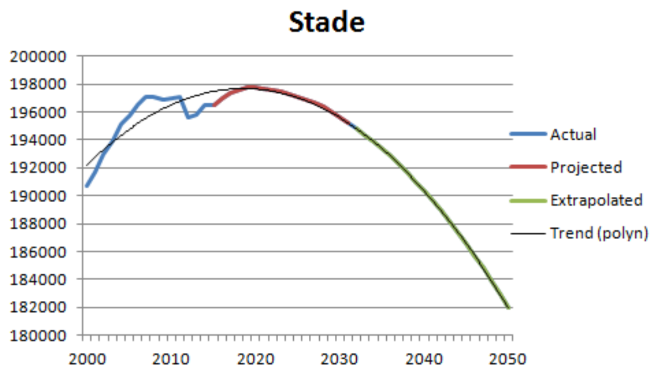


Figure 162: population's development in Stade district.

And the last district of Lower Saxony is Stade which shows a totally different trend than the two previous districts. This time the trend is represented by a polynomial curve reaching its peak in 2020 and then steadily decreasing to a projected 182,000 in 2050 (about 10,000 less than in 2000).

Federal state of Schleswig-Holstein

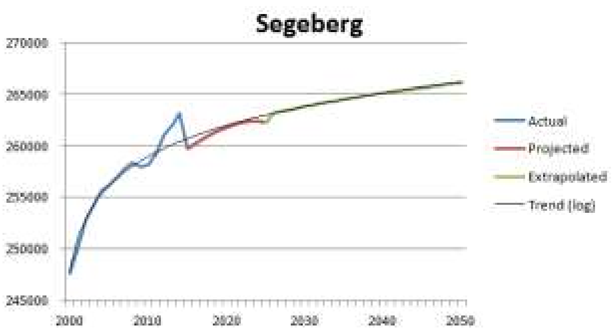


Figure 163: population's development in Segeberg district.

The first district of Schleswig-Holstein is the Segeberg. The population's development in Segeberg is represented by the logarithmic function. The peak in 2012 is also identified as a data error, with the entire trend showing an slight increase in population.

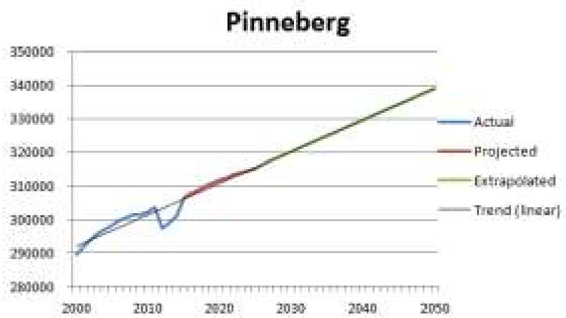


Figure 164: population's development in Pinneberg district.

The Pinneberg's population's development is represented by the linear function. If the trend will follows the linear progression, by 2050 the population should reach 340 000.

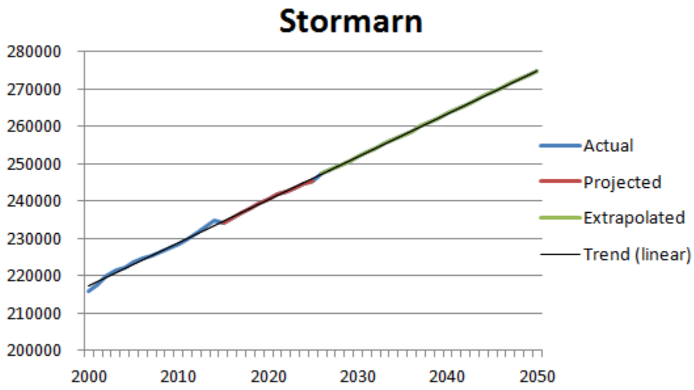


Figure 165: population's development in Stormarn district.

The other linear trend is typical for the district of Stormarn. This time the actual-historical data and projections show a great match, with no major peaks.

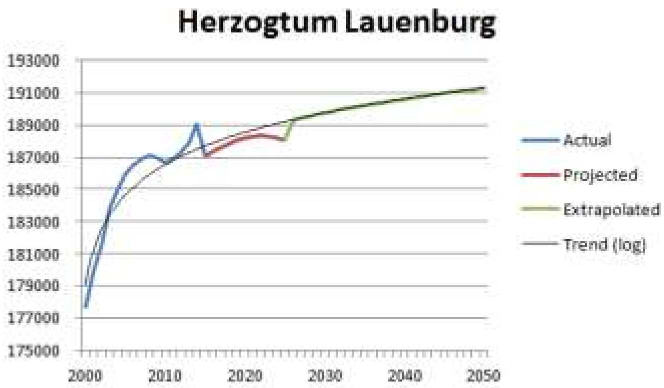


Figure 166: population's development in Herzogtum Lauenburg.

The last district of the Schleswig-Holstein is the Herzogtum Lauenburg. Its population follows the typical logarithmic function and is similar to the trend of Segeberg district. According to the extrapolated projection, the population count over time should increase slightly, but not as much as was seen in 2000-2010.

City-state Hamburg

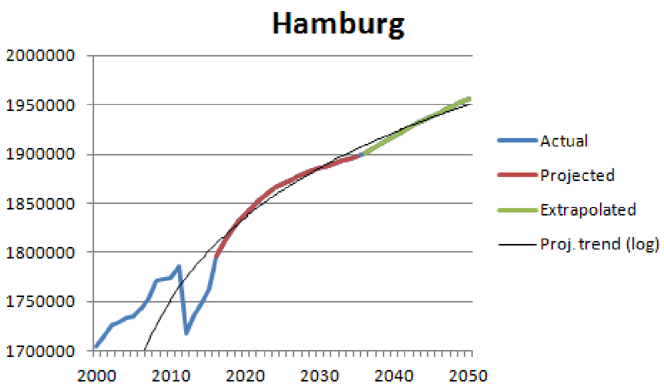


Figure 167: population's development in Hamburg city-state.

And the last, but not least is the population's development in Hamburg city-state (figure 167). At first it seems that the function is linear, but if we exclude the actual-historical data and consider only the projection, the function is more logarithmic than linear. The 2011 census error can be seen to have a great impact on the Hamburg data as well. However, if the extrapolated projection is followed, the number of the population in Hamburg in 2050 should exceed 195,000, with the threshold of 2 million people not being reached.

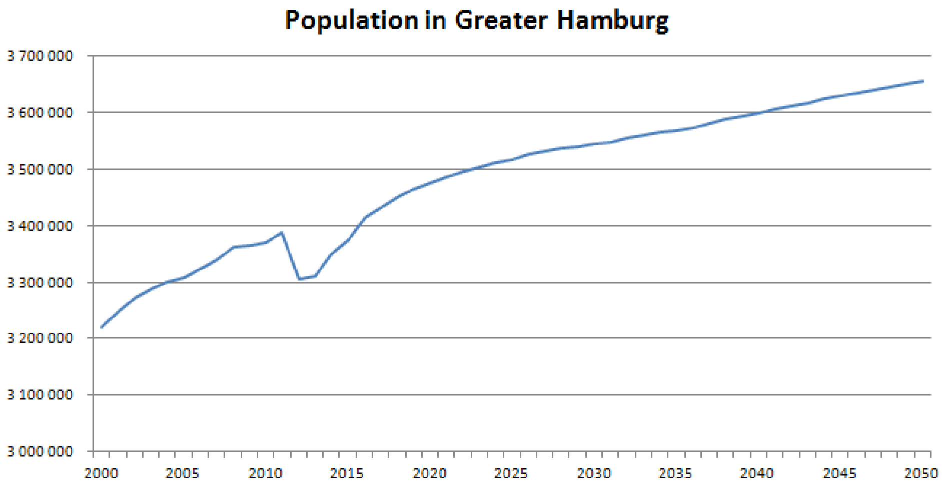


Figure 168: population's development in Greater Hamburg.

The objective of acquiring the population's projections is to know how the population will develop for the whole Great Hamburg study area in the future. This can be done by combining the population projections of all districts of both federal states and federal city-state Hamburg. Because the data was developed from multiple datasets with different actual, projected and extrapolated data, the final graph does not differentiate between the actual, projected and extrapolated data. The population's development in Greater Hamburg (figure 168) follows linear trend and, if it stays the same, the total number of population in Greater Hamburg should be around 3 650 000, about 13% more than in 2000).

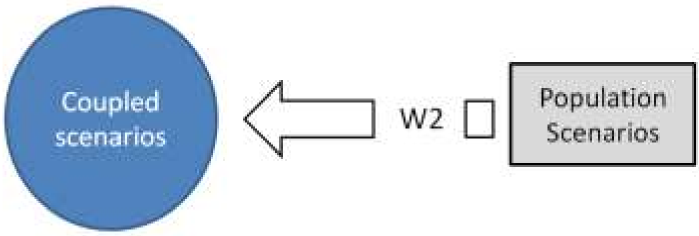


Figure 169: one W2 population scenario has been used for the Great Hamburg case study. This scenario afterwards will be coupled with other scenarios.

Figure 169 shows the final input of the population scenario to the Greater Hamburg case study. Later it will be coupled and merged with the environmental scenarios in relationship to the population growth. The population increase causes the development of new urban land (potential residential UVCZ). Therefore later on the population's growth will be converted to the demands of the specific UVCZ cells, based on their capacity to house a certain amount of people. But in order to fill in the demands, the environmental scenarios have to be developed.

7.3 Zoning

Zoning is a small part of the environmental scenario. It represents the institutional suitability which would happen regardless of which environmental scenario might occur. Zoning defines the possible future occurrence of a UVCZ function in a certain cell, based on urban planning and legislation and specifies whether or not a cell is allowed to be occupied by a certain UVCZ function. For instance, if the certain area is restricted for any type of new development at any point in the time period, the model will prevent any type of occurrence in the new cells. If a certain area is defined, for instance, for only harbor UVCZ, and there is no demand or need for a new harbor UVCZ, then no cells will be allocated for that certain period of time. Zoning in the Metronamica model can be added by defining the polygon of the affected area, the UVCZ type and the state (whether the cells should be actively simulated (promoted) or limited) and time frame for when the zoning should be applied. In reality, though some may disagree, the German laws and regulations are not as strictly enforced as one might think. This can cause a lack of clarity, some "fuzziness" if you will, and might require the inclusion of some randomness into the model. After considering a significant amount of information, including the formal urban development plans, the utopian environmental ideas and the strictly defined environmental zoning projects, I was able to determine that, generally speaking, the future allocation of the UVCZ is affected by three types. The first type of zoning is the "environmental restrictions."

Environmental restrictions

Environmental restrictions are typical legislation that is passed to conserve and save national parks, heritage sites, animal breeding areas and may other environmentally sensitive areas. In Greater Hamburg case study, I collected and included the following types of environmental areas with restrictions which are in the ascending order (National parks being less restricted the natural reserve, which is the most environmentally restricted area):

- National parks;
- Protected landscape;
- Natura 2000 sites (CAT II – V);
- Reserve of Biosphere (CAT IV);
- Conservation area (CAT IV);
- Nature reserve (CAT V).

Due to the German translation, some of the entities can be misleading. However, the higher category (CAT), the stricter restrictions. For instance, it is forbidden to build in the natural reserve which is the most protected area. The legislation protects the landscape but does allow the performance of agricultural and forestry-related activities.. All the environmental zones were separately added as zoning layers with special values that stimulate or limit the appearance of specific UVCZ cells, as assigned. It was assumed that the environmental restrictions will not change over time.

Special development projects

The special development projects are planned urban development projects already approved by the local government. These projects are currently being constructed or should be started soon. Similar to the environmental restrictions, they are scenario independent. In reality, of course, things can happen to change the timing or course of these developments (funding is cut, or the project is abandoned) but these possibilities are not in the model and it is assumed that these projects will take place as planned.

At the time of this writing, there are many smaller and larger projects currently going on or being planned. Figure 170 shows the geographical locations of some of the more well known projects in Hamburg which could affect the future urban development in Greater Hamburg. The first such project is the “Altone Mitte”, which is located in the middle of the town of Altona, which is now a part of Hamburg city. This project is converting the rail infrastructure to a residential perimeter open mid rise area. It is projected to start in 2020 and be completed around 2030. The second such project is “Hafen City”. This is a modern waterfront concept-based project on the Northern bank of the Elbe River. This project will convert a portion of the harbor to the compact mid-rise with modern offices and some residential spaces. This project was initiated after 2000 and is planned to be completed by 2028. The last project is the harbor development plan, or expansion plan. Decision makers in Hamburg some time ago decided that the harbor would not expand on the Northern Bank of the Elbe River or further to the East. Possible expansion was defined as a specific zone to the Southwest of the harbor, where industrial compounds and agricultural land is currently located. Today, however, the harbor has experienced financial difficulties and further expansion has been suspended and the area once dedicated for expansion has been restricted and no further development should occur in that area in the next few decades.

Figure 170: listed Altona Mitte, Hafen City and Harbor expansion’s projects within the Hamburg city-state.

Of course, many other smaller urban projects are planned, but it is unclear if they will be finished or not. A few of the projects that have been announced to the public are shown on figure 171, including “Elbinsel, “Jenfelder Au”, and “Stromaufwarts, an Elbe und Bille”. These are large and well known urban development projects in Hamburg, with some of them affecting only small areas and very little impact on the class of the UVCZ.

Figure 171: other urban development projects in Hamburg. They are excluded from zoning, due to small size or no effect to the UVCZ. Based on official posters of the planned projects, found in the official website of Hamburg City Administration (Hamburg.de, 2015).

The last zoning input is the refugee settlements. As is well known, the war in Syria has caused a migrant and refugee crisis in Europe in 2015. The German government has shown solidarity with the Syrian people and has invited refugees to Germany. Hamburg, as one of the largest metropolitan cities in Germany, has received a tremendous amount of refugees who are now sheltered in temporary camps around Hamburg. Local governmental officials established preliminary locations for the refugee settlements and established an official website on which the urban plans of these settlements were announced. In this study I decided to address the largest settlements (Figure 172) which is capable of housing more than 1000 inhabitants and incorporating them in the zoning.

Figure 172: development of new refugee settlements within Hamburg city-state. Official data and preliminary numbers of planned locations were obtained from the official website of Hamburg City Administration (Hamburg.de, 2015).

A large part of the refugee settlements' development started in 2016, with the dominant UVCZ type being the dense open low rise and a small portion planned to be terraced open mid rise UVCZ type. All the refugee settlements presented in figure 172 were added to the zoning as layers and having special values (stimulating the appearance of specific potential housing UVCZ cells) assigned.

7.4 Urban development

The urban development scenarios are the most important input, having the most impact on the final outcome, because urban development is represented by a different allocation of UVCZ which is the proxy and the main parameter of the CA model. All future urban development scenarios are extrapolated from the historical allocation of UVCZ, which is, basically, the UVCZ model. This UVCZ model was successfully calibrated (more about calibration can be found in chapter 5.3). Future urban development scenarios are nothing more or less than different allocations of the modeled UVCZ cells within the case study area. The UVCZ allocation depends on many factors which are presented as main drivers of the Metronamica model in chapter 3.2, and can be represented as scenarios or stories. For example, the new urban green trend encourages the expansion of urban parks all around the city, which could cause a change in the zoning rules, UVCZ and accessibility (proximity) if the location of the urban green is preferable.

In order to create such urban development scenarios I organized five two hour session workshops to which social and physical scientists and geographers from the Institute of Geography, University of Hamburg were invited.

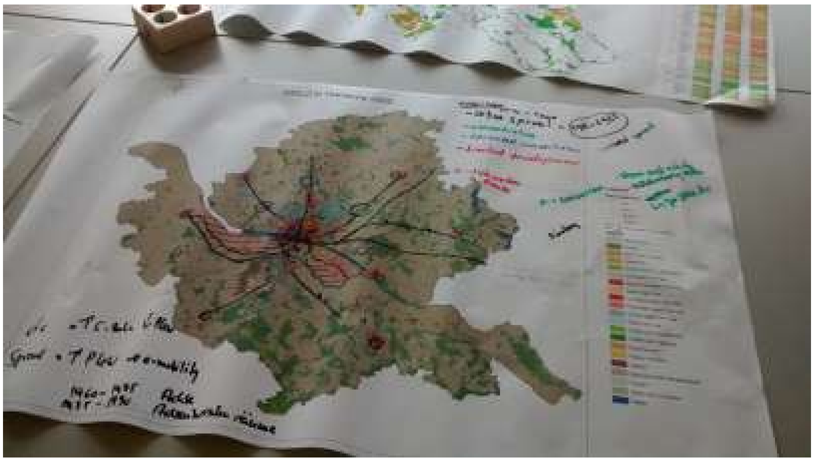


Figure 173: moment of workshop on crafting urban development scenarios.

The first goal of the workshop was to create the concept of urban development scenarios as possible urban development trends in Greater Hamburg up to 2050. I followed the same path as I did previously - in order to keep complexity low, I avoided a high number of scenarios. One of the scenarios, had to be, of course, the business as usual scenario, with the development trend of 1990-2000 remaining unchanged, which was identified through calibration. This trend was identified as "controlled urban sprawl" with some conversion in the central area. Because one scenario is not enough for this study, a second goal of the workshop was to include extreme urban development scenarios which would represent totally different urban development trends, and at the same time show how each would affect the vulnerability of the people.

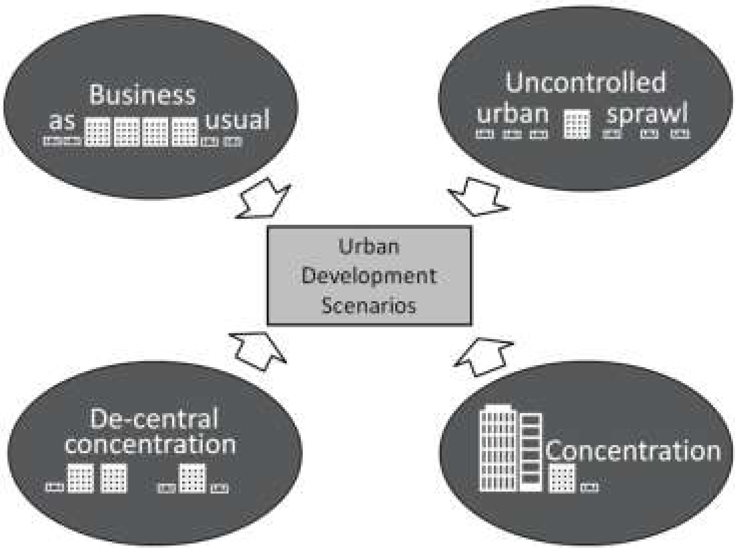


Figure 174: summary of custom urban development scenarios.

The first of the extreme scenarios was “uncontrolled urban sprawl” – the growth of the suburbs. Some signs of this urban sprawl is seen in Greater Hamburg between 1960 an 1990. It might be seen today as a result of lower costs in fuel and land acquisition, as well as a desire on the part of people to have more personal space that is closer to green areas.

Another extreme scenario is the “concentration scenario”. The concentration scenario is based on the idea that as fuel prices increase people are willing to live within walkable distances to their workplace and commute to the city using public transportation. This is similar to the compact, or the medieval city. More about concentration and other scenarios can be found in chapter 2.7.

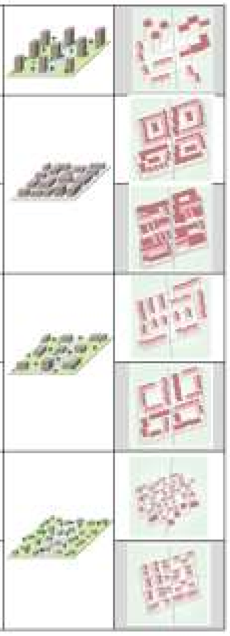
The last, but not least is the “de-central concentration” scenario which is the typical transition between concentration and urban sprawl scenario. This scenario is based on concentration around the sub-centers, residential areas in the countryside and the transportation hubs. The sub-centers are small towns or residential centers with walkable distances between the residential areas, the work spaces and transportation, and the public and commercial services. In this scenario, people avoid the city center because there is less space and what space is available is expensive so the move out to the sub-centers where they can reach transportation hubs quickly and travel to the city centers where they can access all services and do their shopping, etc.

The developed scenarios are very similar to the scenarios used in the study by Daneke (2013). This study used the basic trend, the compact city, the de-central concentration and the de-centralization scenarios. The basic trend scenario is the baseline scenario which is the BaU scenario in this study. The compact city was identified as an extreme scenario and matches very well with the concentration scenario. The de-central concentration is exactly the same scenario with the focus on the sub-centers. And the de-centralization was identified as another extreme scenario, known as the uncontrolled urban sprawl in this study. Daneke’s study and this study are both consistent in the selection of the scenarios although any other urban development scenario could also be added. The development of the scenario itself however, might not be as complicated as incorporating it into the model.

The urban development scenarios in Metronamica are nothing more than the different trend of UVCZ cells’ allocation within the case study. Once the concept of the scenarios themselves is developed, the problem of incorporating them in to the Metronamica model must be solved. One of the most important inputs in Metronamica is the land use demands, which, in this study, are the demands of the UVCZ (potential housing UVCZ and other active UVCZ classes). Demands show the number of cells for certain UVCZ needing to be allocated within the case study for each year. For instance, if it is known that in the urban sprawl scenario there is a high demand for dense open low rise, and no new development of open high rise, then the open high rise demand will be set to zero and dense open low rise demand is set to the number of cells needed to allocate with the CA model. The historical cells' demands and changes are analyzed in detail in chapter 5.2.

Obviously, certain rules to define the demands are necessary. As discussed previously, most of the demands of the potential housing UVCZ in the Metronamica model are driven by the population growth. The demands of other UVCZ, such as parks, harbor and commercial are driven by other factors like economical development etc. The future population growth in Greater Hamburg is analyzed in detail in chapter 7.2. While we know that a growing population requires housing, we also know that different urban development scenarios would encourage an increase in different types of potential housing UVCZ. Because of this, I thought that each urban development scenario should have a different fraction for each of the growing population for the growing population for the potential housing UVCZ.

These fractions were defined by local experts during the workshops. Based on their opinions, the typical housing in uncontrolled urban sprawl is dense open low rise, open low rise and terraced open mid rise, with the respective fractions of 70%, 25% and 5%. In other words, 70% of the population, increased during a specific time period, would populate new dense open low rise UVCZ, 25% would populate open low rise and the remaining 5% would move into terraced open mid rise housing. These fractions can be seen in figure 175. The fractions of the business as usual scenario were identified via the historical changes in population in certain UVCZ types between 1990 and 2000.



	Business as usual	Uncontrolled Urban Sprawl	Concentration	Decentral concentration
	Fraction of Population within UVCZ (%)	Fraction of Population within UVCZ (%)	Fraction of Population within UVCZ (%)	Fraction of Population within UVCZ (%)
Open high rise	0	0	5	5
Compact mid rise	0	0	30	2
Dense compact mid rise	0	0	5	0
Terraced open mid rise	15	5	25	45
Perimeter open mid rise	0	0	30	20
Dense open low rise	78	70	5	26
Open low rise	7	25	0	2

Figure 175: fractions of future populations' distribution among the potential housing UVCZ.

Concerning the other UVCZ, the experts concluded that there is no potential to increase the demand of urban parks, heavy industry, harbor, rail and road infrastructure or airport. The only exception is the commercial areas. It was decided that for all scenarios, the commercial demand will use the business as usual value from the 1990 – 2000 trend, which is 53 cells per 5 years.

The following figure (176) shows the fragment of the cells' demand for uncontrolled urban sprawl scenario for 5 year periods starting in 2000. The population scenario of Greater Hamburg (described in chapter 7.2) is divided into population growth periods of 5 years. For instance, according to the population W2 scenario, in 2010 – 2015 there had to be an increase of population only by 1785 people because of a census correction, while the increase between 2015 and 2020 would have to be 93553 people. Using the fractions defined earlier, this population is distributed among the terraced open mid rise, the dense open low rise and the open low rise UVCZ. These UVCZ all have different population density/capacity (more people live in terraced open mid rise than in the same area covered with dense open low rise). The factor of population density, therefore, delivered via statistical analysis in chapter 6.1, must be involved. The fraction of certain UVCZ is multiplied by the total growth of population, then divided by 100, and again divided by the density. The result will be the demand of a certain amount of UVCZ cells (example of uncontrolled urban sprawl in figure 176). All other scenarios have such demands' allocation tables up to 2050. Although the demands are very important, they are not the only items put into the Metronamica model. Another important factor is the neighborhood function and the conversion from one UVCZ to another.

Uncontrolled Urban Sprawl

	Mean of population count	Population growth 2000 - 2005		Population growth 2005 - 2010		Population growth 2010 - 2015		Population growth 2015 - 2020	
		85428		56980		1785		93553	
		Fraction of all demand (%)	Demand of cells	Fraction of all demand (%)	Demand of cells	Fraction of all demand (%)	Demand of cells	Fraction of all demand (%)	Demand of cells
Open high rise	700	0	0,0	0	0,0	0	0,0	0	0,0
Compact mid rise	803	0	0,0	0	0,0	0	0,0	0	0,0
Dense compact mid rise	226	0	0,0	0	0,0	0	0,0	0	0,0
Terraced open mid rise	420	5	10,2	5	6,8	5	0,2	5	11,1
Perimeter open mid rise	768	0	0,0	0	0,0	0	0,0	0	0,0
Dense open low rise	218	70	274,3	70	183,0	70	5,7	70	300,4
Open low rise	160	25	133,5	25	89,0	25	2,8	25	146,2

Figure 176: fragment of UVCZ cells demands' allocation, based on population growth, in uncontrolled urban sprawl scenario.

The neighborhood function (more details about it in chapter 3.2) does not only affect the appearance of new cells in the neighborhood, but also causes the conversion from one UVCZ to another. The neighborhood functions for the time periods 1960-1990 and 1990-2000 were calibrated and documented in chapter 5. The same functions are used for business as usual scenario. Other scenarios, however, might have other trends from the neighborhood effect or the conversion. For instance, in the de-central concentration scenario, the open low rise UVCZ have higher potential to be developed closer to already developed open low rise areas, while in the uncontrolled urban sprawl scenario the dense open low rise would be preferred to be more isolated. Fortunately, the Metronamica model allows the implementation of these various trends of neighborhood and conversion functions among the urban development scenarios. During the workshop the following neighborhood and conversion trends were identified for each urban development scenario:

Uncontrolled urban sprawl

- New terraced open mid rise develops close to terraced open mid rise;
- New open low rise develops farther from harbor;
- New dense open low rise develops close, but not too close to urban parks;
- New commercial develops close to commercial;
- Dense open low rise converts slightly to terraced open mid rise;
- Commercial slightly converts to terraced open mid rise.

Most of the neighborhood rules in uncontrolled urban sprawl do not represent the conversion, because the conversion in such scenario is not necessary. The rules mainly cover the allocation of low density mid rise or low rise housing UVCZ.

Concentration

- New compact mid rise develops very close to compact mid rise;
- New dense compact mid rise develops very close to dense compact mid rise;
- New terraced mid rise develops close to terraced open mid rise;
- Terraced open mid rise converts to compact mid rise;
- Perimeter open mid rise converts to compact mid rise;
- Compact mid rise converts to dense compact mid rise;
- Terraced open mid rise converts to perimeter open mid rise;
- Dense open low rise converts to terraced open mid rise;
- Commercial slightly converts to terraced open mid rise.

The neighborhood rules in concentration scenario represent the new development as being very similar to the existing UVCZ. It means that the more UVCZ cells are present in the area, the higher the potential for new development. Seen in reality, the higher the concentration of services and high quality apartments in a limited space, the higher the potential for new development, or even the conversion of existing housing. The other consideration is the conversions of various UVCZ to the denser UVCZ. This is especially typical for the compact city (the concentration scenario).

De-central concentration

- New terraced mid rise develops close to terraced open mid rise;
- Terraced open mid rise converts to compact mid rise;
- Perimeter open mid rise converts to compact mid rise;
- Terraced open mid rise converts to perimeter open mid rise.

The de-central concentration scenario has less affect on compact mid rise and no dense compact mid rise, in comparison to the concentration scenario. It considers only slight conversion from the open mid rise to the denser classes. However, the main changes in this scenario are related to the proximity to the city center and sub-centers.

The accessibility, or proximity, is the last, but not least important factor in Metronamica. More about accessibility can be read in chapter 3.2. The proximity to certain assets can increase the potential of the new development. For instance, in the urban sprawl scenario, the dense open low rise and open low rise UVCZ have high potential when closer to the major and secondary roads, and highways exits. Higher proximity means higher potential.

The typical accessibility layers of urban applications in Metronamica are transportation networks. The accessibility data can be any area that increases potential for development with a closer proximity. Therefore, in order to increase the potential for new development close to the city center and sub-centers, they were added as a separate accessibility layer. These will have a greater impact in both the concentration and de-central concentration scenarios. Other accessibility elements, such as highways and their exits, major and secondary streets, bus and railway stations, metro and surface rail stations are typical in all scenarios, with each scenario having different weights for each accessibility element. Figure 177 shows the accessibility layer of roads, bus stations, highways' exists, city center and sub-centers.

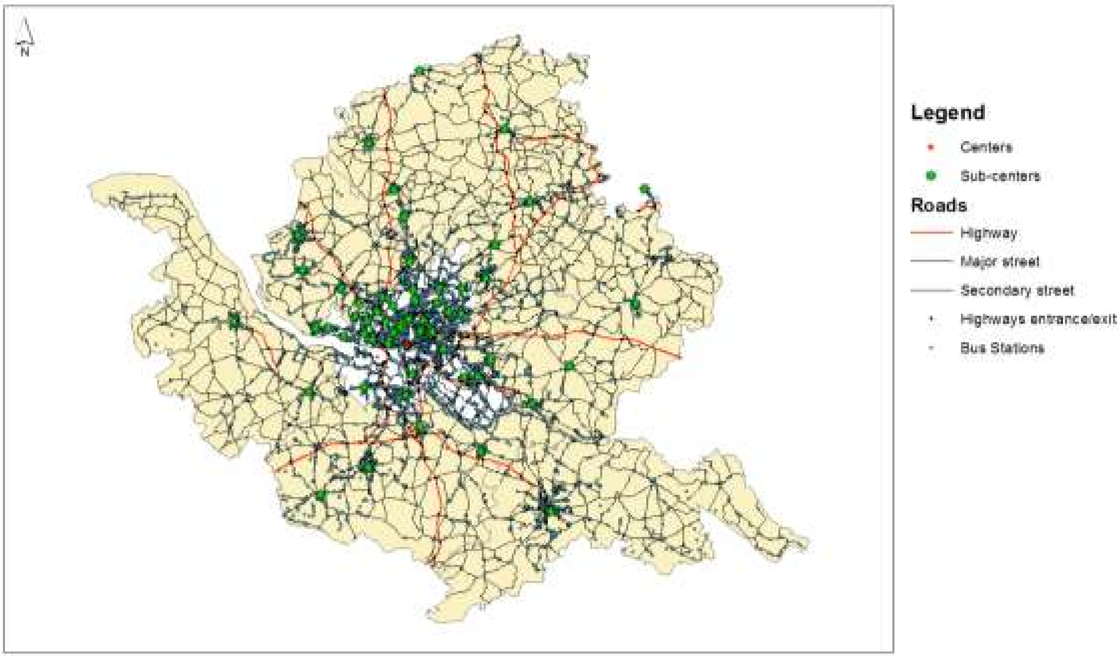


Figure 177: accessibility layer of roads, center and sub-centers (source: Open Street Map and Hamburg City Planning Department).

All transportation data was added from the Open Street Map portal. Meanwhile the center and sub-centers within the Hamburg city-state limits are developed by Hamburg City Planning Department. The sub-centers of surrounding districts are geoprocessed centroids of the urbanized areas, and received from the Hamburg City Planning Department as well.

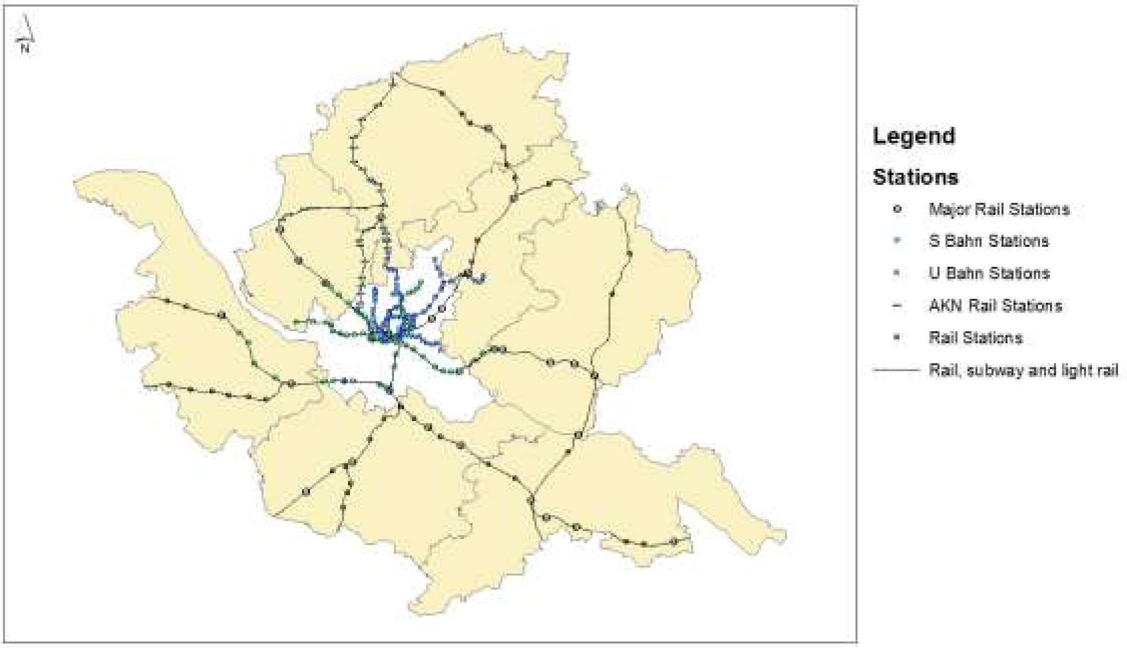


Figure 178: accessibility layer of railways, rail, subway and light rail (source: Open Street Map).

Figure 178 shows the railroads and rail stations (train, metro and surface short distances rail). The stations are attractive to people who commute longer distances to work every day, making the proximity to rail stations significant. The following information shows how accessibility varies among the UVCZ and accessibility elements between the scenarios. Instead of adding the tables of proximity (accessibility) values of each scenario, I added the general guidelines/rules:

Uncontrolled urban sprawl

- Open low rise and dense open low rise have higher potential closer to highways exits and major and secondary roads;
- The center and sub-centers have no affect on dense open low rise and open low rise;
- Terraced open mid rise have a slight potential closer to the sub-centers and rail stations.

Concentration

- Practically all potential housing UVCZ have a higher potential closer to the city centers;
- There is no effect of highways exits or major and secondary roads;
- Commercial prefer to leave the city and locate closer to highways exits;
- Open high rise have a slight potential closer to the sub-centers and metro stations.

De-central concentration

- Similar to concentration, however all potential housing UVCZ have higher potential closer to the sub-centers, instead of the city center;
- Commercial is no longer attracted to the sub-centers (more space is required by potential housing UVCZ);

- High potential of all potential housing UVCZ closer to the major train and metro stations.

As you might noticed, the proximity factors differ greatly among the scenarios. The concentration scenario focuses mainly on the city center with no effect of roads and highways, and the uncontrolled urban sprawl is totally opposite. Meanwhile the de-central concentration is something in between. In the end, when the factors of neighborhood rule, accessibility and demands are defined, the final results of environmental scenarios can be generated.

Results

The results shown on this collage present the UVCZ allocation for the years 2000, 2015, 2030 and 2050. The results are focused on the Hamburg city-state (figure 179) for better visualization. It should also be noted that Metronamica has a stochastic factor which may show slightly different results each time the model is done, although the trend should be consistent.

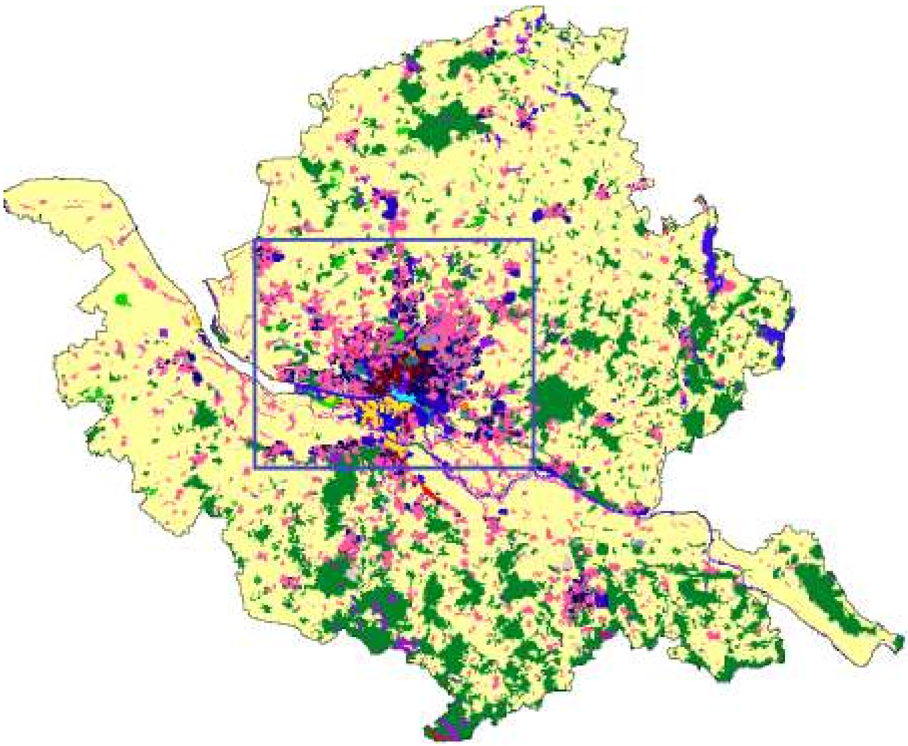


Figure 179: in order to see the differences between scenarios, only the UVCZ allocations within the Hamburg city-state (marked rectangle) are presented.

Because the animations which would show the continuous development cannot be included in this document, I decided to show discrete UVCZ allocations' steps in different years. All figures have the same legend presented in figure 180.

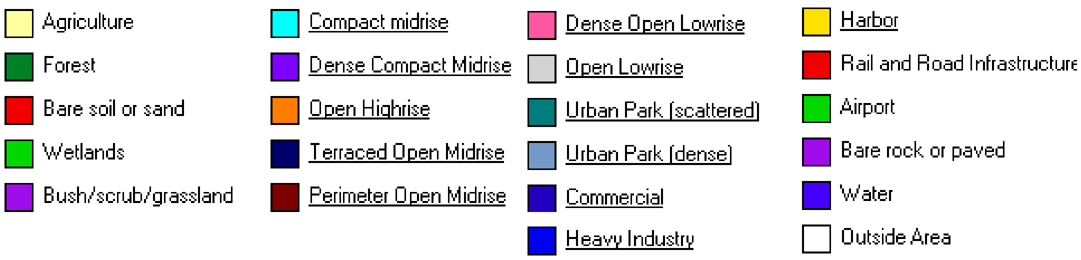


Figure 180: legend of the UVCZ values.

Business as usual scenario

The first result is business as usual scenario (figure 181). The main differences between the years 2000 and 2050 are marked in dashed circles. The obvious influence of the special urban planning is the Hafen city area (light blue) taken from the harbor UVCZ.

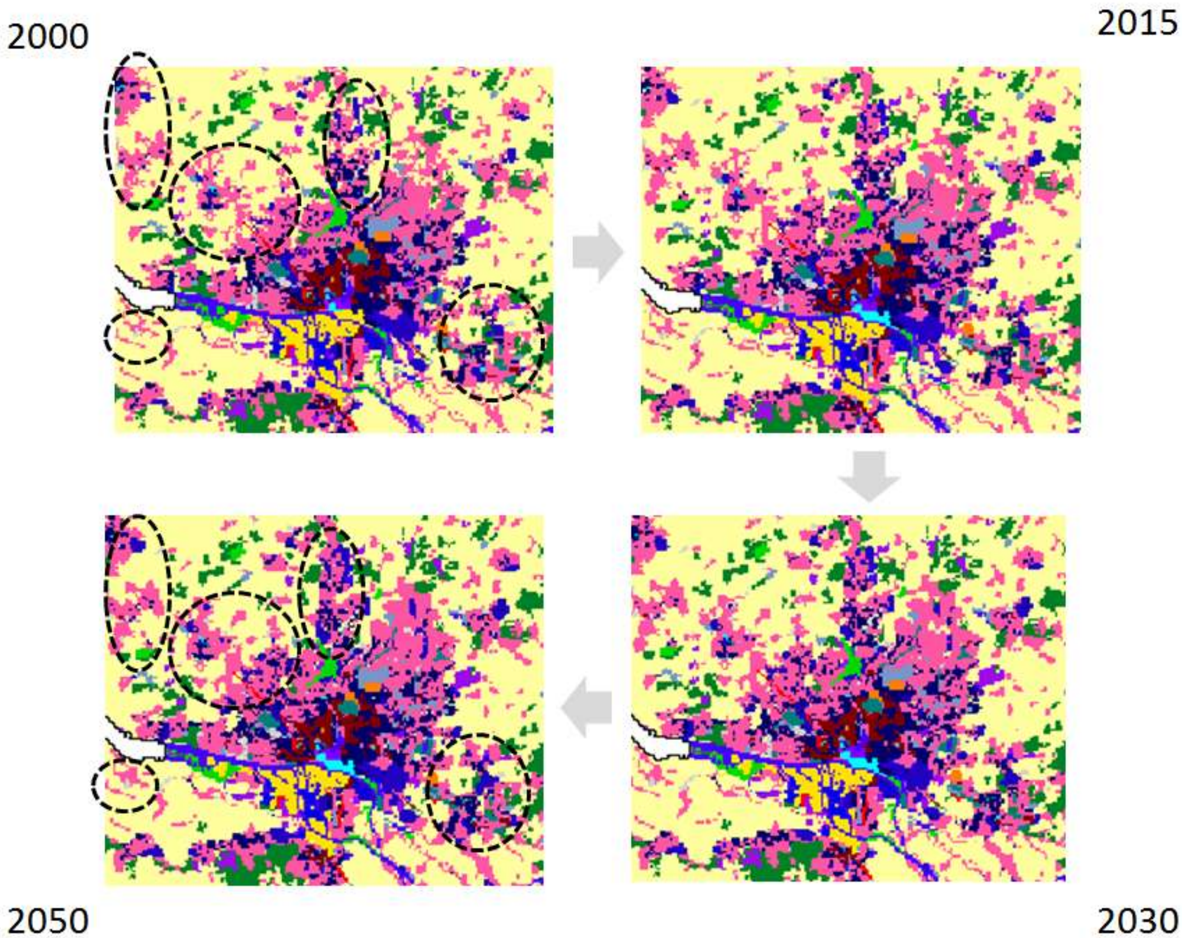


Figure 181: results of business as usual UVCZ scenario. The focus on Hamburg city-state.

The other developments show mostly the increase of dense open low rise and terraced open mid rise development in the North and Northwest, with some sort of development in West and Southeast. I want to note that most of the new UVCZ development for this scenario is dense open low rise (78% of all population).

Uncontrolled urban sprawl

The scenario of uncontrolled urban sprawl is similar to business as usual, with a lower emphasis on terraced open mid rise, and a higher emphasis on open low rise. Figure 182 shows some of the differences in Hamburg city-state area for uncontrolled urban sprawl scenario.

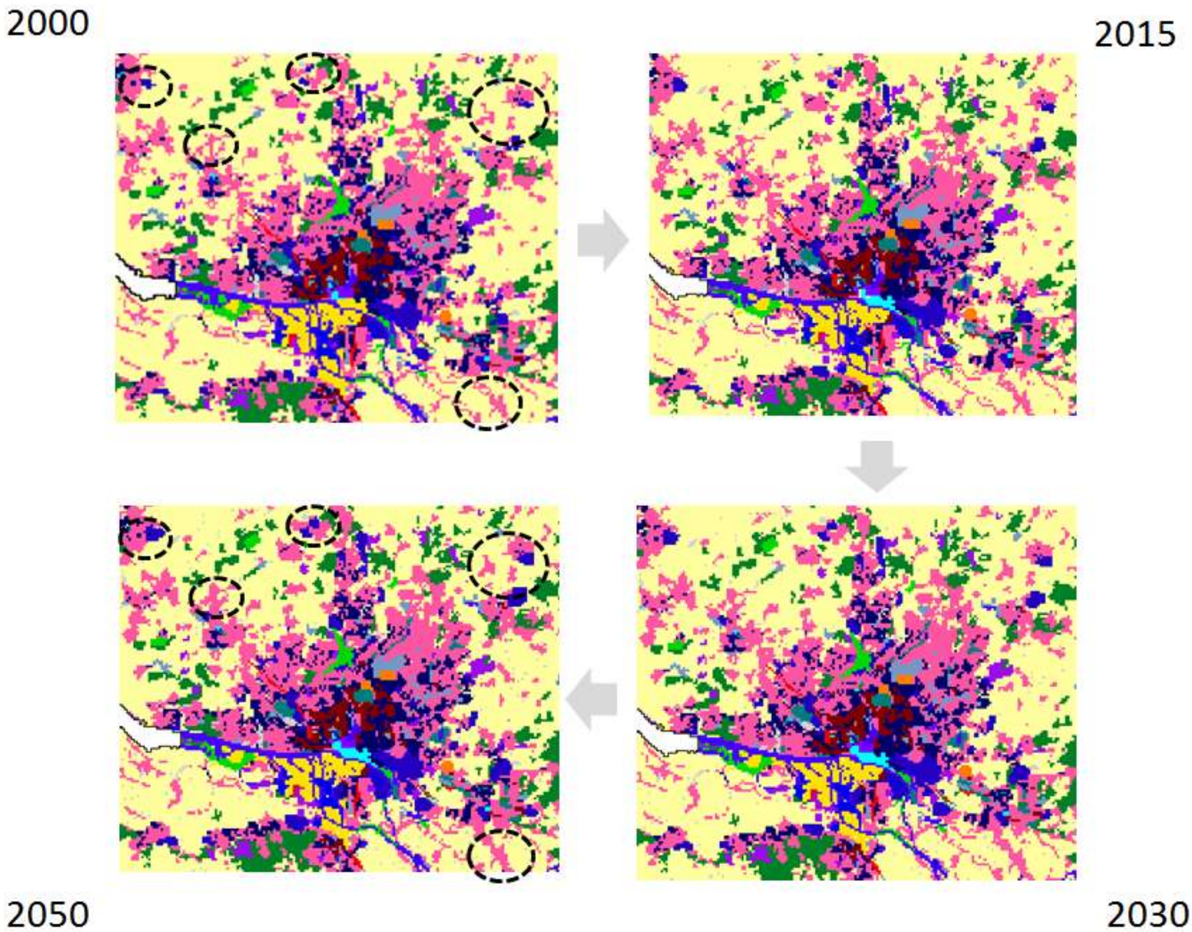


Figure 182: results of uncontrolled urban sprawl UVCZ scenario.

The results show a slight development of terraced open mid rise, but not as spread out as it was in the business as usual scenario, except that there is more concentration to the train stations, when the proximity factor was implemented. Other development of dense open low rise is similar to business as usual scenario, just more dispersed. The biggest difference, which is not marked in the figure above, is the development of individual grey cells around the entire study area. This is the development of open low rise, which can be seen better in the figure below.

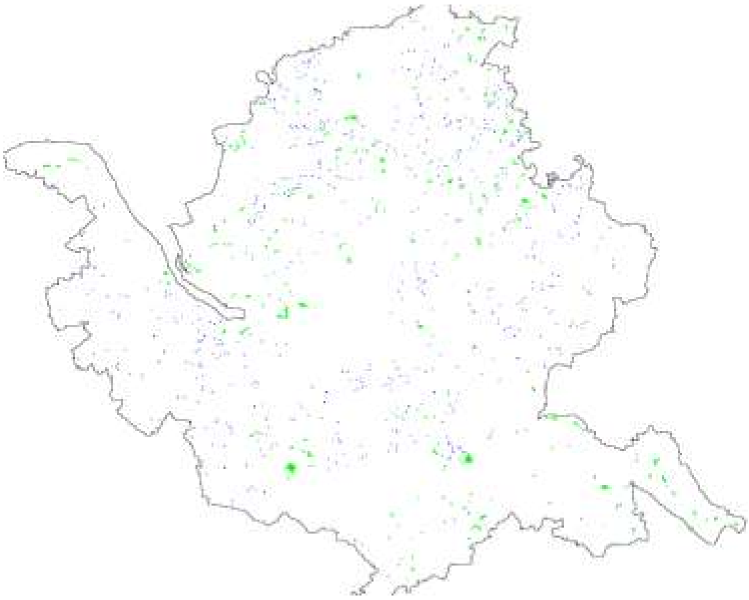


Figure 183: comparison of the new development of open low rise UVCZ between 2000 and 2050. The green colored cells are the actual 2000 year open low rise UVCZ and the blue ones developed in 50 years.

Figure 183 shows the development of the new open low rise cells (blue color) from 2000 till 2050. This is typical urban sprawl development. The people prefer to settle away from the city center to the country side, closer to the roads and highways' exits. Based on visual comparison it can be stated, that the allocation of UVCZ fully represents the urban development, typical for the uncontrolled urban sprawl.

Concentration

In comparison to other scenarios, the concentration scenario focuses mainly on the conversion and development of compact mid rise. That can be clearly seen in figure 184 as isolated light blue cells in the central area. Another significant difference that can be seen is that the central part is covered with a very large cluster of dense compact mid rise UVCZ (purple color in figure 184). This is caused by the conversion from compact mid rise to dense compact mid rise. Many agricultural cells close to the central area are now occupied by compact mid rise.

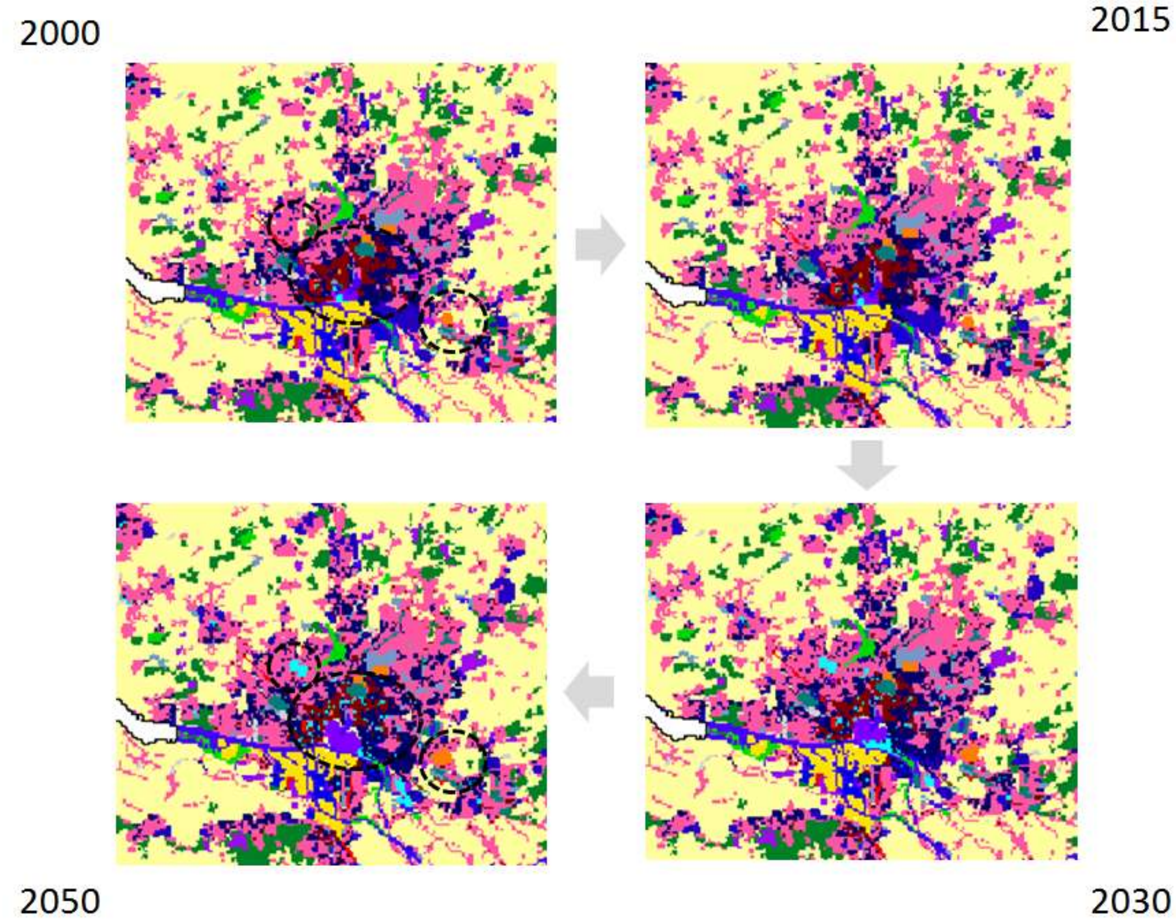


Figure 184: results of concentration UVCZ scenario.

Because the central area is concentrated with potential housing UVCZ, the existing commercial area expands to the outskirts and occupies the free agricultural area. Based on these observations, it can be confirmed that these identified trends are typical for the concentration scenario.

De-central concentration

The last, but not least scenario is the de-central concentration. In comparison to concentration scenario, it focuses mainly on the dense open low rise, the terraced and perimeter open mid rise UVCZ and less on housing conversions. The development should occur within the central area, but around the transportation hubs and urbanized sub-centers.

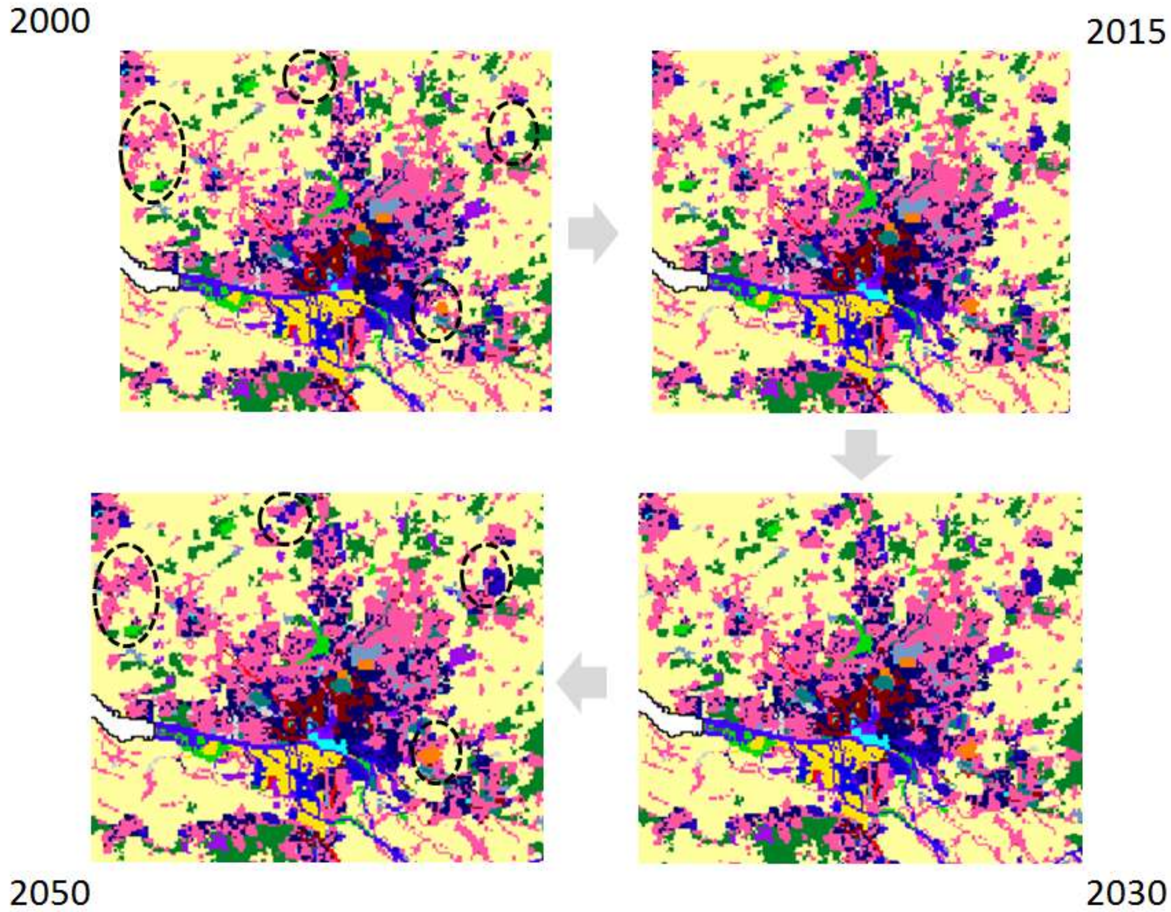


Figure 185: results of de-central concentration UVCZ scenario.

Figure 185 shows the differences between the indicated years in the de-central concentration scenario. It is possible to see similar development of commercial assets as were seen in the concentration scenario. There is not as much conversion in the central part. There is also some concentration of terraced open mid rise and dense open low rise, located in the North, East and West close to transportation hubs.

The next figure shows clearer differences in the allocation of terraced open mid rise and perimeter open mid rise. Both UVCZ are dominant in this scenario and, as can be seen in the map, most of them are allocated not in the city center, but clustered around the sub-centers. Because there are more cells, there are many more clusters of newly developed terraced open mid rise, while the perimeter open mid rise is more scattered. The trend of de-central concentration in this model is presented very well.

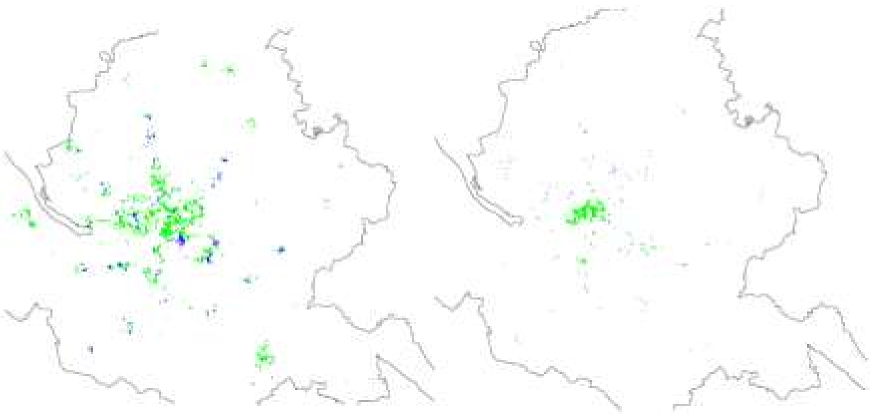


Figure 186: de-central concentration scenario. The new development of terraced (blue colored cells on the left) and perimeter (blue on the right) open mid rise in 2000 – 2050.

The following figures show the differences not between the different years of the same scenario, but the final year (2050) of the different scenarios. The first figure (187) shows the differences between the terraced open mid rise in the de-central concentration and the concentration scenario for the entire area of Greater Hamburg.

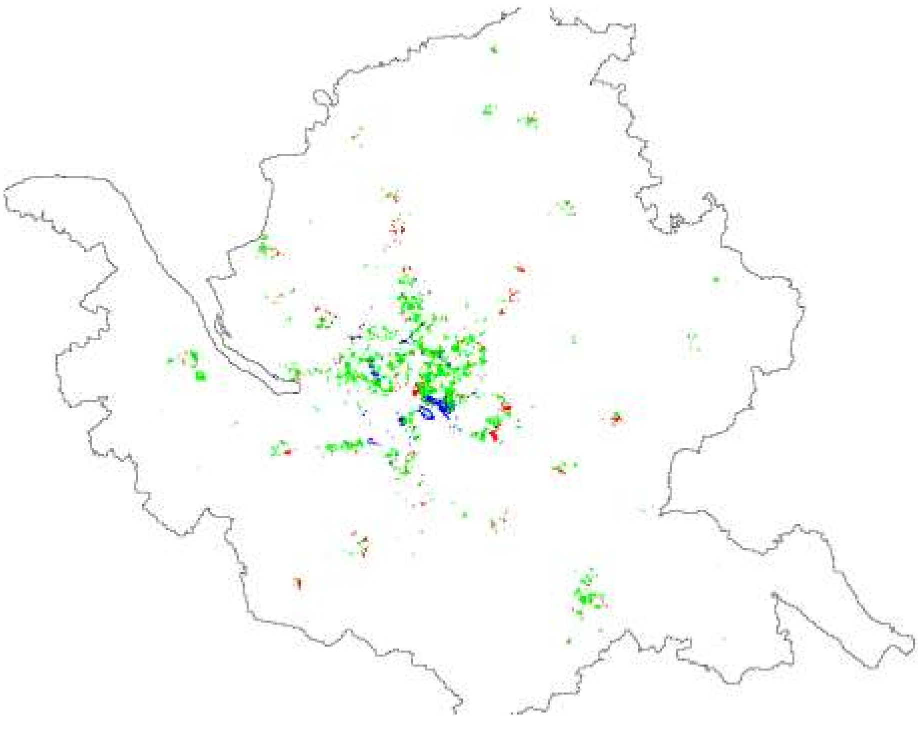


Figure 187: terraced open mid rise in 2050 in de-central concentration (red) and in concentration (blue) scenario

The red colored cells represent the new development of the terraced open mid rise in the de-central concentration and the blue colored cells are from the concentration scenario. It is obvious that the blue cells are more concentrated in the central area of the city, while the red ones are situated around the sub-centers. Such patterns are a great representation of the concentration and de-central concentration scenarios.

Figure 188 shows the comparison between the commercial UVCZ in the concentration and de-central concentration scenarios. The red color shows the development of new commercial assets in the central area, because the sub-centers are occupied by potential housing UVCZ, while the concentration scenario shows the opposite trend - the development of commercial in the outskirts and around sub-centers, because the central area is occupied by residential UVCZ.

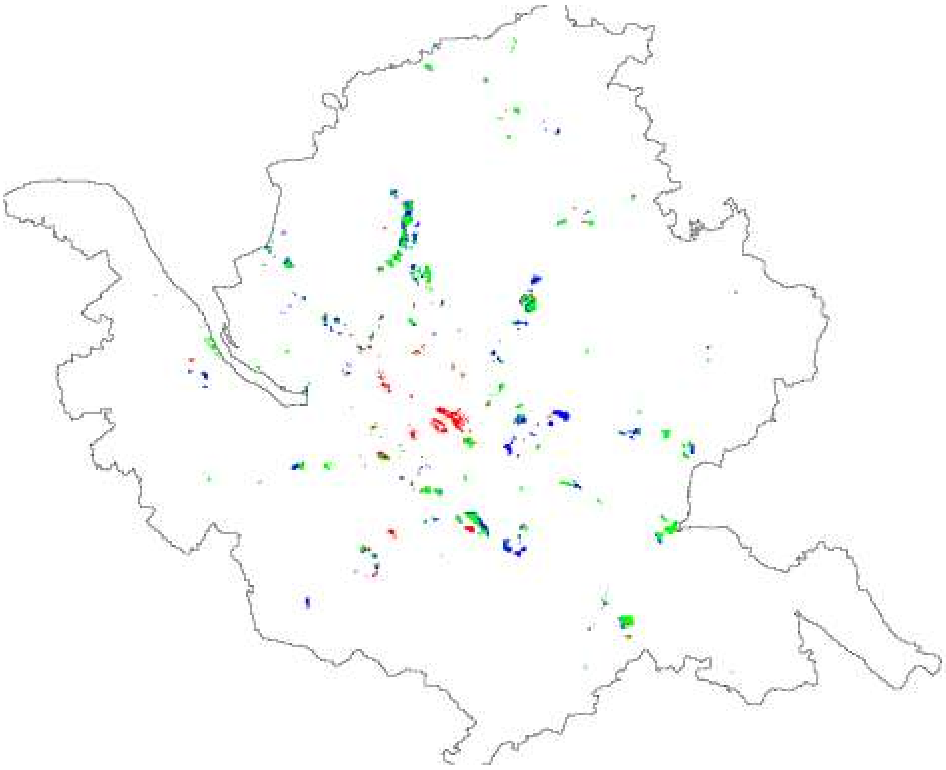


Figure 188: commercial in 2050 in de-central concentration (red) and in concentration (blue) scenario.

In general all the scenarios are quite well represented in the model. Even though the comparison of the data may be difficult to clearly see on the maps and charts, the advanced raster technologies allow us to see the differences between certain UVCZ cells and identify those differences. Another challenge to seeing the differences is that the growth of the population is small enough that the demand for the new UVCZ appears to be insignificant. Figure 189 shows the number of cells for the baseline (historical up to 2000), as well as the number of cells for each of the four scenarios.

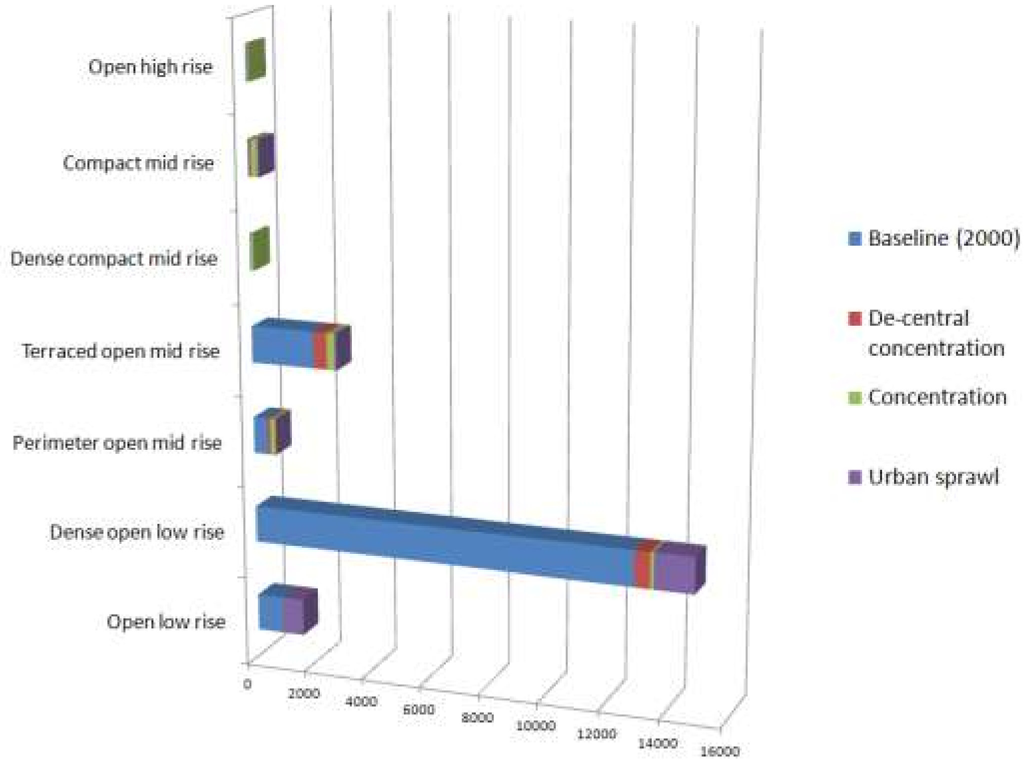


Figure 189: number of cells in 2000 (baseline) and number of new cells for each scenario.

The amount of dense open low rise UVCZ cells in 2000 was so high that an increase of just a few thousand people, even in the urban sprawl scenario did not have a very significant impact. The same could be said for all potential housing UVCZ, especially the ones with a very small amount of cells, such as open high rise, compact mid rise, dense compact mid rise and perimeter open mid rise. This proves that, no matter what urban development scenario is used in the future, the general UVCZ allocation will not change significantly. The low population growth, and the high quantity of existing cells in the pre-2000 time period makes it difficult to observe the differences between the different scenarios. If such a study had been initiated in 1960, it would be possible to study how the UVCZ allocations would look today, if the three different urban development scenarios would have been initiated 50 years ago. It would have been possible to see the effect of a larger population growth over a longer period of time, looking back, rather than looking into the future.

7.5 Alternate history

The concept of applying the environmental scenarios from the past was born by asking what would happen if the decisions posed in the study would have been made in the past. Although the outcome will not give any scientific meaning, the results would at least be interesting. As a result of this curiosity, three alternate scenarios were created and studied.

All three alternate scenarios use the historical population growth (1960 – 2000), but with different population fractions with different potential housing UVCZ demands. However, the high variance of the population within the UVCZ classes cannot represent the real historical densities, and is therefore possible that the alternate scenarios would have unrealistic UVCZ demands.

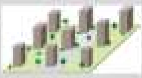
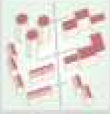
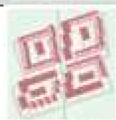
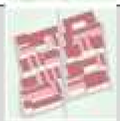
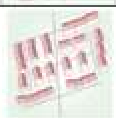
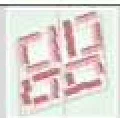
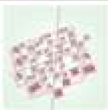
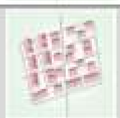
			Mean of population count	Population growth 1960 - 1990 1467722		Population growth 1990 - 2000 242518	
				Fraction of all demand (%)	Demand of cells	Fraction of all demand (%)	Demand of cells
Open high rise			700	5	104,8	5	17,3
Compact mid rise			803	2	36,6	2	6,0
Dense compact mid rise			226	0	0,0	0	0,0
Terraced open mid rise			420	45	1.572,6	45	259,6
Perimeter open mid rise			768	20	382,2	20	63,1
Dense open low rise			218	26	1.750,5	26	289,0
Open low rise			160	2	183,5	2	30,3

Figure 190: demands' allocation, based on historical population growth, in alternate de-central concentration scenario.

Ignoring the historical UVCZ demands, for instance, the dense open low rise in 1960-1990 indicates the numbers are not significantly high. Figure 190 shows the demands' allocation for the de-central concentration scenario using the historical population growth and different fractions. Although the demand of the dense open low rise is highest, the terraced open mid rise takes second place. The modeled alternate UVCZ allocations for each scenario can be observed in the following figures.

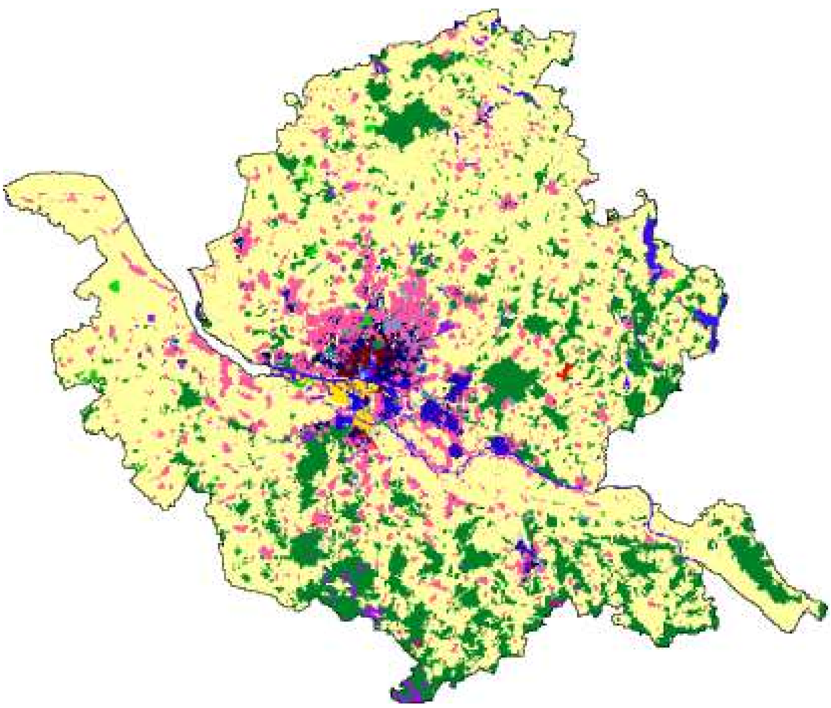


Figure 191: alternate urban sprawl UVCZ scenario year 2000.

Figure 191 is the alternate urban sprawl scenario. Compared to the other scenarios, the large clusters of commercial (blue) areas can be seen in the South and Southeast of Hamburg. Also many more dense open low rise and open low rise (grey) cells spread all over the Greater Hamburg. The terraced open mid rise is more clustered in the city center where no development of compact mid rise can be seen.

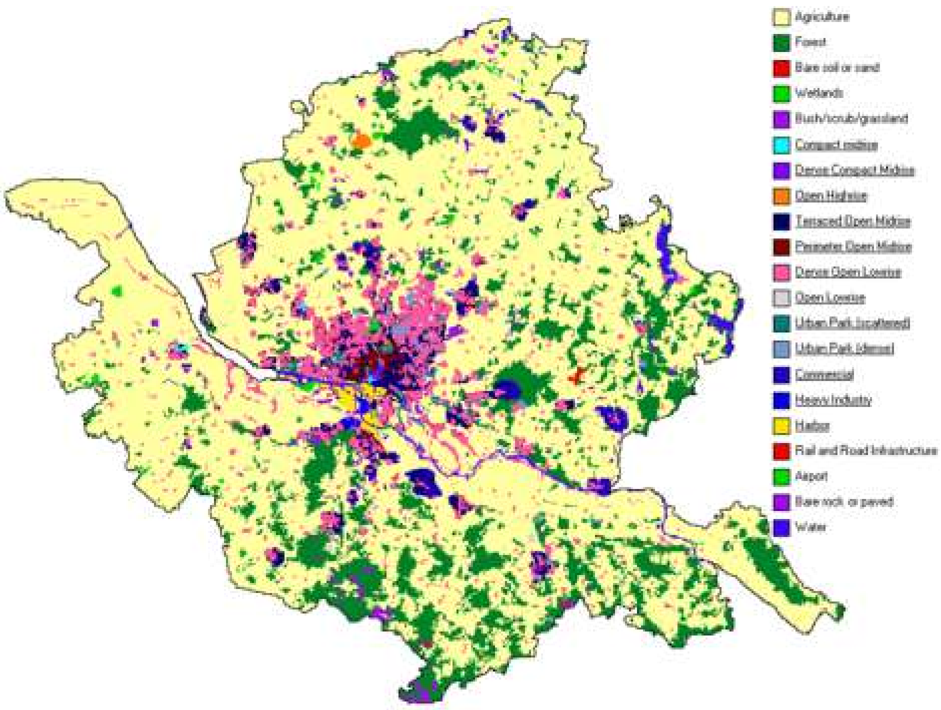


Figure 192: alternate de-central concentration UVCZ scenario year 2000

Meanwhile the de-central concentration has a quite different pattern. Instead of the central areas, the terraced open mid rise expanded into the sub-centers (dark blue color). The dense open low rise and open low rise did not spread as much as it was in the urban sprawl scenario. Not much conversion was detected as well.

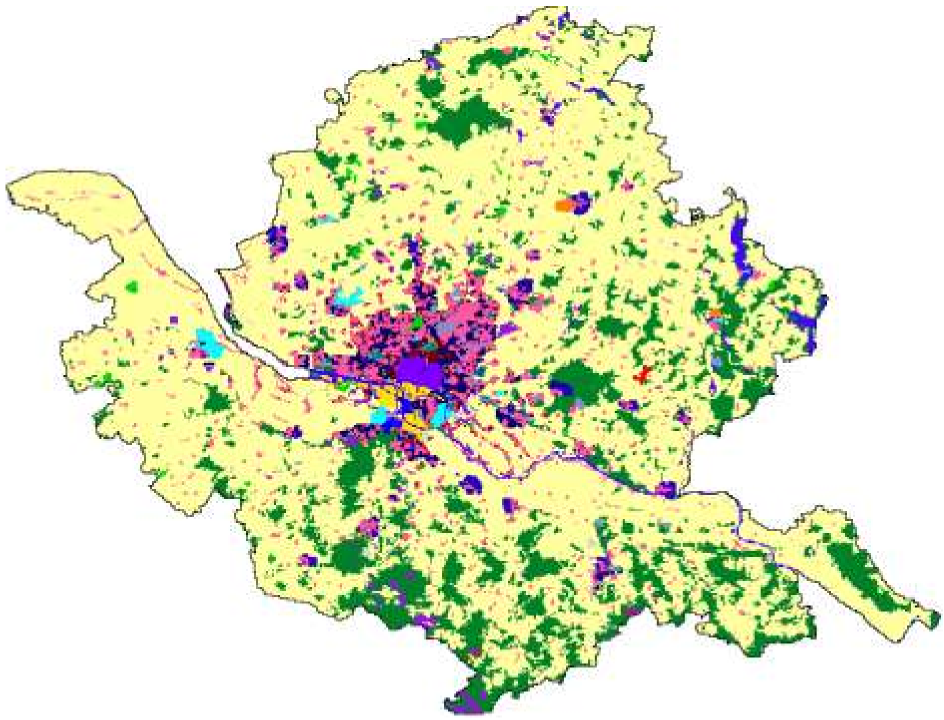


Figure 193: alternate concentration UVCZ scenario year 2000.

The concentration scenario has a very different development. There is almost no new development of the dense open low rise and open low rise, and instead, the large cluster of dense compact mid rise (purple) can be detected in the city center. The compact mid rise develops in the sub-centers, while in the city center it is converted to dense compact mid rise.

The figures above (191 – 193) show quite a diversity of UVCZ allocation for each of the urban development scenarios. Although the future scenarios did not show a significant difference, the alternate scenarios with a higher population growth presented great diversity where the typical urban development trends were identified. This confirms that the rules and the demands for each urban development scenario were well defined.

Conclusions

In the end there are seven different scenarios: one climate, one population and five environmental (including business as usual) scenarios. Because there is only one population, one climate and one zoning scenario, the combination gives four different outcomes. The climate change scenarios with changes in the temperatures are pretty clear. The population scenario was constructed from three different types of projections and extrapolated into the future. The output was used as demands for the urban development scenarios which are the part of the environmental scenarios. The environmental scenarios took into account zoning scenarios which are not really scenarios, but are more likely strictly planning, that probably will be implemented in the near future. Other changes, such as in urban planning, or changes in attitudes toward refugee settlements, can change everything, causing different results. These kinds of changes can affect any future urban development, or in a certain district change the densification program to be implemented and change the entire landscape. Such events are hardly predictable, but the zoning was implemented assuming that it will definitely make a difference. The last, and most important input were the urban development scenarios which were created during the workshop and based on the knowledge of local experts. It is important to mention that these scenarios, and all the scenarios in general, were selected only for the Greater Hamburg case study and would probably not fit for other case study areas.

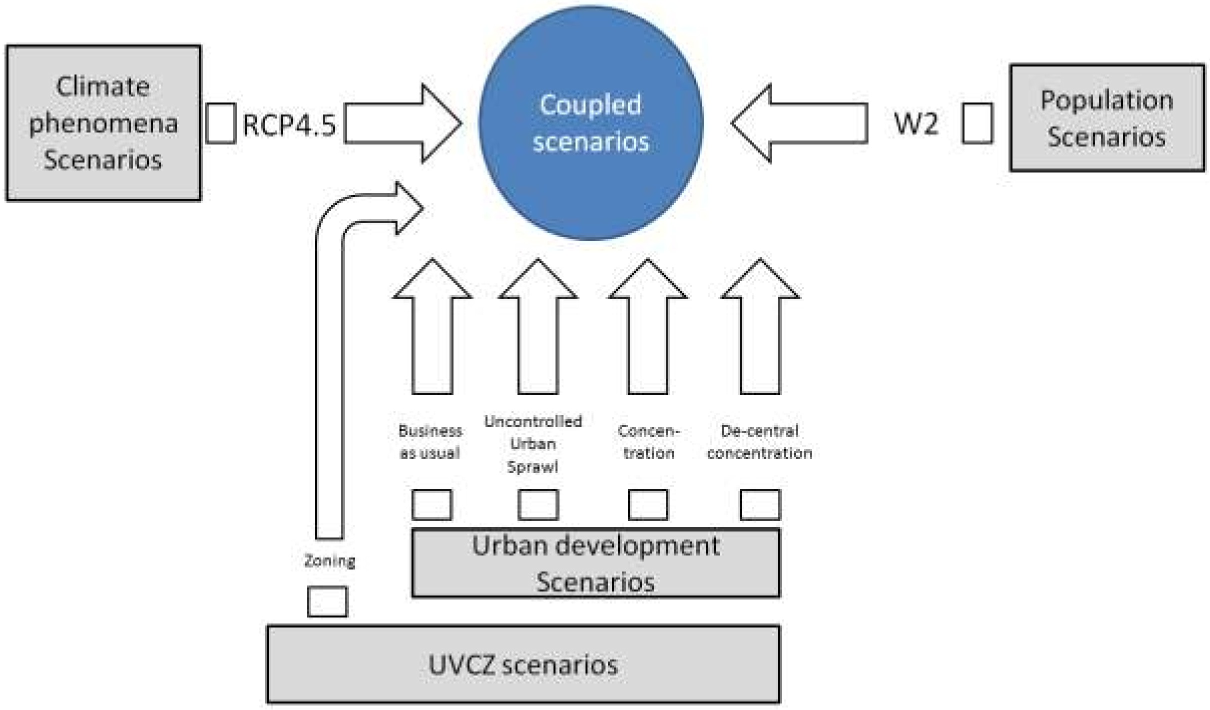


Figure 194: coupled climate, population and UVCZ scenarios give four different outcomes.

The alternate urban development scenarios do not have any influence on future urban development, but they might just raise some discussion and do show interesting results. The four urban development scenarios UVCZ presented in this chapter are able to shift future vulnerability. Based on their outcome, the modeling of the vulnerability indicators will precede.

7.6 Future modeled indicators

For this case study, there are two types of future vulnerability indicators: modeled and auxiliary. Because auxiliary indicators are already modeled and can be easily integrated, there is not much that needs to be done to make them usable for this study. The modeled indicators, however, need to be processed in order to represent future conditions.

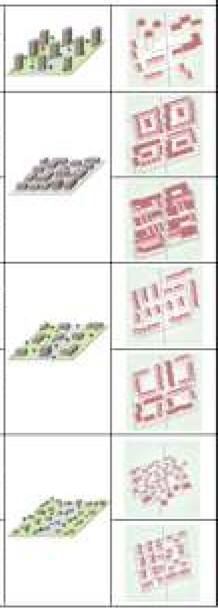
The modeled indicators are the indicators which have been disretized or “packed” into the potential housing UVCZ classes and now after the future UVCZ have been modeled by four scenarios, they will be “unpacked” by assigning random values to the new or changed potential housing UVCZ cells within the certain value range, which was identified during the statistical analysis of the historical data. Based on the assumption that the relationship between vulnerability indicators and the UVCZ have not changed during the time, the “unpacked” indicators can be known as “future vulnerability indicators”.

Of course, the random values were assigned (or the UVCZ have been “unpacked”) only to the new or changed cells, developed by the four scenarios. The number of the new cells was based on official extrapolated population projections. Therefore, I assumed that the relationships of the “old” cells, which have not changed during the time, to the vulnerability indicators have not changed as well. This would mean that the population density, the number of welfare recipients and the degree of soil sealing have not changed over time. The percentage of the elderly for both ("old and new cells) has been adjusted, based on the local aging projections.

The local aging projections were developed by analyzing the official population projections. Although the case study covers not only the Hamburg city-state, it was assumed that the aging process between Hamburg and the other two federal states is similar. In 2000, 17% of all the people in Greater Hamburg were over 65 years of age (elderly). The official population projections indicated that in 2030 about 22% of the population would be elderly (Statistiches Amt fur Hamburg und Schleswig-Holstein, 2010). After extrapolating the data I find that in 2050 about 26,3% of the population will be over 65 years old. That is 54,71% more than in 2000. In order to include the aging process into the model, the relative number of elderly was multiplied by 1,5471.

The next step was populating the new or converted UVCZ cells. As discussed previously, all new or changed potential housing UVCZ cells need to be assigned random values within a certain range. The range was defined via statistical analysis (chapter 6.1) for each modeled indicator. The thresholds of the range were identified +/- 0,5 of the standard deviation from the mean. For instance, the lower threshold for the new open high rise cells is 608, because the 700,4 (mean) minus 0,5 multiplied by 184,37 (standard deviation) equals 608,22 which is 608. Meanwhile the upper threshold is 700,4 (mean) plus 0,5 multiplied by 184,37 (standard deviation) equals 792,59 which is 793. The thresholds of all modeled indicators can be found in figure 195. The green colored numbers are the lower thresholds and the red colored are the upper ones. The higher the standard deviation of the historical statistical data, the larger the range between the thresholds.

In addition to the new and changed cells, all the cells outside Hamburg city-state area received new random indicators as well. This was necessary because there was no historical data of the indicators (elderly, welfare recipients) outside the Hamburg city-state. Therefore, assuming that the social and physical properties of the potential housing UVCZ in all of entire Greater Hamburg are similar, all the cells outside the Hamburg city-state have been assigned random values of vulnerability indicators.



	Population density		Elderly (+aging)		Welfare recipients		Soil sealing	
	x < 0,5ST	x > 0,5ST	x < 0,5ST	x > 0,5ST	x < 0,5ST	x > 0,5ST	x < 0,5ST	x > 0,5ST
Open high rise	608	793	17	21	13	16	59	79
Compact mid rise	664	943	16	21	11	14	72	91
Dense compact mid rise	164	288	16	18	9	11	73	92
Terraced open mid rise	312	529	24	32	7	12	54	77
Perimeter open mid rise	646	889	20	26	6	10	77	94
Dense open low rise	161	275	26	30	4	8	25	50
Open low rise	128	192	28	34	6	11	10	31

Figure 195: thresholds of the new minimum and maximum values for new potential housing UVCZ cells.

The random values were assigned via ESRI ArcMap Field Calculator using the Visual Basic script. The script is rather short, as the input uses the minimum and maximum thresholds and produces a random integer value. The whole script can be seen in the equation below.

```
dim max, min
max= upper threshold
min= lower threshold
x=(Int((max-min+1)*Rnd+min))
```

(10)

The random assignation of the values to the new or changed cells would generate random vulnerability indicators, no matter how close the cells are or other even if they are adjacent to and belong to the same UVCZ class. For instance, the script could assign a value to population density of 161 to the one new dense open low rise, while the other adjacent new dense open low rise cell would receive a population density of 275. That is not a realistic clustering pattern of the homogenous UVCZ class with similar social and physical properties. Instead of the emergence of isolated cells with quite random value, it would be better to group the new cells close to each other diagonally or adjacent. Such groups of cells I called "patches". However, in all the scenarios, some of the new developments or changes of the UVCZ were very limited – one cell basis. This one cell, therefore, is also identified as a patch, which will be assigned a random value by a previously discussed framework. A realistic example of such development or change could be an emergence of new dense open low rise or open low rise on what was previously agricultural cultivated land, or the densification of a building block from perimeter open mid rise to the compact mid rise etc.

The procedure is better seen in figure 196. In it the patches outside the Hamburg city-state are clearly seen. Each patch is visualized by a different color and assigned by a random vulnerability indicator value. The cells of the UVCZ zone 10 (dense open low rise) within the patch on the upper left (dark pink color) received the same population density value, but the patch (indicated with 10s) in the bottom right (green) received a different population density value. Both values had to be within the range 161 – 275.

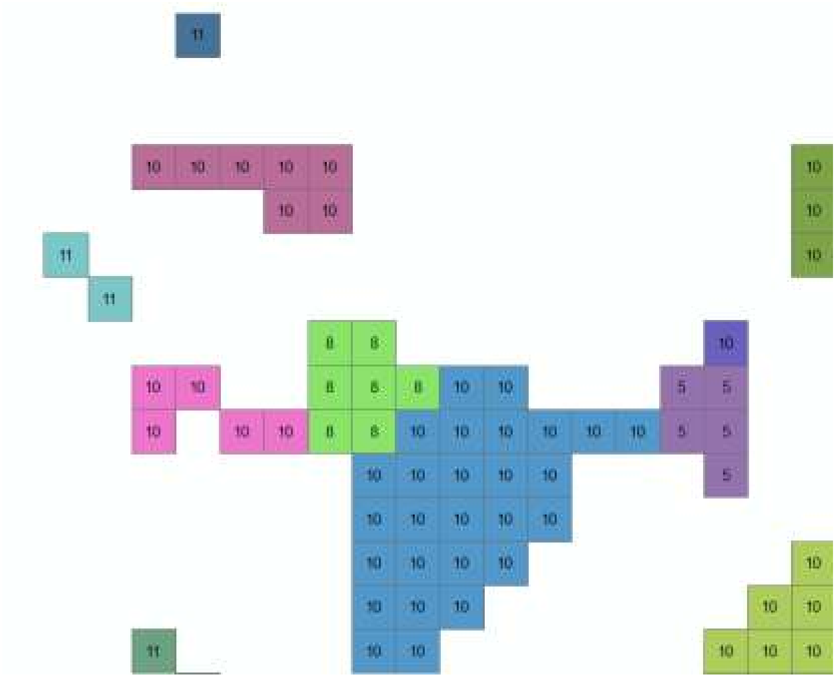


Figure 196: patches of the clustered cells of the same UVCZ class (with the class numbers shown).

The cell marked with the number 11 (open low rise) in the upper left (blue) is an isolated cell. Although there is no other cell around, it was identified as a patch and random values of indicators have been assigned. Another instance is the purple/blue color cell marked with the number 10 (dense open low rise) in the middle of the right side just above the cluster of five cells, indicated with number 5 (compact mid rise). It is isolated and not adjacent to any other clusters of the same class. Therefore it received a different value as well. The following figure shows the modeled future indicators of business as usual (one out of four) scenario within the central Hamburg area.

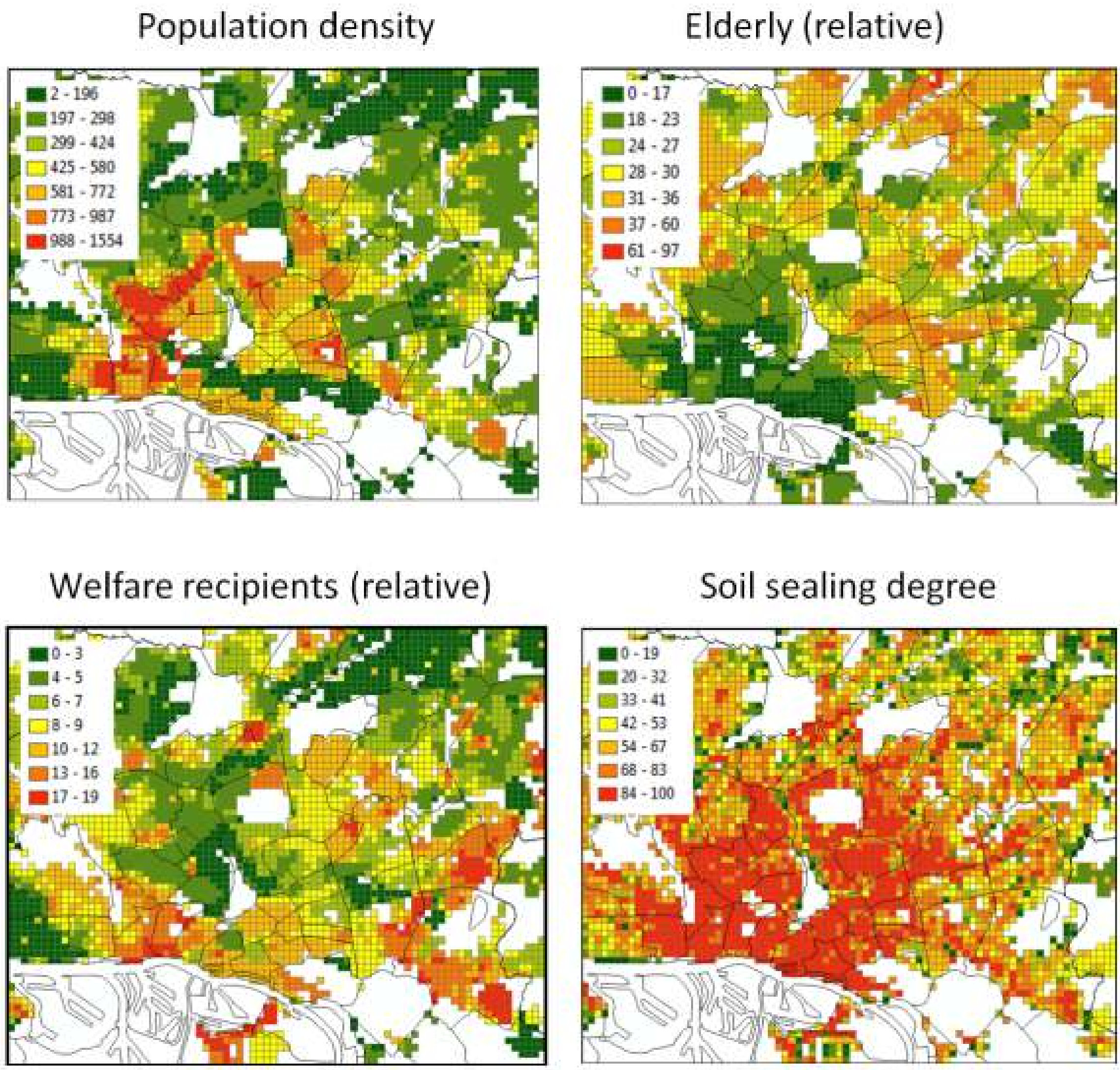


Figure 197: future vulnerability indicators of "old" and new cells within the Hamburg central area. business as usual scenario, 2050, natural break classification.

Such datasets of future vulnerability indicators were generated for all four UVCZ (urban development) scenarios and represent different social and urban patterns. Although these indicators have important meanings, the aim of the study is to aggregate them into the vulnerability assessment and produce a vulnerability index. First, however, they need to be coupled with auxiliary indicators.

7.7 Future auxiliary indicators

The auxiliary indicators are the indicators supplied by other sources. A total of two auxiliary indicators were used in Greater Hamburg case study – the monthly average minimum and maximum temperatures, supplied by WorldClim database and the distance to the nearest hospital. As it was discussed previously, it would be very complicated and probably not possible, to model the locations of new hospitals accurately, so it was decided to use the current locations with the assumption that no new hospitals will be built in the future (till 2050). Based on this assumption, the current proximity (distance) to the nearest healthcare facilities will be used as future data. Therefore, this indicator has not been changed or modified. The details about this indicator can be found in chapter 6.2. The further information presents the future monthly average minimum and maximum temperatures.

The search of the future temperature at the local scale was a difficult task. Fortunately I found the WorldClim initiative. WorldClim is a set of global climate layers provided as gridded climate data with a spatial resolution of one square kilometer. The article about WorldClim data was published in the International Journal of Climatology in 2005 titled “Very High Resolution Interpolated Climate Surfaces For Global Land Areas” (Hijmans et al., 2005). According to the Google Scholar platform, the article was cited 8500 times (accessed on 18.08.2016). The number of citations and the credibility of the journal show extremely trust of this data.

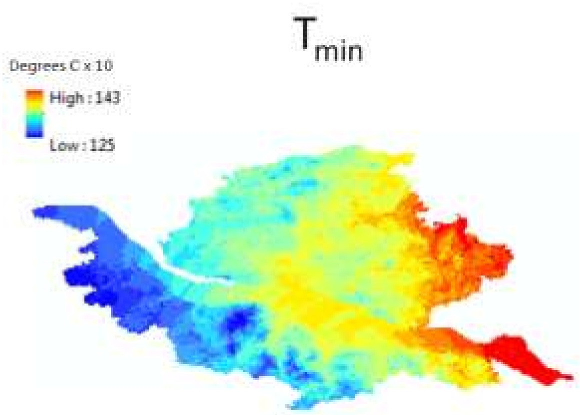
The WorldClim data contains the past (Mid Halocene, about 6000 years ago), current and future climate data. The past data is the output of a downscaled global model. The current data is the interpolations of 1960 – 1990 observed data, and future conditions are based on the downscaled global climate model CMIP5 which is known as Coupled Model Intercomparison Project Phase 5. The CMIP5 started in September 2008 as a consortium of twenty climate modeling groups from all around the world which agreed to promote a new set of coordinated climate model experiments. More information about the downscaling methods of the future data in WorldClim can be found in the article “Very High Resolution Interpolated Climate Surfaces For Global Land Areas” (Hijmans et al., 2005) and on the WorldClim website (http://www.worldclim.org/).

The future WorldClim data is available for the number of global climate models, each containing four representative concentration pathways (RCPs): RCP2.6, RCP4.5, RCP6.0 and RCP8.5. The RCPs are the greenhouse gas concentration projections, adopted by IPCC in the fifth Assessment Report (AR5) in 2015 (more about RCPs can be found in chapter 7.1). For some unknown reasons, some of the RCPs projections are not available for some of the climate models. The climate data contains four variables in total: monthly average minimum temperature (°C multiplied by 10), monthly average minimum temperature, monthly total precipitation (in milliliters) and index of bioclimatic indicators. The bioclimatic indicators were received from monthly temperature and rainfall values in order to generate more biologically meaningful variables, such as precipitation of the wettest month, maximum temperature of the warmest month, mean diurnal range etc. At this moment, there are two time periods of available future data: 2050 (average of 2041-2060) and 2070 (average of 2061 – 2080).

The interest of this case study is the time period of 2041-2060. From all the global climate models, I decided to choose the MPI-ESM-LR which is known as Max Planck Institute for Meteorology Earth System Model. The Max Planck Institute for Meteorology is based in Hamburg and conducts a lot of research inside and outside Hamburg. From all the climatic measures available, I decided to choose the monthly average minimum and maximum temperatures which are good measures of the hot days and tropical nights. The monthly average maximum and minimum temperatures as well as other indicators are available at different spatial resolutions: 10 arc-minutes, 5 arc-minutes, 2,5 arc-minutes and 30 arc-seconds (about 900 m at the equator). Because the grid of Greater Hamburg is 250 x 250 meters, I selected 30 arc-seconds as the highest resolution data. Concerning the different RCP scenarios, the only RCPs scenario (RCP4.5) was selected. This scenario indicates the intermediate emissions and intermediate radiative forcing. It is the business as usual climate scenario with a slightly lower energy intensity than today, strict climate policies and maintains a decrease in the use of croplands and grasslands.

The future monthly average minimum and maximum temperatures as raster data were downloaded from the same WorldClim database as the historical data and masked out with the Greater Hamburg area. The future temperatures are downscaled global climate models for the period of 2041- 2060 and available for four RCP scenarios. As discussed previously, in order to keep the model simple I decided to choose the MPI-ESM-LR model and only the one, the RCP 4.5 scenario.

The following figure (198) shows the future monthly average minimum and maximum temperatures for the Greater Hamburg. The map on the left presents the future monthly average minimum temperatures and the map on the right shows the future monthly average maximum temperatures. The patterns are almost exactly the same as the historical data. It is not surprising, knowing that the historical information was used to model the future temperatures.



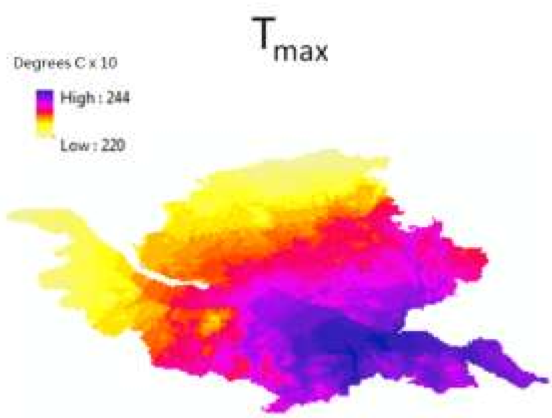


Figure 198: future (2041-2060) monthly average minimum (left) and maximum (right) temperatures. Downscaled MPI-ESM-LR climate model, the RCP 4.5 scenario (source: WorldClim, 2016).

It is worth noting that the future minimum and maximum temperatures are slightly greater. The future monthly minimum temperature ranges from 12,5 to 14,3 °C (11,0 – 12,9°C in 1960 - 1990) and the maximum temperature ranges from 22,0 to 24,4 °C (20,9 – 23,2°C in 1960 - 1990). Based on the statistics (discussed in chapter 6.2), such temperatures are a danger to human health and can cause the appearance of heat days. If there ever was a place in Greater Hamburg (either today or in the past) which did not experience a hot day or a tropical night, this is certain: in the future there will be no place to hide. The minimum temperature is about 1,5°K higher and the maximum temperature is about 1°K higher than historical temperatures. Although one degree looks small, it can double the appearance of heat days. According to the (IPCC, 2014a), one degree can have a high impact on the likelihood of greater frequency and severity of heat waves in the future. This impact can be reflected by the results found in the vulnerability assessment.

8 Vulnerability assessment

The outcome of the vulnerability assessment accomplishes the main goal (research question) of this study – where the heat impact will be the highest and where the heat-vulnerable people will live in Greater Hamburg? The answer to these questions is a great finding, but it is not the only result of this study. The future population's vulnerability to heat waves in Greater Hamburg is an outcome of various data processing and modeling approaches and techniques. The final outcome might be very relevant to the people having an interest in Greater Hamburg, but it is only an example of a case study which was done using new methods and approaches in order to discover how the future population's vulnerability to heat wave might be modeled. The other studies, using the same methods and approaches, may likely give a result of quite different population's vulnerability. Therefore, the outcome of the vulnerability assessment should not be the judgment of the entire study.

Vulnerability assessment is not a simple composition or aggregation of the indicators. The final index depends on how the indicators are combined, how the values of an indicator can change and how one can be more important than others. Using the different vulnerability assessment approaches, even with the same data, can give very different results. My objective, therefore, is to give a clear explanation of how the vulnerability index for this case study was aggregated.

As it was discussed in chapter 4.2, the population's vulnerability to heat waves in Greater Hamburg addresses eight indicators which affect vulnerability in a positive or negative way: population density, monthly average minimum temperature, monthly average maximum temperature, degree of soil sealing, relative population over 65 years old (elderly), distance to the nearest hospital and relative number of welfare recipients. All these indicators are aggregated into vulnerability elements: exposure, sensitivity and adaptive capacity. Names of the elements help to understand the purpose of the indicators within the element and their contribution to the final vulnerability index.

Based on the presented population's vulnerability to heat waves in Greater Hamburg assessment's framework (figure 55 in chapter 4.2) the exposure consists of population density (social exposure), soil sealing (territorial exposure) and monthly average minimum and maximum temperatures (physical exposure). Although the population density is often identified as sensitivity, I decided to have it in exposure's element as a part of the exposed population to heat waves. The population density is not aggregated into exposure element, but rather used in the end to find the absolute vulnerability by multiplying it with the vulnerability index. The reason for this is that if the population density is included into the vulnerability index, then there is no point to assess vulnerability – just consider the higher vulnerability where the population density is the highest. The other vulnerability element is the sensitivity which contains the elderly as the only indicator. The combination of sensitivity and exposure is the potential impact (PI). PI is the effect of climate change to the sensitive system. The potential impact can be softened by adaptive capacity which practically is used to reduce vulnerability. In this case study the adaptive capacity is the combination of the distance to the nearest hospital and the relative number of welfare recipients. In the end vulnerability is composed of potential impact and adaptive capacity. If the absolute vulnerability has to be found, vulnerability (or relative vulnerability) is multiplied by the population density. Such a conceptual representation of vulnerability broadly shows the roles of each vulnerability indicator in the vulnerability assessment. The further information presents in detail how each indicator was processed and had changed from its primary condition, was aggregated to vulnerability components and, later, to vulnerability index.

8.1 Rescaling, normalization, transformation and weighting

The more indicators are composed, the more complicated the process of composition becomes. This is because each indicator usually represents data with different or no units, different scale and different pattern. In order to fit them together, the indicators have to be rescaled, normalized, transformed and weighted. If qualitative indicators would be used, it would be even more complicated. Fortunately, this study uses the quantitative indicator-based approach and all the indicators can be expressed as a quantity. But that does not mean that the quantity of different indicators can be easily combined. For instance, potential energy is the combination of the mass, gravity and height. If we want to find out if the potential energy is high or low, we have to know some reference, like the range of each of the indicators. We have to identify the minimum and the maximum in order to normalize the values in between. For example, if the maximum is 10 and minimum is 0, then 2 is low. If the maximum is 4, 2 is average. If the minimum is 10 and the maximum is 20, then 10 is low. Because the goal is the vulnerability index which would say if the area has high or low values, these values for the indicators have to be known as well. However, the min/max classification is not always the most suitable method. For instance, the population density of 5000 people per square area would be low if the maximum population density is 50 000 people. But if even the population density of 5000 is high, the other method has to be used. Another issue is that some indicators cannot be represented by linear function. For example, the precipitation from 0 to 200 mm would not have a slight impact on flooding, while the 200-250 mm precipitation would cause a moderate impact, and a heavy impact would be caused by 250 to 280 mm. If the standard min/max normalization would be applied, the 180 would be identified as moderate, but not as a light impact on flooding. Therefore, each indicator is unique and must be considered individually. It should be known in advance which indicators, together with the corresponding weights, have to be combined. Only then can the process of rescaling, normalizing or transforming can take place. In the following sections I describe in detail how each indicator of this study has been processed – normalized, transformed, weighted or only rescaled. Because all four urban development scenarios use the same approach, I present only the BaU scenario. In other scenarios only the range and values' distribution might differ a little bit. It should also be remembered that only potential housing UVCZ data is processed. The other UVCZ, such as agriculture, harbor, forest, park etc. with no population density or elderly, but with certain temperatures, distance to hospital and degree of soil sealing are not considered, because no population would be affected there – it is assumed that people will experience heat hazard only where they live.

Population density (PopDens)

The population density presents the number of people per cell (250 x 250 m). As an indicator it will be used in the end in order to find the absolute vulnerability which is the multiplication between population density and the vulnerability index. Therefore the population density is not actually part of the vulnerability index. It does not have to be rescaled, normalized, transformed or weighted.

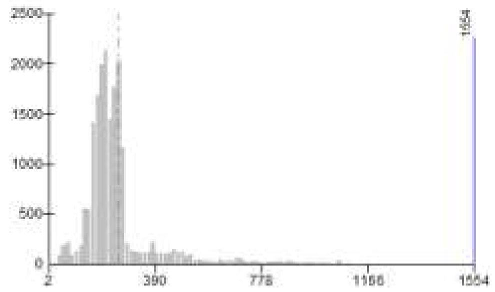


Figure 199: frequency of population density.

The population density varies from 2 to 1554. The distribution is normal with very high extreme which will give very high absolute vulnerability. Meanwhile the highest frequency of cells contains rather low population density which is 150 – 250 people per cell.

Monthly average minimum and maximum temperatures (Tmin_N and Tmax_N)

The monthly average minimum and maximum temperatures originally are available in raster grid format (with spatial resolution of ~ 0,5 km^2). The raster is downscaled to the 100 x 100 meters resolution, converted to points as centroids of the cells. Afterwards the vector potential housing UVCZ is joined with the point (centroid) data. If more than one centroid falls inside the cell, the average value of the centroids is assigned to the cell.

For the selected MPI RCP 4.5 scenario, the monthly average minimum temperature ranges from 12,6 to 14,3°C, while the monthly average maximum temperature ranges from 22,1 to 24,4°C. If only the MPI model would be considered, these would be the minimum and maximum values. However, more global climate models exist which give a higher variety in temperatures. Therefore, in order to perform the sensitivity analysis of the global climate models, the range of all models is required. Twenty different climate models for Greater Hamburg area contain a monthly average minimum temperature from 11,6 to 17,3°C, and a maximum temperature from 21,9 to 29,8°C. In order to keep it simple, I decided to use the range from 10 to 20°C for the minimum temperature and from 20 to 30°C for the maximum temperature. Of course, the higher extreme values can be counted as well, but as the overview analysis has shown, there are none for all twenty global climate models. As mentioned previously, the MPI scenario contains temperatures ranging from 12,6 to 14,3°C (minimum) and from 22,1 to 24,4°C (maximum). Both ranges are above identified thresholds, namely, when the days have mean temperatures above 20 degrees and there is a higher mortality rate. Therefore, the entire Greater Hamburg area in the MPI RCP 4.5 scenario is physically exposed to heat hazard in the future.

The minimum and maximum temperatures (in 10^2) were rescaled (divided by 1000) and normalized using minimum/maximum normalization to the ranges of 10-20 and 20 - 30°C. The cells were reassigned with the new values of minimum temperatures ranging from 0,26 to 0,43 and maximum temperatures from 0,21 to 0,44. The frequency of values before and after the processing can be seen in figure 201.

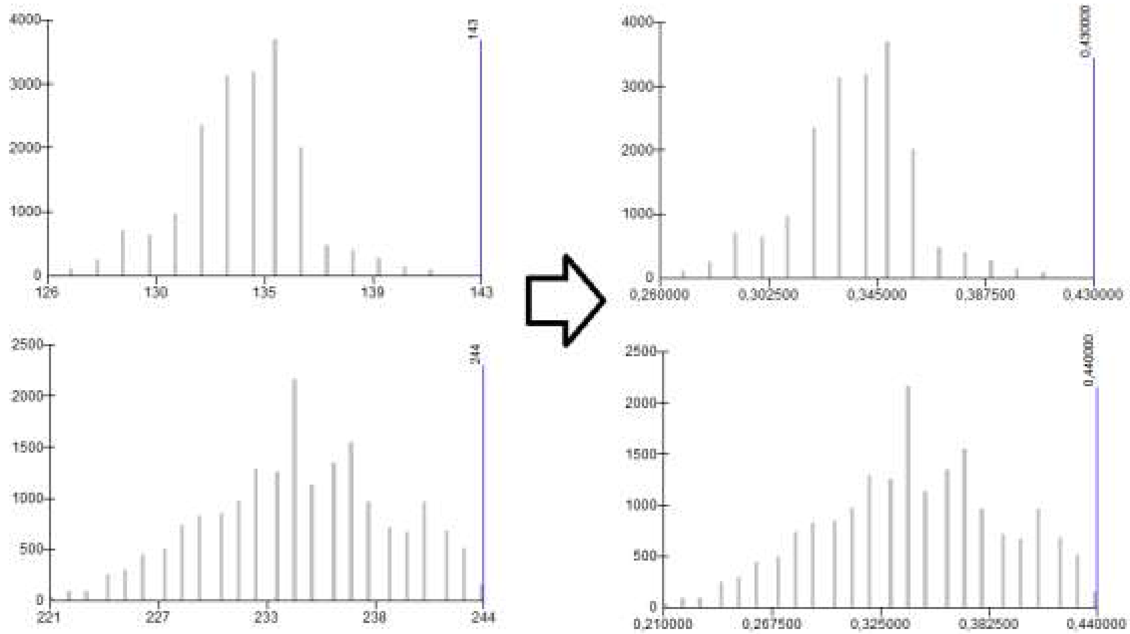


Figure 200: frequency of the monthly average minimum (Tmin_N, upper) and maximum (Tmax_N, lower) temperatures values before (left) and after (right) normalization/rescaling for the MPI RCP 4.5 scenario in 2041 – 2060.

Degree of soil sealing (Soil_R)

The degree of soil sealing is associated with % of area covered by impervious surfaces, causing a higher heat impact. The degree of soil sealing varies from 0 to 100, which means that there is no need to normalize, only to rescale from 0 to 1.

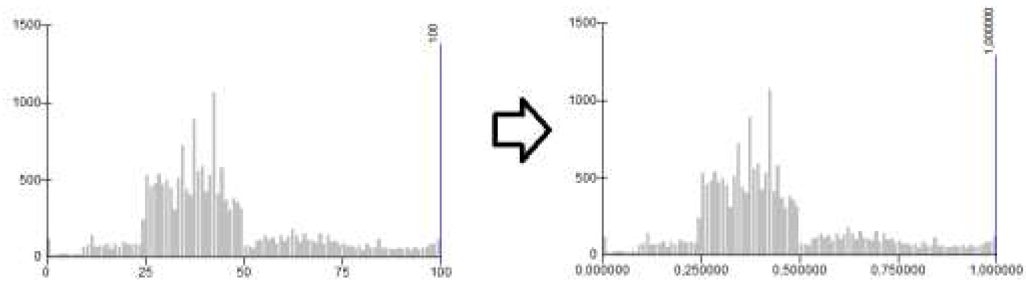


Figure 201: frequency of the degree of soil sealing (Soil_R) before (left) and after (right) rescaling.

Population over 65 years old (relative) (Eld_R)

The relative population over 65 years old shows the number of elderly per 100 people. The higher number means a higher concentration of old people which increases the sensitivity to heat waves. Because the range of the indicator varies from 0 to 97 (close to 100), no normalization is required. Similar to the soil sealing, only rescaling will be applied.

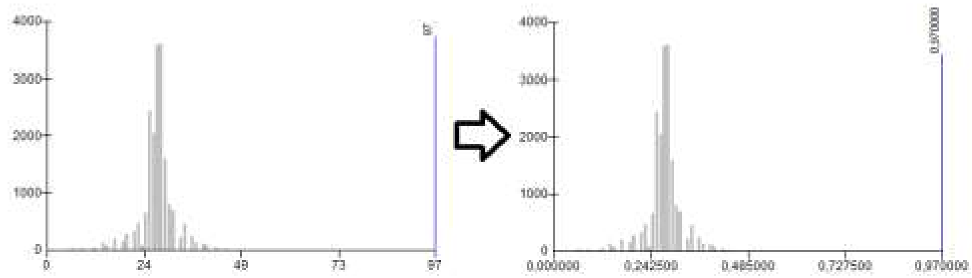


Figure 202: frequency of relative elderly (Eld_R) before (left) and after (right) rescaling.

Figure 203 shows the frequency of the elderly distribution within Greater Hamburg. There is one cell with 97% of elderly, while the majority of the cells have between 25 – 30% of elderly. Although the percentage of 25-30% is already high a proportion of elderly, the 97% is defined as very high and the 25-30% as low-average.

Distance to the nearest hospital (Dist_T)

The distance to the nearest hospital is a proximity indicator which shows the values in meters to the nearest healthcare facility. Contrary to other indicators, the higher value gives lower adaptive capacity and therefore it has to be inverted. The distance to the nearest healthcare facilities in Greater Hamburg varies from 0 to 20947 meters. If the min/max normalization is used, the high number of cells with distances 500 and 3000 meters away from the hospital would receive similar values, while in real situation the 2500 meters difference has a significant impact, especially to the elderly. Meanwhile the 12000 meters and 20000 meters would receive different values, which actually is not the case. In actuality, when the hospital is so far away, the difference is not as high. I decided, therefore, to transform the distance to the nearest hospital to the logarithmic function.

The $-\log_{10}(Dist)$ gives a more realistic distribution; however, it cannot be negative. Because the negative adaptive capacity subtracted from the potential impact would cause an increase in vulnerability even if there is no exposure, I neutralized the negative values by adding the lowest negative value to the function. As a result, the function looks as follows: $-\log_{10}(Dist) + 4{,}32112$. Now it shows a realistic relationship between adaptive capacity and distance to the hospital (figure 204).

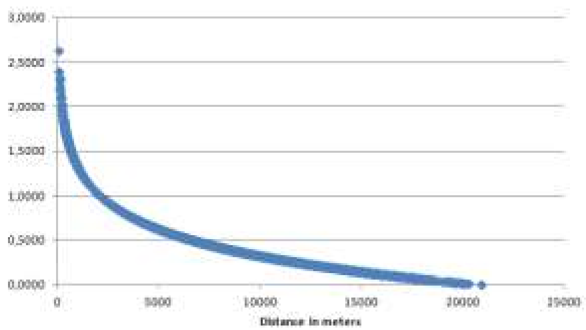


Figure 203: adaptive capacity by distance to the nearest healthcare facility (transformed).

The indicator of distance to the nearest healthcare facility now ranges from 2,62 (0 km away) to 0 (21 km away). The following distances give appropriate values of adaptive capacity, based on the distance: 1km (1,32), 3km (0,84), 5km (0,62), 10km (0,32), 15km (0,14) and 20km (0,02). As the results, the frequency of distance to nearest hospital before and after transformation is presented in figure 205.

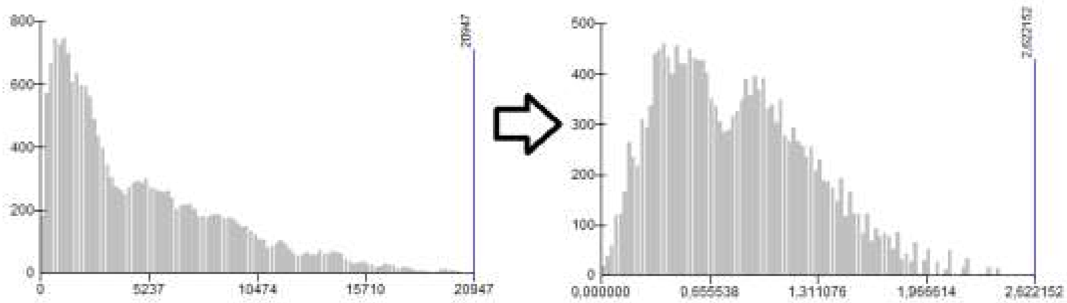


Figure 204: frequency of distance to nearest hospital (Dist_T) before (left) and after (right) transformation.

Welfare recipients (relative) (Welf_W)

The number of welfare recipients is also an adaptive capacity indicator, meaning that increasing values of welfare recipients should decrease adaptive capacity. Thus it has to be inverted as well. The number of welfare recipients represents the number per 100 people who are receiving welfare. For Greater Hamburg the value ranges from 0 to 19%. The rescaling would give values from 0 to 0,19. However, I took into account that distance to the nearest hospital should have the same importance as number of welfare recipients. Therefore, the "high" and "low" values of one indicator should correlate with the "high" and "low" values of distance to the nearest hospital. In other words, both indicators must be equalized. In this case the distance has range from 2,62 to 0 and the welfare recipients ranges from 0 to 0,19 (if rescaled). It has to be rescaled, inverted and weighted. In order to invert it, it has to be multiplied by 5,26 that 0,19 would get the value of 1, the highest value. Then the indicator has to be subtracted from 1 and multiplied by 2,62 (because the lowest number of welfare recipients should have the same effect as the shortest distance to the nearest healthcare facility). As a result, the end the function is expressed as 2,62*(1-Welf*0,0526).

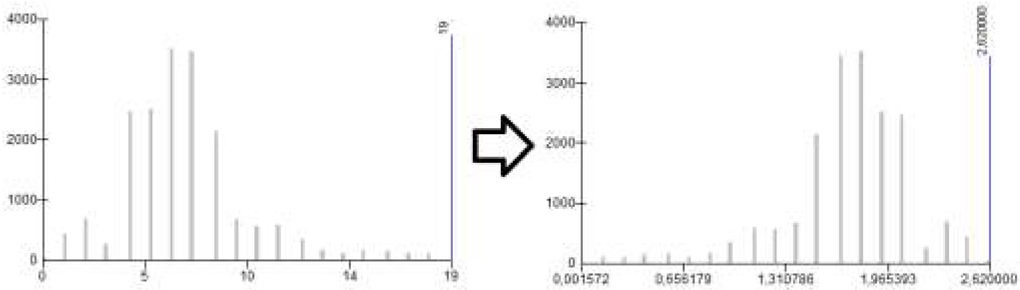


Figure 205: frequency of welfare recipients (Welf_W) before (left) and after (right) rescaling and weighting.

Now, for instance, a lower number of welfare recipients gives a higher number of adaptive capacity with the maximum value of 2,62 when there is 0% of welfare recipients within the cell.

8.2 Aggregation

When all the indicators are processed, the next step is the aggregation to vulnerability elements. In total there are four vulnerability elements: exposure, sensitivity, potential impact and adaptive capacity. The combination of sensitivity and exposure is the potential impact and the potential impact interacts with adaptive capacity to produce a vulnerability index. The vulnerability elements can also serve individually as a good information source to represent high exposure, sensitivity, potential impact or low adaptive capacity.

Exposure

The exposure might be the most diverse vulnerability element, combined from three indicators. As discussed previously, although the population density is the social exposure indicator, I decided to exclude it from the exposure element, but to use it directly with the vulnerability in order to get the absolute vulnerability. The other two indicators of exposure are the monthly average minimum and maximum temperatures and soil sealing. All of these indicators affect the heat impact. The temperatures are the cause and the soil sealing is the contributor. With low temperature, even the maximum soil sealing value would not cause any heat impact. The temperature (min and max) of the MPI model, the RCP 4.5 scenario is high enough to cause the impact - minimum temperature is higher than 12°C and the maximum temperature is higher than 20°C. However, the minimum temperature from other global climate models is below 12°C and this issue is addressed in the model's sensitivity analysis (chapter 8.5). The upper thresholds of the ranges (20°C and 30°C) are often associated with the occurrence of tropical nights and heat waves (DWD, 2016; German Environmental Ministry, 2016). However, if the monthly average temperature would reach these thresholds, it would cause constant tropical night or heat wave. In the end there are two ranges 12 – 20°C for the minimum temperature and 20 - 30°C for the maximum temperature. It is known that the soil sealing in Greater Hamburg can affect the temperature on average by about 2°K difference (Arnds et al., 2015; Schlünzen et al., 2010) which would be associated with the ranges: the maximum temperature should be weighted by 5 (because of the 10 degrees range), the minimum temperature by 4 (because of the 8 degrees range) and the soil sealing by 1. The function of exposure then becomes as follows: Exp= 5*Tmax_N + 4*Tmin_N+1*Soil_R . At that point the impact of the Tmax_N would range from 1,05 to 2,2, Tmin_N from 1,04 to 1,72 and the Soil_R from 0 to 1. The combination of these three indicators (exposure) for the business as usual scenario ranges from 2,47 to 4,44. The frequency of cells and spatial distribution within the Hamburg area is seen in figure 207.

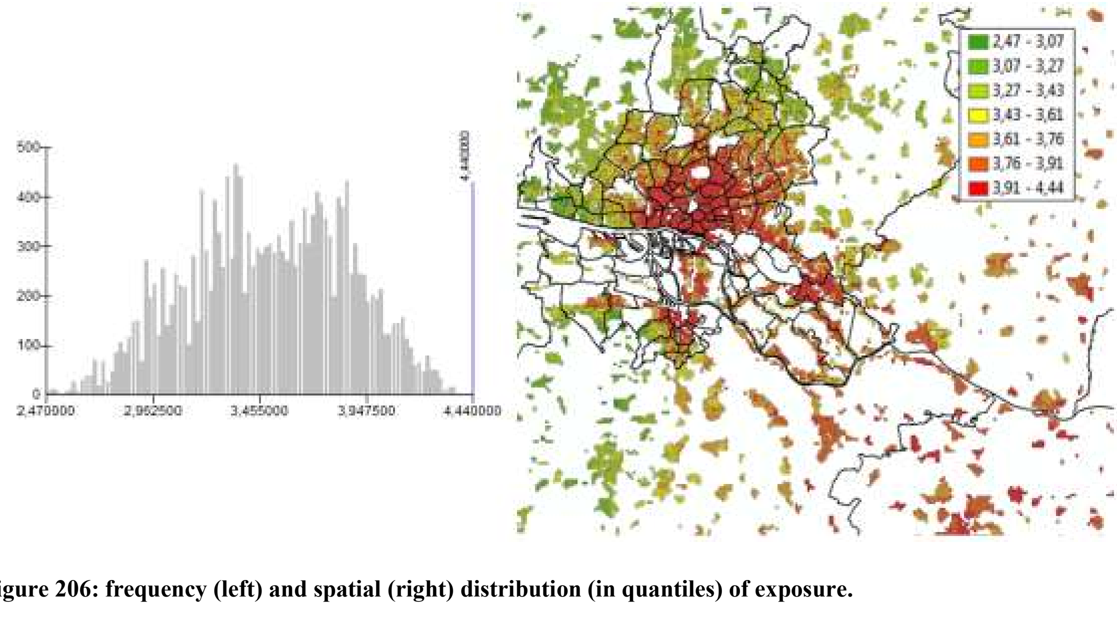


Figure 206: frequency (left) and spatial (right) distribution (in quantiles) of exposure.

Because exposure has a high weight on temperatures, the higher temperatures (both min and max) cause higher exposure in central part, South and Southwest (part of this effect can be seen in the figure above). Although the weight of the soil sealing is low, its contributing effect can be seen in the central areas. Considering all these factors, the spatial distribution of the exposure seems logical and acceptable.

Potential Impact

The potential impact is the combination of the exposure which was just calculated, and the sensitivity. Technically, both indicators could be either added or multiplied. However, a more logical way would be to use the multiplication. Although all cells within Greater Hamburg should experience, more or less, heat impact, if there would be cells with no heat impact, the use of addition would be misleading. The same is valid for the sensitivity – if there are no sensitive people, no vulnerability exists. For instance, if the exposure would be zero and the sensitivity would be 1 which means that all people living within the area are old (very sensitive), but there is no heat impact. The other cell with the high exposure of 0,7 (not based on Greater Hamburg study), and about 30% of elderly (0,3), would have the similar effect, although logically there would be no impact to the elderly in the first case. Therefore, I decided to use the multiplication (geometric aggregation) which is more scientifically appropriate. The multiplication is done by Exp and Sens which is Eld_R, in the end the formula is PI = Exp * Eld_R.

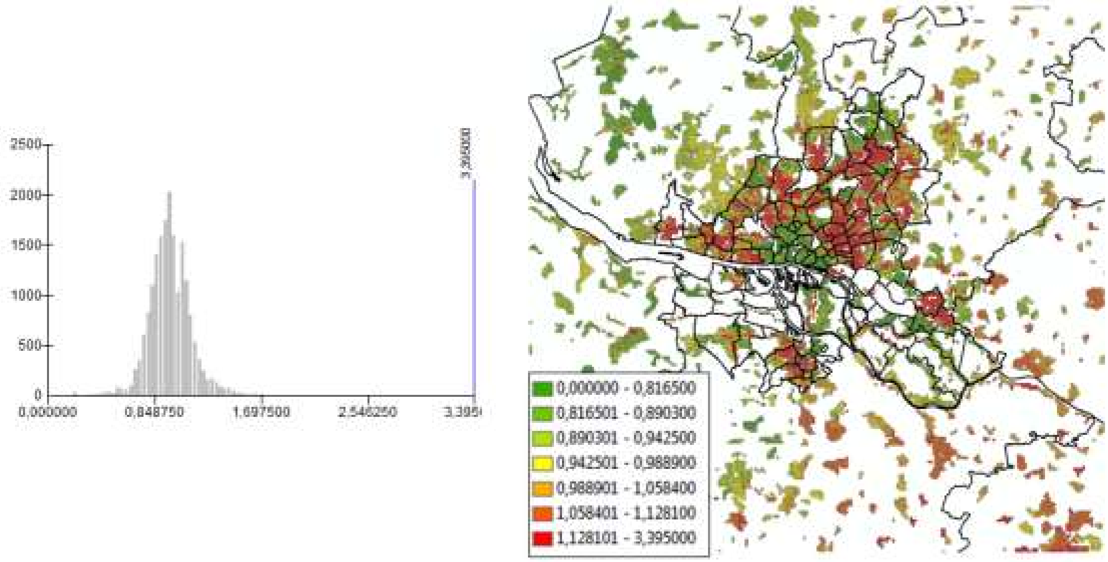


Figure 207: frequency (left) and spatial (right) distribution (in quantiles) of potential impact.

The frequency distribution of potential impact values is much more widely dispersed (figure 208) than the elderly distribution (figure 203). The most frequent cells have the values around 1, a few cells do not have any impact (because of no sensitivity) and one cell with 97% of old people has the impact of 3,395. If we would study the spatial distribution, the effect of elderly can be easily recognized. The city center area which does not have high number of elderly has very low impact, opposite to the surrounding areas in the East, Northeast, North and the West. The areas in the far Northwest and Southeast have similar sensitivity values (about 25%), but the exposure is much higher in the Southeast and it is the reason for the greater potential impact.

Adaptive capacity

The adaptive capacity (AC) is a simple combination of the distance to the nearest healthcare facility and the relative number of welfare recipients. Unlike the other indicators, the AC indicators had to be inverted, so that the longer distance and a higher number of welfare recipients would represent a lower adaptive capacity. The AC also cannot be negative for this case study, because the terms “no adaptive capacity” or “lack of adaptive capacity” exist, but there is no way that the adaptive capacity would increase the potential impact. If that would be true, then the areas with no potential impact, but with the negative AC would have an impact as well. Therefore, the adaptive capacity for this study is positive.

Because the distance to the nearest healthcare facility and the number of welfare recipients contribute to each other it was decided to use addition (arithmetic aggregation). This shows that the closer the areas are to the hospital and the people are less poor, the more adaptive capacity they have. There will be less adaptive capacity if the areas are either poor or far from the hospital.

Both indicators equally affect the adaptive capacity, so their weights have to be equal. In a previous section it was shown that the number of welfare recipients must be weighted by 2,62 in order to have both indicators ranging from 2,62 to 0. The ideal addition (when a cell has the highest values of both indicators) would give adaptive capacity of 5,24, but in the business as usual scenario the values range from 4,69 to 0,56 (figure 209).

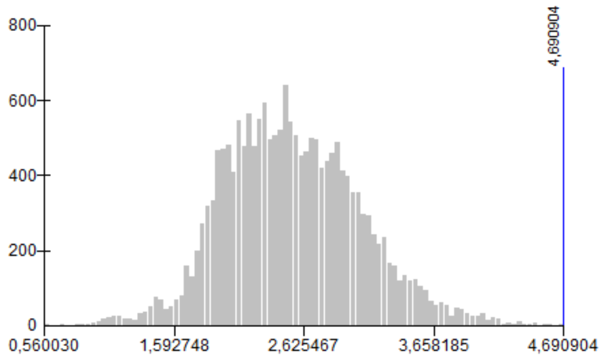


Figure 208: frequency distribution of adaptive capacity

In the next step the AC will have to be combined with the potential impact. Now, with the current weights, when the PI ranges from 0 to 3,395 and the AC from 4,69 to 0,56, what the AC does is to help absorb the effects of potential impacts. Logically thinking, there is no way that the income and good healthcare availability would fully compensate for heat impact. In general, because the concept of AC is very unclear and fuzzy and each vulnerable situation considers different AC indicators or options, it would be very difficult to measure what is the real effect of the AC. But considering that there are many more AC indicators which were not taken into account because of modeling limitations, I assume that even the highest AC cannot compensate more than 30% of the impact. Based on PI distribution, the highest frequency of cells has the value around 1, meaning that the average case in Greater Hamburg would have the PI value closer to 1. Then the AC should range from 0 to 0,3. Because now the existing AC range varies from 0,56 – 4,69, I ran a few experiments with the weights of 1/10, 1/15 1/20 and found that the 1/15 weight had the best outcome.

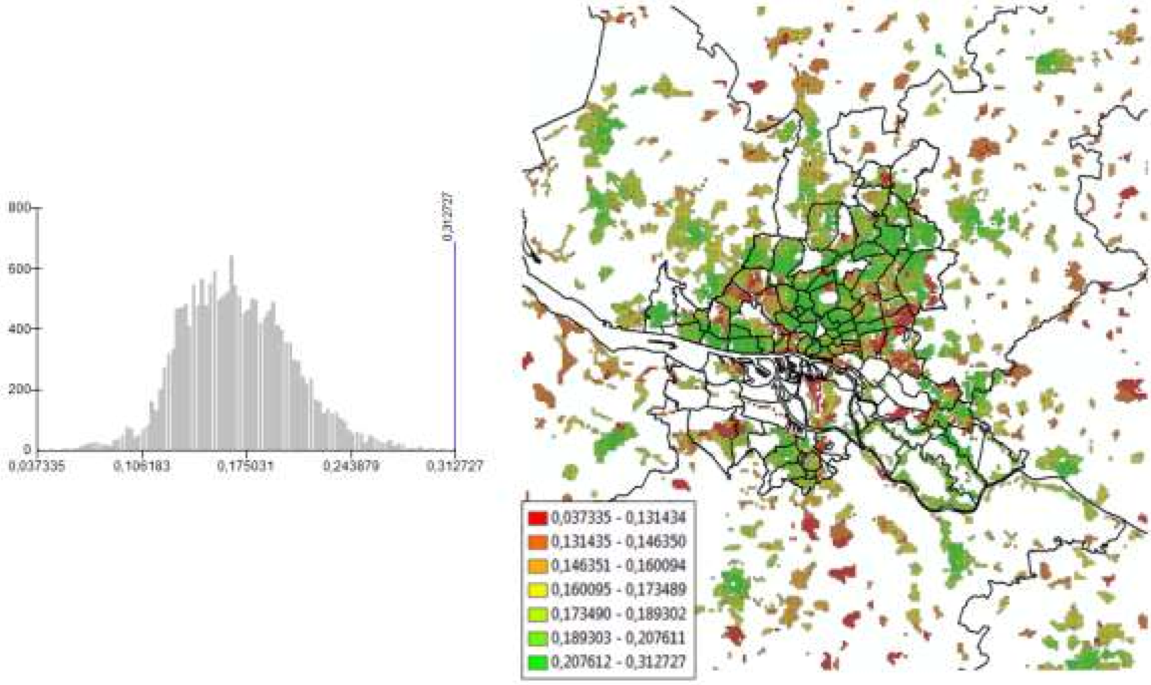


Figure 209: frequency (left) and spatial (right) distribution (in quantiles) of adaptive capacity with the weight 1/15.

Now the maximum AC is close to the 0,3 which would be 30% of the most common PI value within Greater Hamburg. The coloring of the spatial distribution is inverted. The red color shows the low and the green color shows the high AC areas. As might be expected, the lower AC is typical for the areas with the higher number of welfare recipients. The central part of Hamburg is quite well covered with healthcare facilities which partly compensate for the high number of welfare recipients. Meanwhile the isolated clusters in the South, East, West and North are not as poor, but are generally at a greater distance from healthcare facilities.

8.3 Results of relative vulnerability

The relative vulnerability is the final composite index which composes all indicators except the population density. The definition of vulnerability remains the same: a function of the climate variation to which the system is exposed, the system's sensitivity and its adaptive capacity. Now the conditions of the definition are fulfilled: vulnerability in Greater Hamburg depends on how the system is exposed to heat, its sensitivity and adaptive capacity. There is only one more step necessary to assess vulnerability, and that is to combine the potential impact (PI) and the adaptive capacity (AC). Vulnerability is the difference between the potential impact and the system's ability to cope with these impacts. Mathematically it can be expressed as $V = PI - AC$ (that is why the AC cannot be zero, because with no impact vulnerability would be negative which is not possible).

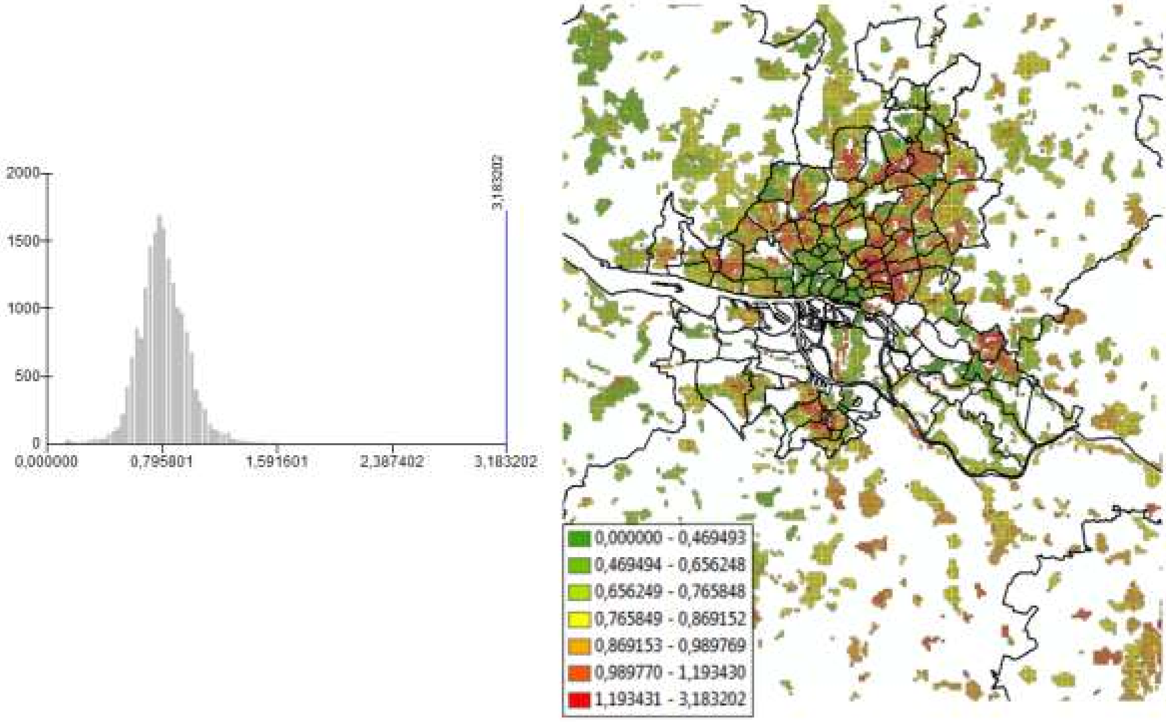


Figure 210: frequency (left) and spatial (right) distribution (in quantiles) of vulnerability, BaU scenario.

Vulnerability for the BaU scenario in 2050 ranges from 0 (no sensitivity) to 3,18 at its maximum. Most of the cells' vulnerability varies from 0,6 – 1. Some of the areas with a very high number of the elderly actually reach three times the amount of vulnerability. There are only 32 cells with vulnerability higher than 1,5, and these cells may contain senior living areas and/or nursing homes. The other ones are isolated cells in the areas where the relative number of the elderly is over 40%. In order to evaluate the different degrees, or classes of vulnerability, I decided to assign five classes to show the relative vulnerability: very low, low, moderate, high and very high. The very low and very high classes would represent about 10% of all cells, the low and high classes represent about 25% and the moderate class would represent about 40% of all the cells. The classes, their thresholds and the values are shown in the table below.

Table 23: vulnerability classification (x̄ - mean, SD – standard deviation).

	Lower thresold	Upper threshold	Lower thresold (vuln)	Upper threshold (vuln)	# of cells	% of all cells
Very low	...	x̄ - 1,2SD	0	0,5980362	1603	8,7
Low	x̄ - 1,2SD	x̄ - 0,4SD	0,5980362	0,7365394	4557	24,7
Moderate	x̄ - 0,4SD	x̄ + 0,4SD	0,7365394	0,8750426	6554	35,5
High	x̄ + 0,4SD	x̄ + 1,2SD	0,8750426	1,0135458	4036	21,9
Very high	x̄ + 1,2SD	...	1,0135458	3,183202	1705	9,2

The classes of very low, low, moderate, high and very high vulnerability are relative classes. If this study, using the same indicators and same methods were to be applied to some other area, the low vulnerability in Greater Hamburg may not mean the same in that other area. This issue is highlighted in the discussion section.

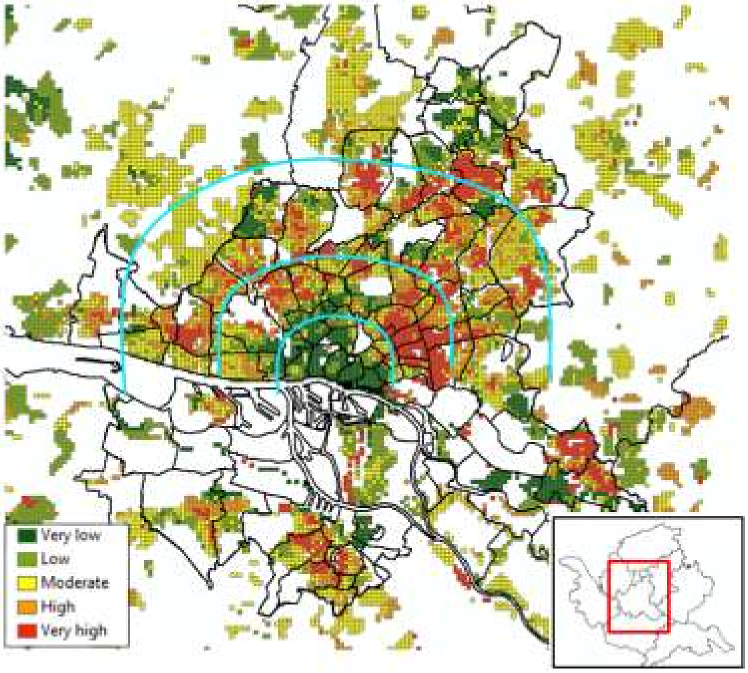


Figure 211: spatial distribution of vulnerability classes (central area), BaU scenario.

Figure 212 shows the central area of vulnerability, assigned to the classes. The central area represents the Hamburg city-state and surroundings. I will start with the Northern bank of the Elbe river. For a better orientation I have drawn three cyan colored semi-circles. The city center area within the first semi-circle has a very low vulnerability value, although this area contains high soil sealing. The reason for this rating is the high proportion of elderly persons in the population. The area within the second semi circle is quite diverse. The East has a very high vulnerability which is associated with a high elderly population percentage. Northeast contains a fairly high vulnerability, which is caused by the elderly population as well. The Northern part of the second semicircle is quite different. The upper areas have a higher elderly population as well as a higher number of welfare recipients. The Northwest, meanwhile, has a low number of welfare recipients, but has more elderly people present. The West part is also diverse, with moderate numbers of the elderly but a high number of welfare recipients. Although the Eastern part of the third semicircle has a higher number of welfare recipients, it is less vulnerable than the Northeast, because of the number of elderly persons. The North has a similar situation. The Northwest contains two areas with fairly low vulnerability, even though the adjacent clusters have higher values. Again, the reason for this is the same – the number of the elderly. The West, as well as the outer areas, experiences the same pattern. The West and Northeast contain higher number of elderly persons, which causes high vulnerability; the North and Northwest have moderate vulnerability while the far Northeast has low values, even though it has limited healthcare services. The area has a similar profile as the Northwest in the third semicircle – the elderly numbers are lower than 30%, which gives low vulnerability. In the far Southeast there is on cluster with a very high vulnerability, and another with a low value. The first has average elderly population but fairly high percentage of welfare recipients. The second has a low population of welfare recipients and elderly people. Figure 212 shows only a few settlements on the Southern side of the Elbe's bank. The Wilhelmsburg area (between Elbe and Südelbe) is affected by higher welfare recipient values but the higher vulnerability is noted where the elderly percentages are higher than average. The elderly population is also dominant in the South of Wilhelmsburg – in Harburg city and partly in Fischbek, which is situation in the Western part of Harburg. A similar pattern is in Finkenweder and in the West of Wilhelmsburg, very close to the Elbe

River. In general, the entire central area is similarly covered by the high soil sealing and the close distance to the hospitals. The welfare recipient numbers have an effect, as well as the temperatures, but the main driving factor is the elderly population. This is not surprising, knowing that the major factor in high heat-related deaths is old age.

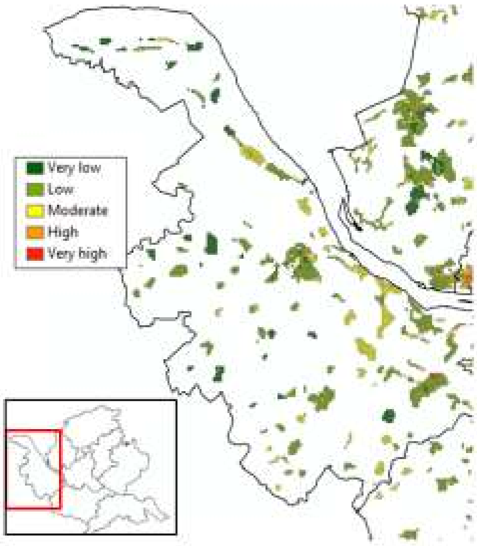


Figure 212: spatial distribution of vulnerability classes (Western area) , BaU scenario.

The Eastern area covers the Stade and part of Pinneberg districts. This Greater Hamburg part is less vulnerable. Most of the clusters contain low or very low vulnerability. In the East-center locations some of the clusters have moderate vulnerability because of distance to the hospitals. Some other cells have high or very high vulnerability because of soil sealing, not the elderly population.

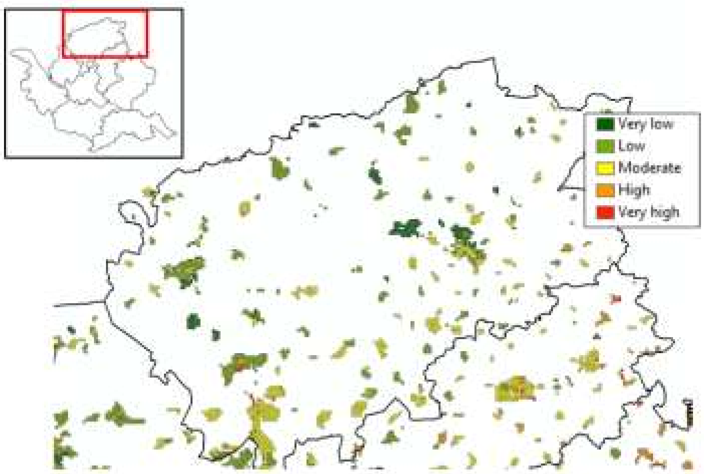


Figure 213: spatial distribution of vulnerability classes (Northern area), BaU scenario.

A similar situation exists in the Northern part of Greater Hamburg, which covers a small part of Pinneberg, the entire area of Segeberg and part of the Stornmarn districts. The proportions of low and moderate vulnerability are smaller and there are not many high or very high vulnerability cells either. The percentage of elderly is quite homogenous, and the higher vulnerability is mostly affected by the higher soil sealing and composition with increased distances to hospitals. Areas to the North and East of Greater Hamburg have a lower impact because of the lower monthly minimum and maximum temperatures which cause lower exposure.

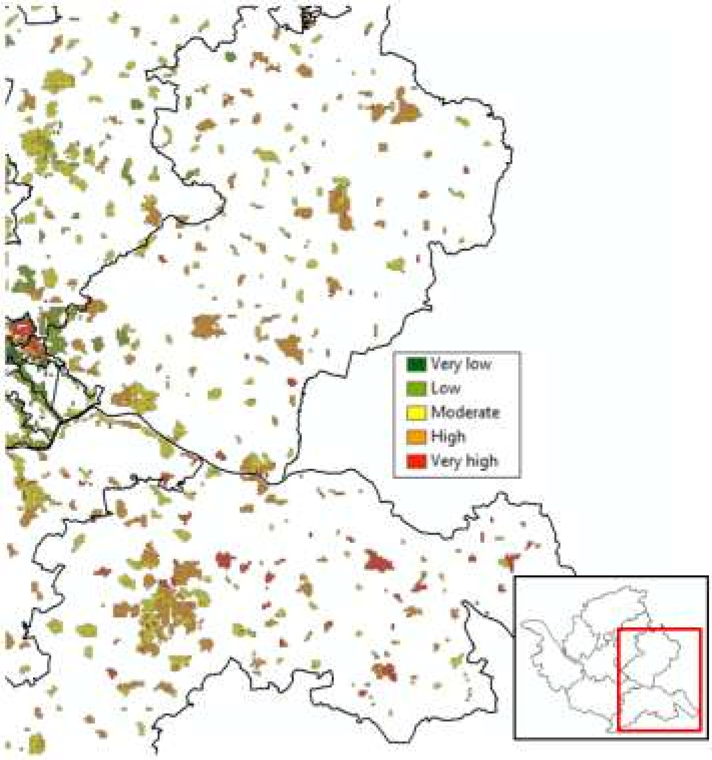


Figure 214: spatial distribution of vulnerability classes (Eastern area), BaU scenario.

The first thing we see when looking at the above figure is that the Eastern, South and Southeastern areas (a small part of Stormarn, Lauenburg and Lüneburg districts), are more greatly affected by higher temperatures than other areas, although the degree of soil sealing is similar to the Northern and Western areas. This is especially seen in the far Southeast where exposure is seen greater than 50% in some areas. Some of the remote areas are highly affected by longer distances to healthcare facilities. In fact however, there is a very limited number of cells with low or very low vulnerability. Most of the clusters have moderate, high or very high vulnerability. Contrary to the Hamburg city-state, the main factors that contribute to vulnerability in these areas are exposure and distance to hospitals, not the number of elderly or welfare recipients.

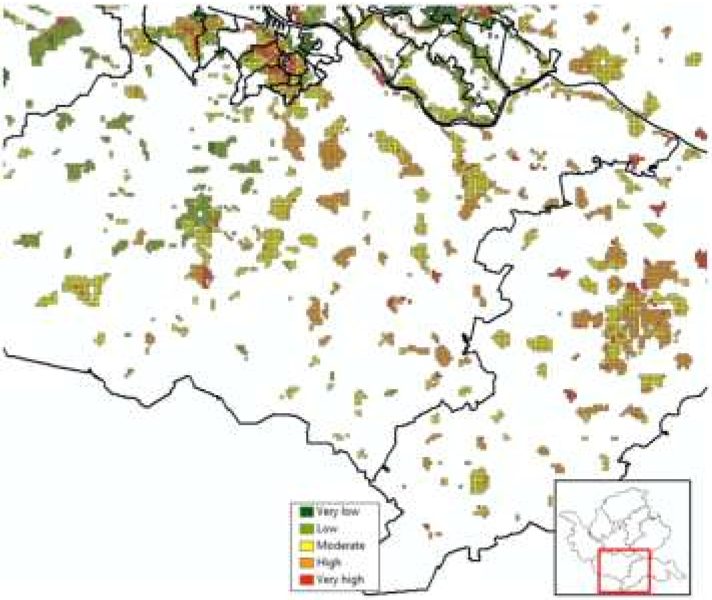


Figure 215: spatial distribution of vulnerability classes (Southern area), BaU scenario.

When considering vulnerability, the Southern areas which consist of part of Lüneburg and Harburg are quite diverse. The clusters, found more in the Western area, have lower vulnerabilities, lower exposure and adaptive capacity, while the numbers of elderly and degree of soil sealing seen to be not that much different. Few clusters contain low and high vulnerability cells, although the distance to hospitals, exposure and number of elderly is similar. The difference between these areas is mainly caused by the fact that the number of welfare recipient is double the amount.

The table below shows the absolute and relative numbers of cells between the areas (districts) for the BaU scenario in 2050. Additionally it shows the sum and the mean values per cell. If we more closely, Lüneburg and Lauenburg districts are the Eastern and Southeastern districts, that represent more than half of all the cells having a high or very high vulnerability. We see an exactly opposite situation in the Stade and Pinneberg districts in the East. More than half of all the cells there have a low or very low vulnerability. Hamburg city-state has the most homogenous distribution among all districts.

In concerning the total vulnerability, from all areas, this is what we see: the least total vulnerability, in the BaU scenario, is in the Stade district. This would be because total vulnerability is strongly influenced by the number of cells and a lower amount of cells in an area can lower the total vulnerability, as in the Stade district. The business as usual scenario is favorable for Lüneburg and Pinneberg, and is least favorable to Segeberg and Harburg. The de-central concentration scenario is similar to the average vulnerability, which is just slightly lower, because of the higher number of cells.

Table 24: absolute (left) and relative (right) number of cells by classes, BaU scenario. Total vulnerability shows the sum of vulnerability and the mean is the average vulnerability per cell.

	Absolute					Relative						
	Very low	Low	Moderate	High	Very high	Very low	Low	Moderate	High	Very high	Mean	Total Vulnerability
Harburg	10	391	1010	634	108	0	18	47	29	5	0,843689	1816
Lüneburg	0	7	567	798	368	0	0	33	46	21	0,929868	1616
Stade	311	890	443	36	8	18	53	26	2	0	0,689656	1164
Segeberg	225	691	885	96	20	12	36	46	5	1	0,728494	1397
Pinneberg	181	948	763	75	9	9	48	39	4	0	0,713465	1410
Stormarn	9	334	840	329	46	1	21	54	21	3	0,80997	1262
Lauenburg	0	155	549	908	112	0	9	32	53	6	0,888637	1532
Hamburg	895	1197	1608	1219	1048	15	20	27	20	18	0,818447	4884

The highest total vulnerability is definitely for Hamburg, because of the high number of the cells. However, the leading position of having the average vulnerability is held by Lüneburg in the Southeastern district. As might be expected, Hamburg city-state has the highest degree of soil sealing, and is quite homogenous in values. Meanwhile, the surrounding districts experience a low variety of the elderly, and isolated cells are affected more by the degree of soil sealing and longer distances to healthcare facilities. The isolation and a higher number of welfare recipients cause a lower adaptive capacity, which is important in lowering the potential impact. The South, East and Southeast areas are affected more by greater minimum and maximum temperatures. Together with a higher degree of soil sealing they cause higher exposure. Again, this is very dangerous to distant areas, with limited healthcare services and a higher concentrations of welfare recipients.

Vulnerability in compact, de-centralized and urban sprawl affected cities

In order to compare vulnerability between all urban development scenarios, I assigned the vulnerability values to the classes, with the same ranges valid for the BaU scenario. The scenarios are presented one by one, starting with the most vulnerable scenario for the Greater Hamburg – the uncontrolled urban sprawl

Urban sprawl

The most vulnerable scenario is the urban sprawl. The lower population density causes a higher amount of cells to be occupied and populated. More cells mean a higher total vulnerability which is equal to 15149. The urban sprawl scenario is not favorable to any district of Greater Hamburg, except Hamburg city-state. Vice versa, it is least favorable to Lüneburg, Stade, Pinneberg and Stormarn districts. In the urban sprawl scenario, large proportions of the population are assigned to open low rise UVCZ. This type of UVCZ cells are spread all over Greater Hamburg, located at a distance from the sub-centers and healthcare facilities and increasing the vulnerability in the surrounding districts. For Hamburg city-state the average vulnerability in the urban sprawl scenario is not the lowest, but the total vulnerability gets a value of 4780 which is the lowest among all the scenarios. This is not surprising because if more people relocate to the surrounding districts in the countryside, there will be less people staying in Hamburg, which means there will be fewer cells and less vulnerability in Hamburg city-state.

Table 25: absolute (left) and relative (right) number of cells by classes, urban sprawl scenario. Total vulnerability shows the sum of vulnerability and the mean is the average vulnerability per cell.

	Absolute					Relative						
	Very low	Low	Moderate	High	Very high	Very low	Low	Moderate	High	Very high	Mean	Total Vulnerability
Harburg	7	291	1177	607	133	0	13	53	27	6	0,841097	1863
Lüneburg	0	11	373	833	534	0	1	21	48	30	0,956969	1676
Stade	198	987	464	68	1	12	57	27	4	0	0,693901	1192
Segeberg	234	1066	617	144	23	11	51	30	7	1	0,713797	1488
Pinneberg	193	759	872	115	29	10	39	44	6	1	0,737958	1452
Stormarn	9	264	684	571	68	1	17	43	36	4	0,843159	1346
Lauenburg	0	57	782	766	156	0	3	44	43	9	0,889763	1567
Hamburg	906	1224	1489	1172	1051	16	21	25	20	18	0,81827	4780

In comparison to the BaU scenario, more cells for all districts result in high and very high vulnerability. Even when there is not a large change in the relative number of cells, the increase in absolute numbers is high (for instance the very high vulnerability cells in Lüneburg). Figure 217 (below) shows the differences between BaU and urban sprawl scenario. The urban sprawl scenario contains a high amount of isolated cells with high vulnerability which is caused by a higher degree of soil sealing. Another factor causing differences in vulnerability among the scenarios is randomness. Some patches in the urban sprawl scenario have moderate vulnerability, but in the BaU scenario the same patches receive a very high vulnerability rating. This happens because, for instance, in one scenario the elderly indicator for a specific patch randomly receives the lowest value, while in another scenario the elderly indicator for the same patch randomly receives the highest possible value. But it is an example of only one indicator. If this happens to more indicators, the vulnerability index of the same patch can vary significantly. This is a big issue which will be analyzed in more depth in the discussion chapter.

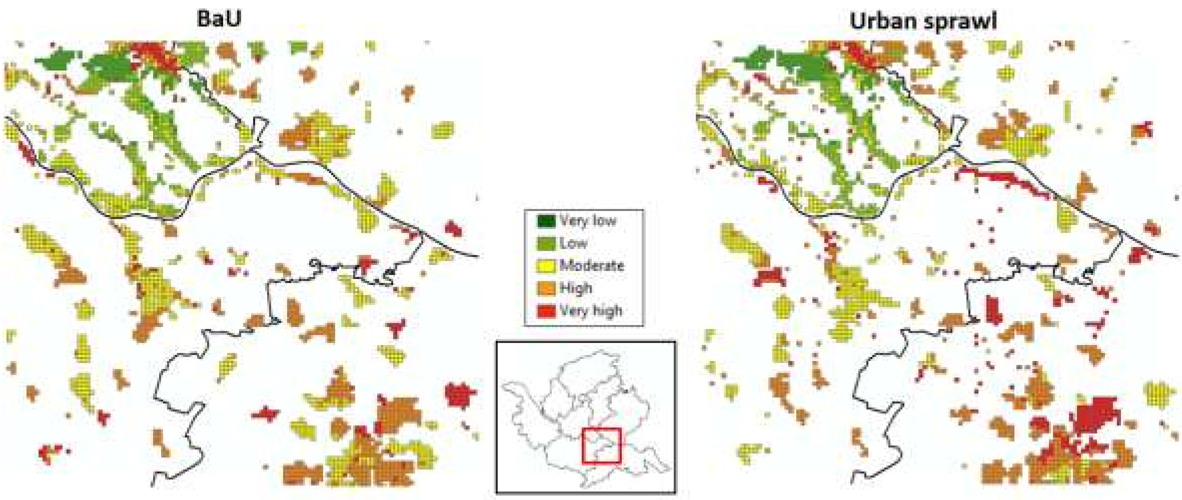


Figure 216: comparison between the BaU and urban sprawl scenarios the south east of GH.

Figure 218 shows the spatial distribution of the vulnerability classes in the Hamburg city-state. The circles show the positive changes of clustered cells compared to the BaU scenario and the rectangles show the negative changes. Because it is very hard to compare the cell to cell changes on the very local level, I marked only the larger clusters. These changes are more typical for outskirts of the Hamburg city-state, because the inner areas are quite packed with other non-residential UVCZ. Moreover, the urban sprawl scenario focuses on small isolated lonely cells which emerged far from the urbanized areas.

In comparison with BaU, the urban sprawl scenario in and around the Hamburg city-state caused different impact. Some of the clusters in North and Northeast (marked as circles in figure 218) become more vulnerable. Meanwhile other clusters nearby (rectangles) received a lower vulnerability than in the BaU scenario. The Southeast area seems to be the one most negatively affected. The large clusters with high vulnerability are mostly affected by the degree of soil sealing and the number of welfare recipients. In the South and West of Hamburg city-state, however, there were no significant differences seen between the urban sprawl and BaU scenarios. When some differences in vulnerability are present, some can be explained by the conversions made, the cells' allocation and neighborhood effect while most of the differences in the surrounding areas are probably due to the randomness effect.

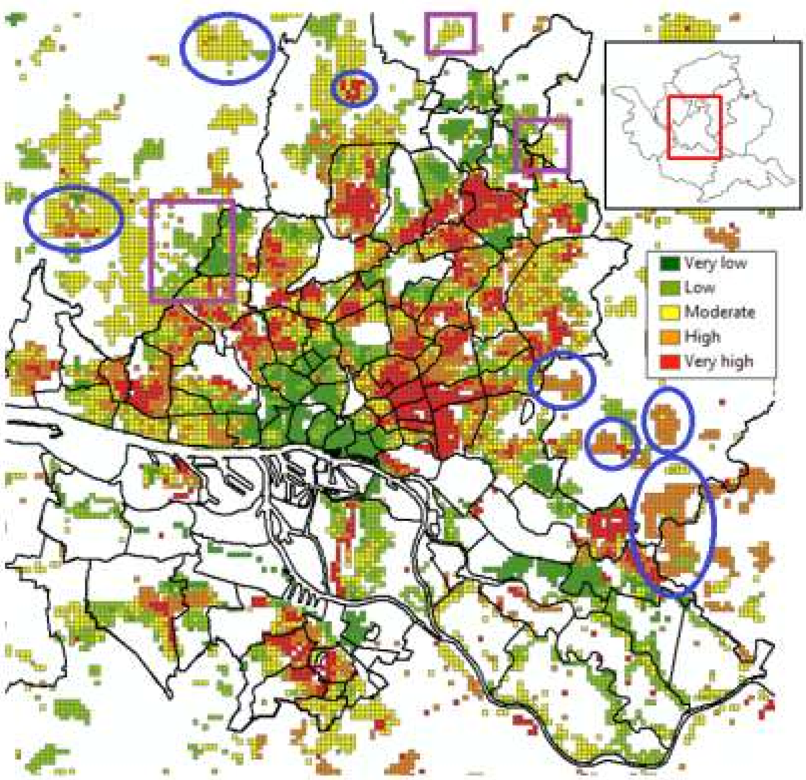


Figure 217: spatial distribution of vulnerability classes (central area), urban sprawl scenario. Circles represent higher vulnerability and rectangles represent lower vulnerability in comparison with the BaU scenario.

The individual lonely and isolated cells (mostly seen in South and Southeast) can be clearly seen on the map. Such cells are spread all over the Greater Hamburg and cause a high vulnerability result. As mentioned previously, if these isolated cells were eliminated, the absolute vulnerability where the population density is highest might look very differently.

De-central concentration

The de-central concentration is another scenario which focuses on the sub-centers and is similar to the BaU scenario in terms of the total vulnerability result. The relative and absolute cells among the vulnerability classes are similar, except in the Lüneburg district, where de-central concentration scenario has a lower amount of high vulnerability, even though there are more very high vulnerability cells. Meanwhile the Stormarn and Launeburg districts have lower amount of high vulnerability cells. The de-central concentration scenario is the most favorable scenario for Harburg and Lauenburg, while it is the least favorable to Hamburg city-state, from the perspective of the average vulnerability. Differences between all the scenarios are very small and can be affected simply by the randomness factor. In considering total vulnerability, the de-central concentration falls somewhere between the BaU and concentration scenarios. In considering average vulnerability, it is very close to the BaU scenario results.

Table 26: absolute (left) and relative (right) number of cells by classes, de-central concentration scenario. Total vulnerability shows the sum of vulnerability and the mean is the average vulnerability per cell.

	Absolute					Relative						
	Very low	Low	Moderate	High	Very high	Very low	Low	Moderate	High	Very high	Mean	Total Vulnerability
Harburg	13	422	971	510	84	1	21	49	26	4	0,823797	1648
Lüneburg	0	17	509	663	469	0	1	31	40	28	0,94777	1571
Stade	300	749	400	43	10	20	50	27	3	1	0,685917	1030
Segeberg	250	773	663	130	5	14	42	36	7	0	0,720248	1312
Pinneberg	90	845	944	53	12	5	43	49	3	1	0,727978	1415
Stormarn	19	219	731	503	64	1	14	48	33	4	0,83969	1290
Lauenburg	0	71	739	671	115	0	4	46	42	7	0,88193	1408
Hamburg	949	1213	1512	1237	1080	16	20	25	21	18	0,819444	4909

The main visual differences of large clusters in BaU scenario can be easily identified in the south east (figure 218). Comparing to urban sprawl, the outcome of the de-central concentration scenario is more affected by the conversion which can be seen as an area closer to the center and marked with the circle. This area in BaU scenario is occupied by the non-residential UVCZ, but in de-central and concentration scenarios it is occupied by open high rise UVCZ. The few other large clusters, situated in the east, receive pretty high vulnerability values. But the few clusters nearby have the lower values. Such pattern was also noticed in the northern areas in the urban sprawl scenario.

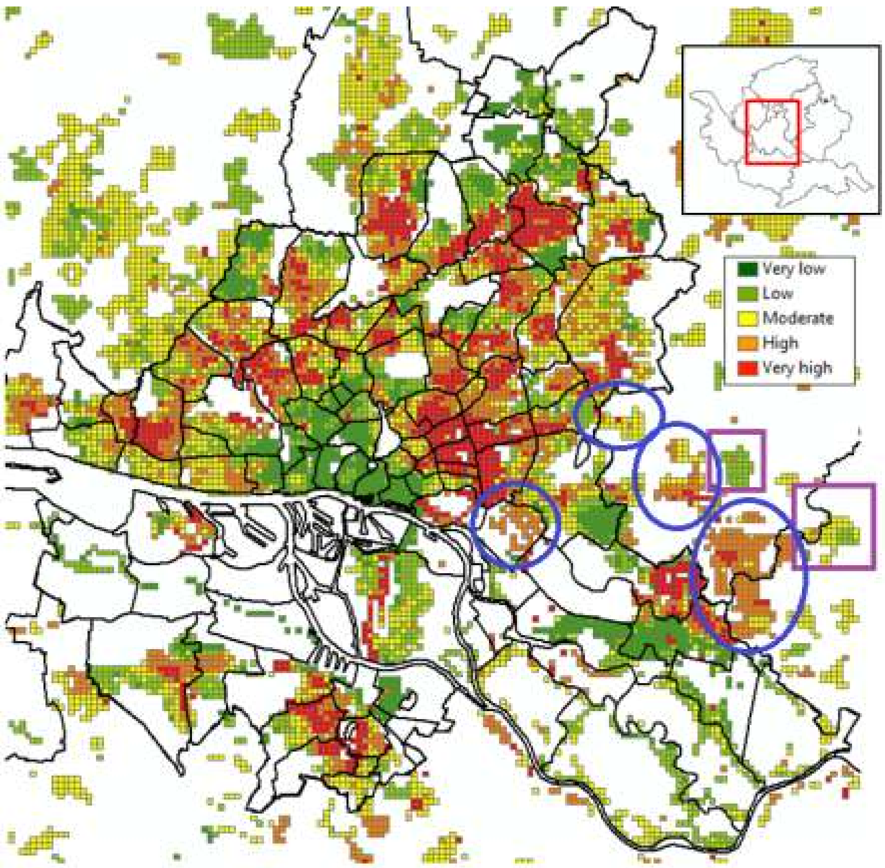


Figure 218: spatial distribution of vulnerability classes (central area), de-central concentration scenario. Circles represent higher vulnerability and rectangles represent lower vulnerability in comparison with the BaU scenario.

Although the de-central concentration scenario has an increase in mid rise UVCZ, the changes are very minor. When the indicators of the converted or newly emerged mid rise areas are compared to the vulnerability index, the differences are very small and there is no change of the vulnerability class. The other consideration is that these changes, even when they can be seen clearly, appear as isolated cells and not as large clusters, which probably have been affected more by randomness than actual conversion.

Concentration

The concentration scenario is the last, but not least, scenario. This scenario focuses mainly on the conversion and development of new mid rise UVCZ within the central area. Surprisingly, the concentration scenario has the smallest total vulnerability. Of course, it has the least number of cells, but it also has the lowest average vulnerability. But knowing the facts, that 1) the population density is not considered; 2) the soil sealing is more or less high for most of the Hamburg city-state; and 3) the spread of the cells in urban sprawl scenario cause decrease in adaptive capacity, the lowest average vulnerability is not surprising in this urban development scenario.

Table 27: absolute (left) and relative (right) number of cells by classes, concentration scenario. Total vulnerability shows the sum of vulnerability and the mean is the average vulnerability per cell.

	Absolute					Relative						
	Very low	Low	Moderate	High	Very high	Very low	Low	Moderate	High	Very high	Mean	Total Vulnerability
Harburg	40	412	738	566	135	2	22	39	30	7	0,832143	1574
Lüneburg	1	16	607	577	419	0	1	37	36	26	0,933483	1512
Stade	335	747	359	24	1	23	51	24	2	0	0,679799	997
Segeberg	268	850	509	78	16	16	49	30	5	1	0,704657	1213
Pinneberg	179	966	629	56	26	10	52	34	3	1	0,71952	1335
Stormarn	20	313	816	252	33	1	22	57	18	2	0,798477	1145
Lauenburg	1	37	621	697	175	0	2	41	46	11	0,898837	1376
Hamburg	999	1273	1500	1328	1061	16	21	24	22	17	0,817505	5037

The concentration scenario is most favorable for Hamburg city-state (by average, but not by total vulnerability) and three districts: Stade, Segeberg and Stornmarn. It is the least favorable to Lauenburg. When compared to the BaU scenario, Harburg has a lower amount of cells with high and very high vulnerability. Lüneburg has fewer cells with high, but more cells with very high vulnerability. Stormarn and Lauenburg districts also have fewer high vulnerability cells.

Considering the spatial comparison with the BaU scenario, most of the changes can be easily identified in Southeast and Northeast areas. The North, West and Northwest have, in general, lower temperatures. Meanwhile the Southeast experiences greater temperatures. In the concentration scenario, the Northern and Western parts have lower vulnerability and the Southeastern part has greater vulnerability, even though the same temperature values were used for all scenarios. This can happen because other factors, most likely the randomness factor, and not actually the temperature as might be expected, causes a different vulnerability.

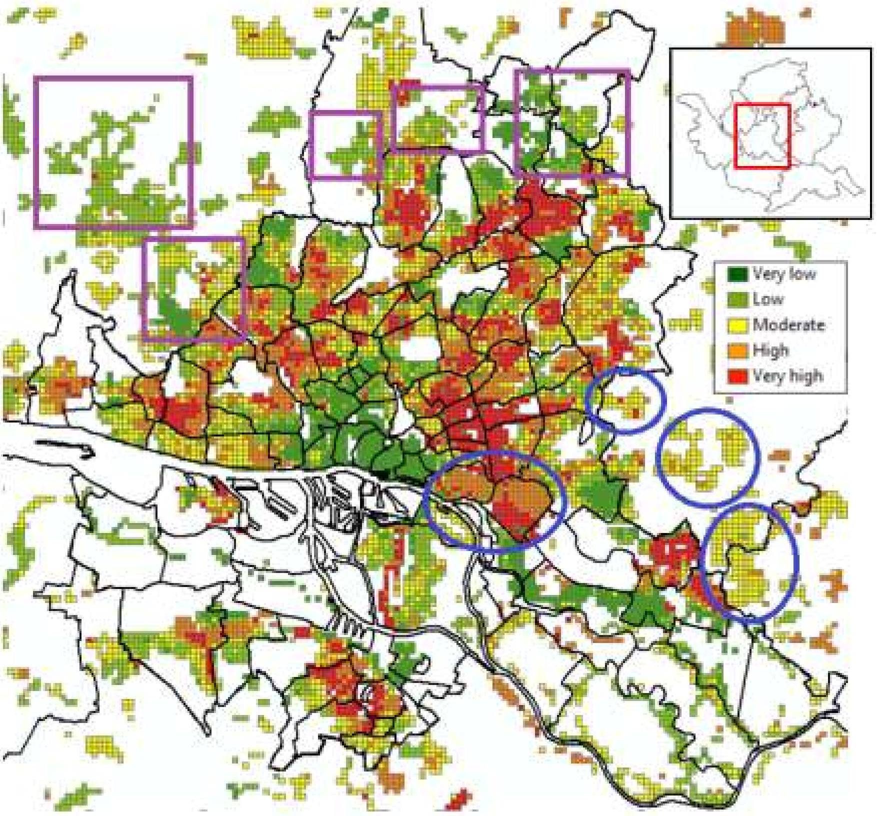


Figure 219: spatial distribution of vulnerability classes (central area), concentration scenario. Circles represent higher vulnerability and rectangles represent lower vulnerability in comparison with the BaU scenario.

Compared to other scenarios, the outcome of the concentration scenario is affected more by conversion, which is greater than in the de-central concentration scenario. A good example of this effect is marked by the blue circle close to the central area. This area was not occupied in the BaU scenario and was only partly covered in the de-central concentration scenario. In the concentration scenario it is actually packed with cells and represents the conversion from commercial to the residential type UVCZ. It is noteworthy that the isolated cells with the low vulnerability in the high vulnerability clusters have been identified explicitly only in the concentration scenario. The appearance of such cells is the conversion to denser structures and represents the demolition of or the densification of the existing UVCZ, which often happens when previous tenants and/or owners leave and new ones move in. What is seen is that old buildings are demolished, or new buildings are constructed near the old one. When this happens, newcomers are younger, less poor and require, or desire, more greenery in their surroundings, which lowers the degree of degree of soil sealing in their immediate area.

Conclusions

Previously I presented statistics and spatial distribution of the vulnerability results as one baseline and three extreme scenarios. Unfortunately, as might be expected, the extreme scenarios do not produce vulnerability results that are extremely different from each other. I identify a few reasons as to why this happens:

- The randomness factor (by "unpacking") of patches, especially outside the Hamburg city-state, has a great impact on the change in vulnerability. It is overestimated and might hinder the identification of actual change of vulnerability;

- Although the scenarios encourage development of certain UVCZ, the variance of vulnerability indicators within the UVCZ classes is high. It causes a high variance of vulnerability and lower effects of extreme urban development scenarios;
- The Hamburg city-state area is packed and can hardly accept new development, without occupying an already built area. Only the concentration scenario ignores this restriction at the greater scale;
- The new development of the cells depends on population growth. If the growth is higher, the differences would probably be higher;
- The previously discussed issue highlights that low future population growth and a number of pre-existing cells (year 2000) decreases the effects of the extreme urban development scenarios.

Although the extreme urban development scenarios produce similar results, some differences can be identified. The most favorable scenario by total and average vulnerability is the concentration scenario. Because vulnerability does not take into account the population density, the concentration scenario, which has the least amount of cells, has the lowest total vulnerability. The least favorable scenario is urban sprawl. It has many cells which are spread all over the area and are located at a distance from the sub centers. It causes a lower adaptive capacity caused by a longer distance to the nearest healthcare facility. This is valid for the entire Greater Hamburg area. A look at the district, or Hamburg city-state only would give different results.

At the greater scale, three vulnerability patterns can be recognized in the Greater Hamburg study. The North and West areas experience lower temperatures and are less vulnerable. South and east have higher temperatures and are more vulnerable. The cells in the areas surrounding Hamburg city-state do not have as high degree of soil sealing, but are affected by the distances to the nearest hospital. The vulnerability in the center of Hamburg city-state, meanwhile, is quite different. It has a higher degree of soil sealing in the center and lower in the suburbs. It is less affected by the distances to the closest healthcare facilities but is influenced more by the higher concentration of elderly people and welfare recipients. The Hamburg city-center areas have lower vulnerability due to a higher concentration of offices and commercial assets in the residential housing which means there is a lower percentage of elderly people and, therefore, lower vulnerability. It is the opposite in the areas located further from the center (the second ring), especially in the East and Northeast. Some of these areas experience higher vulnerability because of a higher number of welfare recipients.

From the scenario perspective, the Hamburg city-state is not as affected as the surrounding districts. The Hamburg city-state is already packed with housing, while the natural areas are strictly protected. The exception is the concentration scenario, which caused a significant conversion within the central areas.

The considerations presented above is the relative vulnerability, which can be used to develop policies, implement various climate adaptation strategies, identify gaps in services or information and lower potential adverse impact. This vulnerability, however, does not take into consideration population density and does not address the challenge of a higher concentration of actual hazard-sensitive people. The absolute vulnerability must be assessed if this gap is to be filled.

8.4 Results of absolute vulnerability

The absolute vulnerability is vulnerability which takes into consideration the population density. Although the absolute vulnerability is absolute for the Greater Hamburg area, it is still a relative vulnerability to the other areas outside the Greater Hamburg. The absolute vulnerability is a useful tool in identifying the number of individuals who would be at risk in a certain area for a specific scenario. Of course, then vulnerability is a function of population density. But based on the guidelines of emergency response, the areas of higher concentration of people at risk is a key during extreme events in order to provide aid to as many people as possible during a very limited time. Population density can also be associated with higher building density, which cause greater UHI effect (Ruth, 2006; Smith and Petley, 2009).

The absolute vulnerability is a function of population density as well as relative vulnerability. Mathematically this function can be expressed as Abs. Vuln = PopDens * Vuln. In order to find the effect of the population density on the absolute vulnerability, I ran the multiple linear regression analysis with absolute vulnerability as a dependent variable and with population density and relative vulnerability as independent variables. The population density had the standardized coefficient with a value of 0,840, while the relative vulnerability had a value of 0,429. The R-squared scored 92,3% while running the analysis with only the population density as an independent variable, and the R-squared was still high enough with the result of 74%. This proves that population density has a much higher impact on absolute vulnerability than the relative vulnerability. But the task for absolute vulnerability is not to equalize the population density and relative vulnerability, but to show how vulnerability would change if the population density would be addressed. Based on the regression analysis, the absolute vulnerability map should be similar to the population density map.

The other objective is to compare how the relative and absolute vulnerability matches visually. If a specific area has a high absolute and relative vulnerability and the adaptation measures would be applied, it would be "one shot two rabbits" (Lithuanian proverb which can be related to "killing two birds with one stone") - one successful adaptation would accomplish two things: decrease the area's vulnerability and lower the number of people who would be vulnerable. If the area has a high relative vulnerability, but low absolute vulnerability, it could be that the adaptation measures are not worth the effort and the better solution might be to relocate the people. If it is vice versa, then maybe it is worth it to implement the measures, even if the relative vulnerability is low, but it might be increased as a result of unexpected events. For example, a nearby hospital closes or people lose their jobs resulting in an increase in welfare recipients. I believe, therefore, that there is a strong case to compare absolute and relative vulnerability.

Such a comparison, however, is not easy because the ranges are quite different. The relative vulnerability ranges from 0 to 3,18 (BaU scenario) and the absolute vulnerability ranges from 0 to 1372. Because of this difference I decided to compare them by the relative classes which I used for relative vulnerability: very low, low, moderate, high and very high. By assigning the cells to the classes, I matched the same number of cells for each class, as it was done for the relative vulnerability. In the BaU scenario the cells with absolute vulnerability lower than 100,36 were assigned to the very low vulnerability class, the cells with value between 100,36 – 151,996 were assigned to the low absolute vulnerability, the cells in the range of 151,996 – 211,67 were assigned to the moderate vulnerability, the range of 211,67 – 371,55 were assigned to the high vulnerability class and all other cells having a higher range was assigned the very high vulnerability class.

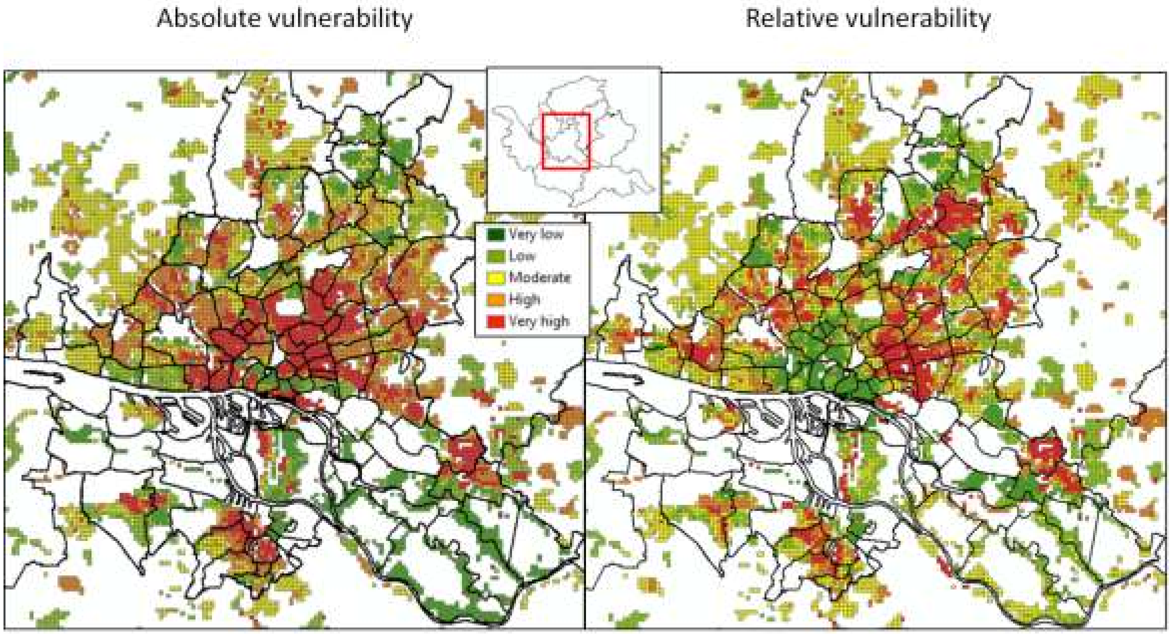


Figure 220: visualization of absolute (left) and relative (right) vulnerability in central GH by classes, BaU scenario 2050.

Figure 221 shows the absolute and relative vulnerability by classes of the Hamburg city-state for the BaU scenario. The high contrast can be seen in the Hamburg center-North, center-West and Southwest areas which are densely populated, but the concentration of the elderly is not so high. However, some of the areas in the center have very low vulnerability. These are mainly office areas, with limited population. Areas in the Northeast and North have a higher number of elderly people, but the population density there is not as high, with a result that the absolute vulnerability is moderate. The Southeast suffers not only with high population density, but also from a higher number of welfare recipients and an average percentage of the elderly.

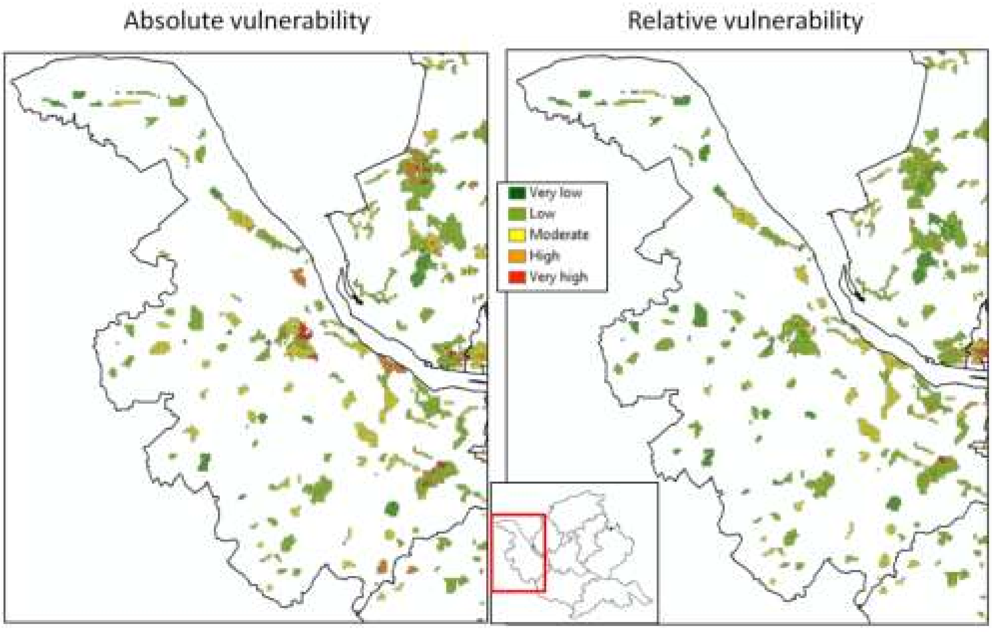


Figure 221: visualization of absolute (left) and relative (right) vulnerability in West of GH by classes, BaU scenario 2050.

The West of Greater Hamburg seems to have a good match between absolute and relative vulnerabilities, except in few more populated areas, like cities of Stade and Elmshorn. The other areas have a significantly low population density, resulting in both vulnerabilities matching quite well. In general, vulnerability in the West varies between very low and moderate, with some small clusters of high and a few very high vulnerability cells in the more populated areas.

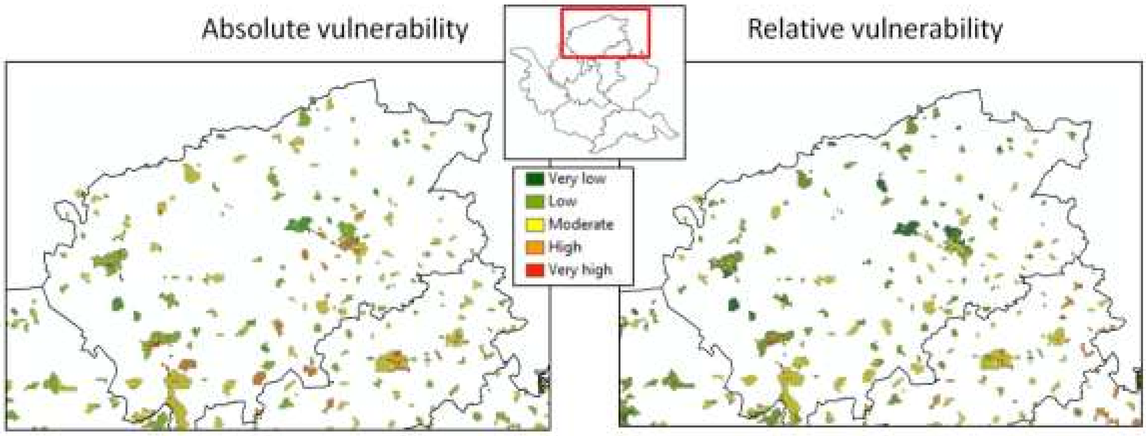


Figure 222: visualization of absolute (left) and relative (right) vulnerability in North of GH by classes, BaU scenario 2050.

The North of Greater Hamburg has even lower impact than the west. The absolute vulnerability is higher only in the more populated towns, like Bad Segeberg, but all the other areas have a fairly good match between absolute and relative vulnerability. West and North of Greater Hamburg are less affected by high temperatures, therefore exposure and vulnerability there is lower than in other parts of the study area. The same pattern is noticed with absolute vulnerability.

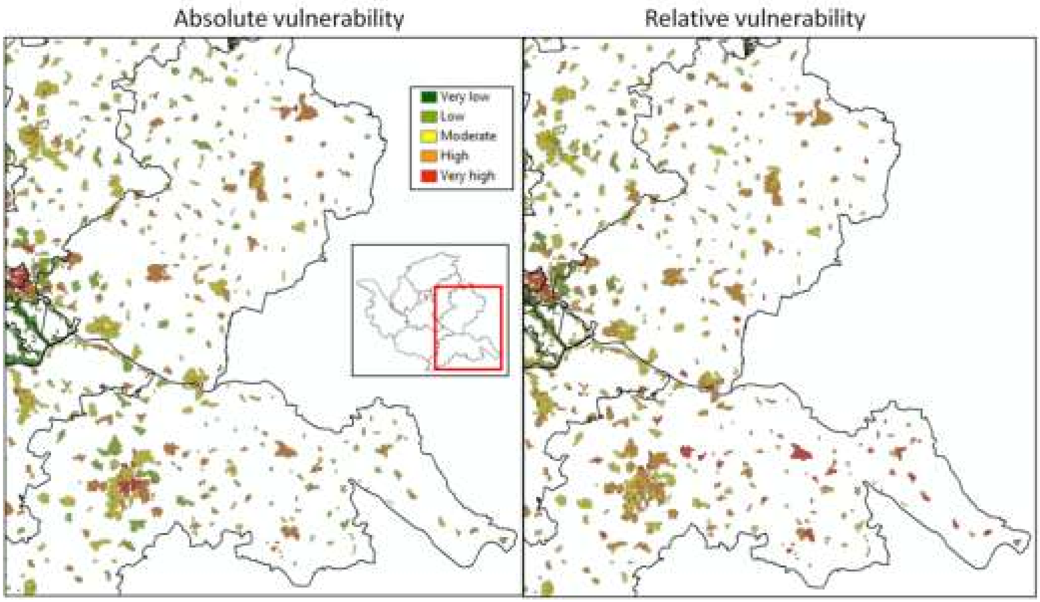


Figure 223: visualization of absolute (left) and relative (right) vulnerability in East of GH by classes, BaU scenario 2050.

The East and Southeast experience much more affect. Comparing between the absolute and the relative vulnerability, the absolute has fewer very high vulnerability clusters. Most of them are located in the Lüneburg city where population density is higher. Very high relative vulnerability is typical for the far Southeast areas and some clusters around the Lüneburg city. Although the population over all the area is not high, the difference can be identified between some of the Lüneburg surrounding clusters which have moderate relative, but low absolute vulnerability. The Eastern district of Lauenburg (above the Lüneburg district) has a fairly good match between relative and absolute vulnerability, because of low population density.

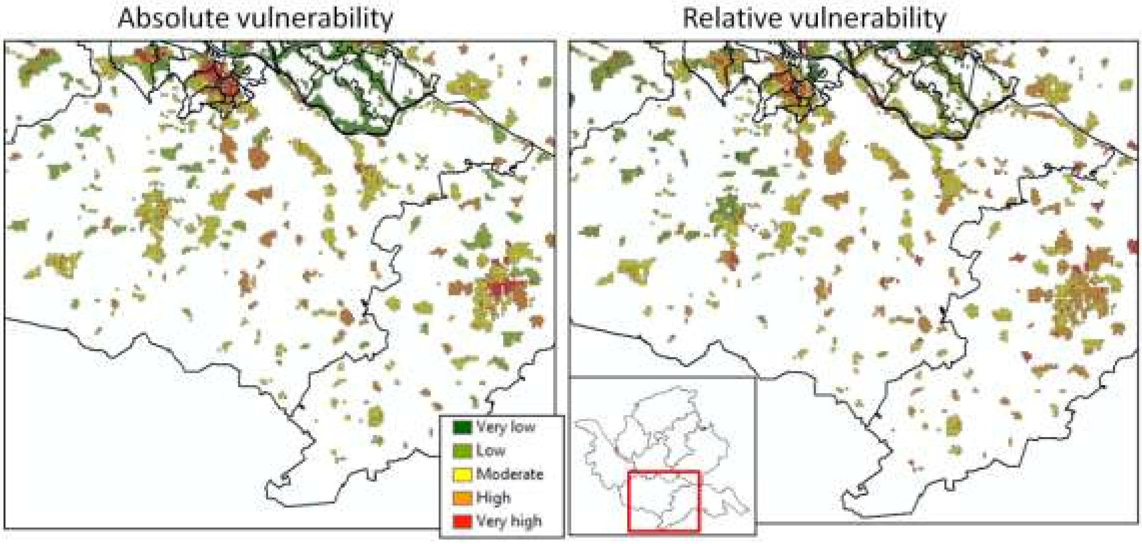


Figure 224: visualization of absolute (left) and relative (right) vulnerability in the South of GH by classes, BaU scenario 2050.

The South area contains the previously mentioned Lüneburg city in the East, while the other areas have a good match between absolute and relative vulnerability. The Harburg and Fishbek-Neugraben areas have higher vulnerabilities because of a higher degree of soil sealing, the number of welfare recipients and the elderly and the population density. The other areas have moderate or low vulnerability, except for a few clusters of high vulnerability in the middle South.

Absolute vulnerability in compact, de-centralized and urban sprawl affected cities

I have already identified that the vulnerability differences between the extreme urban development scenarios are not extreme. Therefore, I will not focus on the visual differences but rather keep it simple and will present only the differences between average and total vulnerabilities among the scenarios. The following table shows the average, total absolute and relative vulnerabilities for all four urban development scenarios.

Table 28: comparison between the average and total absolute and relative vulnerabilities among the urban development scenarios.

	Absolute		Relative	
	Average	Total	Average	Total
BaU	207	3819409	0,805791	14871
Urban Sprawl	208	3883505	0,811521	15148
Concentration	219	3828873	0,802878	14001
De-central concentration	216	3852876	0,808314	14381

In review, the urban sprawl scenario has the highest average relative vulnerability. The lowest average vulnerability is in the concentration scenario, caused by the fact that the distance to the nearest hospital has a lower impact in the concentration scenario but has a higher impact in urban sprawl scenario. The BaU and de-central concentration scenarios are found somewhere in the middle of these two extreme values of average relative vulnerability and they also have similar total vulnerability. But, total vulnerability may not be the best measure because it shows the sum of all cells, and it's natural that a higher spread of cells will have a greater total vulnerability.

As I have guessed, the absolute vulnerability shows different results among the urban development scenarios. It can be easily recognized in the concentration scenario which has the least amount of cells and is least affected by distance to the nearest healthcare facility and therefore has the lowest relative vulnerability. However, if the population is taken into consideration, the higher population density increases the absolute vulnerability and then the concentration scenario is least favorable in terms of average vulnerability. There is not much difference seen in the de-central concentration scenario, while the BaU and urban sprawl scenarios have similar, but lower, values. The urban sprawl scenario has the highest and the concentration scenario has the second lowest total absolute vulnerability. This can be explained through the use of example. In the urban sprawl scenario, 60 people would occupy three cells, 20 people in each. Each cell would have low population density and x relative vulnerability. In the concentration scenario 60 people would occupy one cell with x relative vulnerability. The population density would be higher, but not so much higher than the total vulnerability of three cells of the urban sprawl, because the spread of the cells increases the distance to the nearest hospital and reduces the AC. A high total vulnerability in the urban sprawl scenario is logically understandable.

Conclusions

The absolute vulnerability is important as well as relative vulnerability. Both can be coupled or used separately in different applications. In most of the areas where population density is higher, the absolute vulnerability was higher than the relative vulnerability. Areas which show the highest contrast should be analyze in detail before implementing adaptation strategies. Within the Hamburg city-state, the most focus should be given to the Eastern areas which have a high and relative vulnerability. The other priorities are the North and far West areas, as well as the clusters in the Southeast and South. The area in the Northeast, which has a very high relative, and a moderate absolute vulnerability, should be reconsidered and may not be worth any adaptation investment. The West and North of Greater Hamburg should not experience many problems, at least looking at those areas from the relative Greater Hamburg perspective. Some of the denser urban areas with higher vulnerability should be taken into consideration. The clusters in the East and South need to be analyzed in detail because of the differences found in their vulnerability. While many of them have high or very high relative vulnerability, others have low absolute vulnerability. With these differences it might be efficient to focus on areas which could affect only a small percentage of the population.

8.5 Sensitivity analysis

The term "sensitivity" is already widely used in this research and defines the population's sensitivity to heat waves. However, this sub-chapter presents the sensitivity of a model's parameters – the vulnerability indicators. The sensitivity analysis is defined as an investigation of model parameters' changes, errors and influence to the outcome of the model (Baird, 1989; Pannell, 1997). The aim of a sensitivity analysis in this research is to analyze how the changes of vulnerability indicators affect the final outcome – the vulnerability index. Additionally it can show the impact of climate data from different RCP scenarios and even other climate models. The result of this sensitivity analysis defines which vulnerability indicator has the highest impact on the final outcome and how the final outcome would look if other climate data would be used.

The analysis of sensitivity can be done in many ways, from very simple to very complex. For this model I decided to use the simple one dimension approach by presenting the average relative vulnerability function for different vulnerability indicators' values in order to give a broad overview of indicators' influence. The more complex statistical regression analysis of multi-dimensional sensitivity was used to identify the exact impact of vulnerability indicators. Both methods were applied for the future modeled data of the BaU scenario. The analysis of other urban development scenarios is not necessary because the vulnerability index for each urban development scenario is calculated in the same way. The simple approach of this sensitivity analysis can be presented by changing one parameter, while others remain constant, and observing how the final outcome changes. In this case, one of the vulnerability indicators must be changed and vulnerability has to change as well. Because this model is a spatial model, vulnerability for each potential housing grid cell is calculated. It's obvious that to compare the spatial changes to vulnerability is a difficult task. The solution is to calculate average vulnerability which would be a much simpler measure to compare. The more complex regression approach uses the professional statistical software in which the vulnerability index formula and vulnerability indicators' values are employed. It delivers a standardized coefficient (also known as beta coefficient) which shows the impact of each indicator on the vulnerability index.

The vulnerability indicators affecting the vulnerability index are monthly average minimum temperature, monthly average maximum temperature (both delivered from WorldClim database), degree of soil sealing, relative population over 65 years old, relative number of welfare recipients and distance to the nearest hospital. The population density was not considered, because the absolute vulnerability was not considered. The next task was to vary these vulnerability indicators and observe how vulnerability has changed. I decided to vary the indicators +/- 0,5 of standard deviation (SD) from the original values. Thus I calculated two new values for each indicator and employed it into the formula, which was used to calculate vulnerability (formula can be find in sub-chapter 7.6). The other indicators remained constant. This was done for all potential housing cells for the future modeled BaU scenario in Greater Hamburg. The "new" vulnerabilities with + 0,5 SD and – 0,5 SD for each indicator were calculated. As a final result, the vulnerability values were summed and divided by the number of cells to deliver an average vulnerability. The spider diagram (figure 226) presents the function of average vulnerability for changes of values of vulnerability indicators.

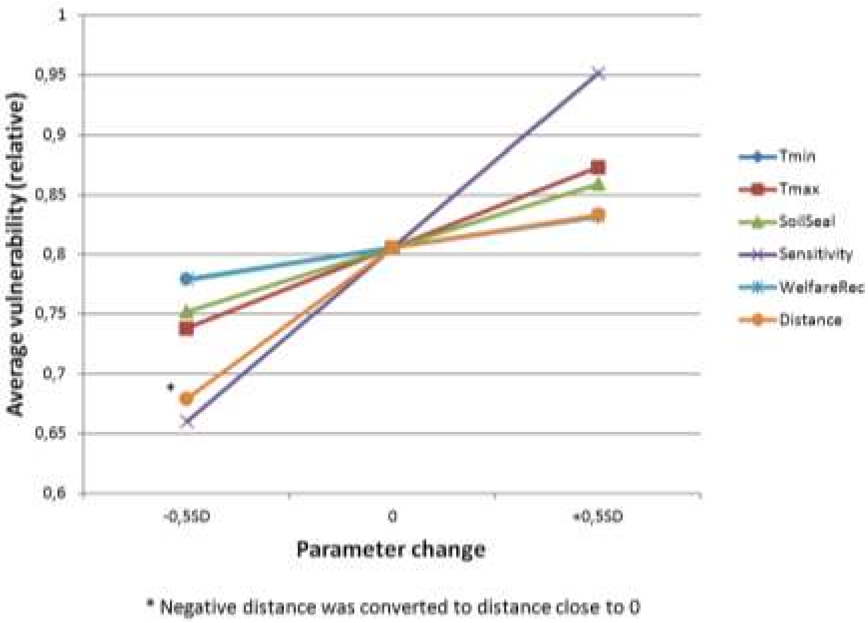


Figure 225: average vulnerability by change of the vulnerability indicators for the future BaU scenario in Greater Hamburg.

The average vulnerability index for future BaU scenario in Greater Hamburg scored 0,8059315. The change of monthly average maximum temperature by 0,5 SD caused the average vulnerability to increase and decrease by 0,06748794 to 0,73844356 and to 0,87341944. The change of monthly average minimum temperature caused the average vulnerability change by 0,02625318 to 0,73844356 and to 0,83218468. The degree of soil sealing has changed by 0,05359598 to 0,75233552 and to 0,85952748. Meanwhile the effect of population over 65 years old (elderly) was the highest by 0,14590045 to 0,66003105 at the lowest point and to 0,95183195 at the highest point of all measures, which means a variation of 18%. The number of welfare recipients had a slight impact, similar to minimum temperature. Vulnerability has changed by 0,02685622 to 0,77907528 and to 0,83278772. The analysis of the distance to the nearest hospital indicator was an issue, because the standard deviation is high and some of the the -0,5 SD values are negative which is an impossibility because of the logarithmic transformation function used to incorporate this indicator to the vulnerability index. My solution was to change the negative values to 1 which is close to zero. That is why the graph of the distance indicator in the spider diagram is not symmetric to the default average vulnerability. The -0,5 SD of distance to the closest hospital caused a decrease of average vulnerability by 0,12684114 to 0,67909036 and +0,5 SD caused an increase by 0,02754253 to 0,83347403. If considering only the positive change, the effect of distance to the nearest hospital is very similar to the effect the number of welfare recipients and minimum temperature had. The degree of soil sealing has almost twice higher impact. The other vulnerability indicator having a high impact is the maximum temperature and the one vulnerability indicator having the most affect is the elderly (population over 65 years old).

The next task was to measure the impact of these indicators, but using the regression analysis. The impact was found by carrying out the multiple linear regression analysis. The regression analysis has been done using the SPSS software. The vulnerability index was selected as dependent variable and the independent variables were the vulnerability indicators, employed in simple one dimension sensitivity analysis. The R-squared which means the statistical measure of how close the data fits to the regression line, for vulnerability regression was 99,4% and has a typical rounding error. The relative number of welfare recipients, monthly average minimum temperature and distance to the hospital had the corresponding standardized coefficients: -0,142; 0,154 and -0,178 which were the smallest among all the independent variables. The negative coefficients mean that they affected the vulnerability index negatively which is perfectly fine, because they were intended to act in that way. The degree of soil sealing had a greater effect with the coefficient of 0,301. Not far from it was the maximum temperature, with the value of 0,393. And the most influencing indicator is the elderly with the coefficient of 0,89. Additionally I ran the regression analysis only with the elderly as an independent variable, to see what will be the statistical measure. This time the R-square was 62%, which means that the elderly indicator alone has a significant influence on the vulnerability index. This is not surprising, knowing that the elderly is the most important indicator in common heat-related mortality studies. The results of regression analysis showed very good agreement (by ranking) between both, simple and complex, sensitivity analysis methods. This shows that in order to perform a sensitivity analysis, the simple approach is enough, although the regression analysis via software would save a lot of time.

The further sensitivity analysis was done not by changing vulnerability indicators from their base as it was done previously, but by changing the base indicator's data, with the data produced by another model or scenario. This was done in order to see how the average vulnerability would change if other RCP scenarios or the temperature data from other global climate models would be used. The future temperature data used in this study was taken from WorldClim database which contains downscaled future climate data, produced by 19 different global climate models. As the most suitable for Greater Hamburg case study, the MPI model and only one RCP 4.5 scenario was selected. However, it is very interesting to see how the average vulnerability would change with other two RCP scenarios for the MPI model, and the other global climate models for the RCP 4.5 scenario. In order to perform a comparison, the monthly average minimum and monthly average maximum temperatures of the RCP 4.5 scenario were obtained from all 19 global climate models. The data was processed and merged with the potential housing cells of the future modeled BaU scenario. Although the minimum and maximum temperatures changed a lot from the default MPI temperatures, the weights of the vulnerability indicators were not changed. This study used the MPI RCP 4.5 climate data which contained monthly average minimum temperature from 12,6°C to 14,3°C and monthly average maximum temperature from 22,1°C to 24,4°C. Meanwhile the MPI RCP 2.6 contained monthly average minimum temperature from 12,1°C to 13,7°C and monthly average maximum temperature from 21,5°C to 23,8°C. Comparing the RCP 2.6 and RCP 4.5, the difference in the highest and lowest temperatures is less than one degree. The similar tendency is in MPI RCP 8.5 scenario. There the monthly average minimum temperature varies from 13,1°C to 14,9°C and monthly average maximum temperature from 22,9°C to 25,4°C. Instead of employing the RCP 4.5 temperature data, I added the RCP 2.6 and RCP 8.5 temperatures into the vulnerability index. This time, not one indicator changed, but two: both temperatures, because both of them are supplied by the same source. The differences of average vulnerability can be observed in an image below (figure 227).

Figure 226: average vulnerability using different future temperatures from three RCP scenarios of the MPI global climate model.

The RCP 8.5 which represents the worst case climate scenario, contained the temperatures which increased vulnerability to 1,00164021 which is 24% higher than the average vulnerability in RCP 4.5 (baseline) scenario. Meanwhile the most optimistic, the RCP 2.6, scenario future temperatures would decrease vulnerability to 0,67472982 which would be 16% lower than RCP 4.5. Although the temperatures are not extremely different between RCP scenarios, the impact on average vulnerability is notable which motivates people not only to apply local adaptation measures, but also focus on global climate change mitigation. The next task was to employ the RCP 4.5 data of all 19 different climate models into sensitivity analysis. The monthly average minimum temperature in all climate models varied from 11,6°C to 17,3°C (MPI: 12,6°C – 14,3°C) and the monthly average maximum temperature ranged from 21,9°C to 29,8°C (MPI: 22,1°C – 24,4°C). The highest minimum and maximum temperatures were in HadGEM2-AO climate model, developed by Meteorological Office of Hadley Centre (UK), and the lowest minimum and maximum temperatures were in INMCM4 climate model, developed by Institute for Numerical Mathematics in Russia (looks like colleagues from cold Russia still prefer lower temperatures). Astonishingly, comparing the MPI and the highest monthly average temperature, the difference is more than five degrees. Knowing that the monthly average maximum temperature has a great impact on average vulnerability, the differences can be even greater as is seen in figure 228. By using the highest monthly average minimum and maximum temperatures (HadGEM2-AO model), the average vulnerability increases by 225% (comparing to MPI) to 1,81554325. Meanwhile the lowest monthly average temperatures (INMCM4 model) does not differ much from the MPI data and is only 16% lower (value of 0,67864366).

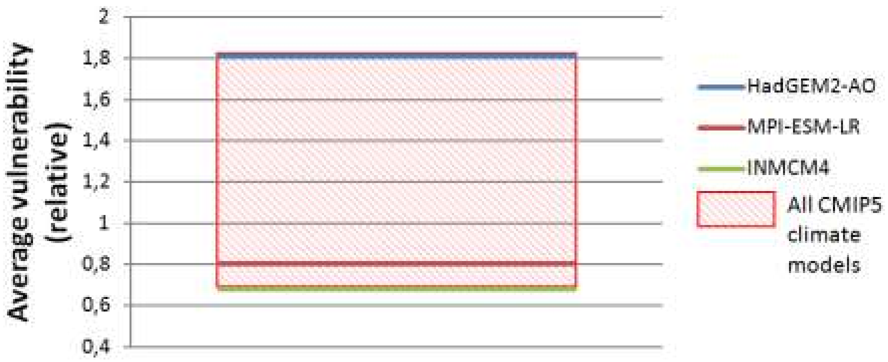


Figure 227: average vulnerability by different minimum and maximum temperatures from all CMIP5 climate models (RCP 4.5 scenario).

The other 16 global climate models cause the vulnerability to change somewhere in the middle, from 0,67864366 to 1,81554325 which would be a change by 1,13689959 and is more than the average vulnerability difference by a change of the highest impact having vulnerability indicator of elderly (change by 0,14590045).

In order to get a better look at vulnerability using different climate models, the next figure 229 shows the frequency of vulnerability within the Greater Hamburg. The vertical axis shows the frequency of cells and the horizontal axis presents vulnerability. The maximum vulnerability in MPI-ESM-LR was 3,18320216, in INMCM4 it was 2,69820216 while the HadGEM2-AO climate model data increased maximum vulnerability to 6,63640216. The graphs and average vulnerability values shows that MPI-ESM-LR frequency is shifted slightly to the left. The HadGEM2-AO model shows lower frequency, but higher standard deviation and much higher vulnerability values.

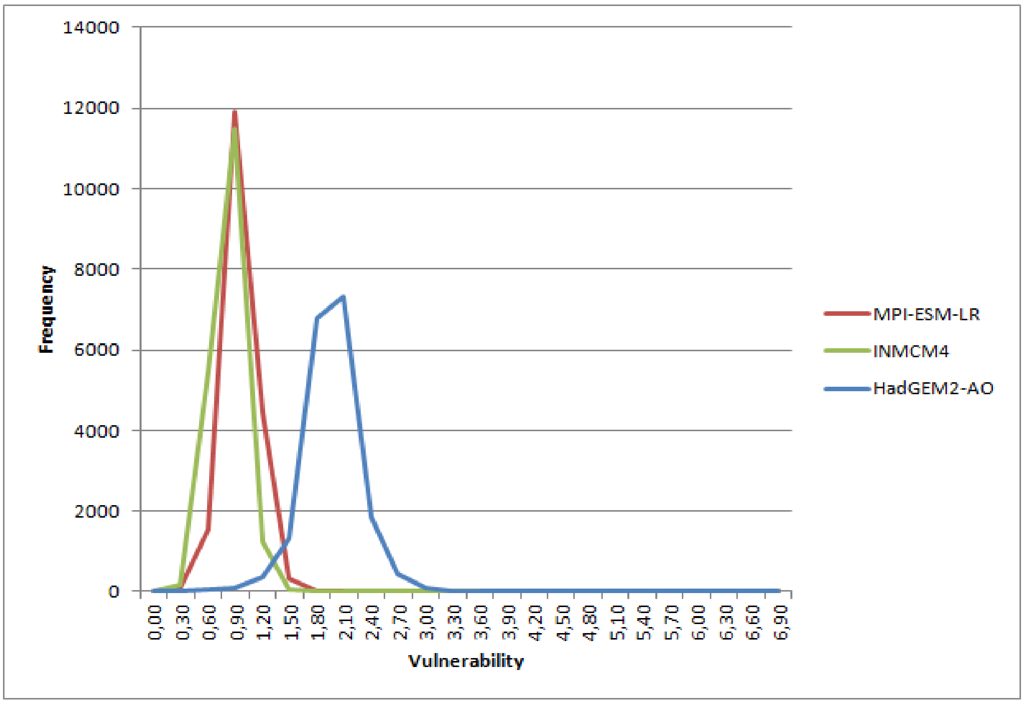


Figure 228: frequency of vulnerability values within GH in MPI-ESM-LR, INMCM4 and HadGEM2-AO climate models, RCP 4.5 scenario.

It is possible to conclude that the difference between the different global climate models cause a much higher change in average vulnerability than any of the vulnerability indicators. Therefore, although the uncertainty of the vulnerability indicators modeled in this study is high, it is not as high as the uncertainty of the global climate data. Therefore, the model can defined as appropriate.

9 Adaptation

More than 40 years ago Oke (1977) declared that there is a need for urban planners and designers to address urban changes and lower the heat impact in the cities. According to Yow (2007), the effective adaptation strategies have to mitigate negative impacts and take advantage of the positive ones by implementing smart urban design and technological innovations. The studies done by Davis et al. (2003 and 2002) showed that the cities which implemented adaptation measures in the way of increased air conditioning, improved healthcare infrastructure and higher awareness of heat impact experienced a decline in heat-related mortality. Therefore, adaptation is a very important step that can be taken to lower the impact of heat and reduce a population's vulnerability to heat waves. Scientific information about this information must be simple and easy to understand so that urban planners and designers can encourage decision makers to act (Yow, 2007) in an effort to lower a population's vulnerability to heat waves.

This chapter of adaptation provides a list of adaptation measures and options dedicated to reduce a population's vulnerability to heat waves. These measures and options are not limited to Greater Hamburg and can be applied in any country. This chapter helps to get an overview of existing possibilities to lower heat impact, reduce population's sensitivity increase the adaptive capacity and adaptation.

Adaptation according to the IPCC (2007) is the adjustment in natural or human systems due to actual or expected climate phenomena or its effects which inflicts harm or exploits opportunities. In other words, it is a reaction of human or natural system to climatic events in order to reduce their negative impacts. The adaptation can be classified by intent, response, stakeholders and temporal scope (Malik et al., 2010). By intent, the adaptation can be autonomous also known as spontaneous adaptation and triggered not by a climatic event but by ecological changes in the natural systems or by market or welfare changes in the human system. Adaptation can also be planned, which is based on policy and is used to return, maintain or achieve the desired state of the system (IPCC, 2007). The response of adaptation can be reactive, taking place after the impacts of climate change are experienced, or it can be proactive, also known as anticipatory and is taken before the impacts of climate change occur. Stakeholders can be private, conducted by the private sector as well as individuals and households and covers personal needs. Stakeholders can also be public, which included action initiated by the government at any and all levels and is focused on collective needs. Lastly, adaptation can be based on a temporal scope, either short or long run adaptation (Malik et al., 2010). Despite the adaptation's classification, it can be increased by adaptation options and measures.

Adaptation options and measures

Adaptation options are considered as possible ways to adapt or as the concepts of adaptation which are more abstract than actual measures. The adaptation option often is considered as a broad adaptation activity, while the adaptation measure (or action) is more specific with known approaches of implementation. The adaptation option can be the warning system and the measure would be a specific warning system with known coordination chains, for instance.

Today many climate change impact studies do not only assess the impact of the climate change, but also suggest the list of adaptation options and measures. Most of these adaptations options and measures, however, are not new. In the past planners, designers and builders were aware of heat impacts and improved urban planning and building design. Many of these measures and options are still reasonable today. However, while a large part of adaptation solutions are based on engineering, there are other options, including disaster preparedness, risk assessment, raising awareness, resilience and other initiatives as well (Wilby, 2007). That follows are three types of adaptation options and measures which are dedicated to reduce vulnerability to heat waves:

The grey adaptation options and measures focus on hard engineering solutions, such as building codes, water cooling systems and other physical implementations, which protect from the impact of heat:

More efficient air conditioning systems

Air conditioning systems tend to consume a tremendous amount of electricity during heat waves and can even lead to blackouts (power grid failures). One of the preventive options to avoid blackouts is to use more efficient air conditioning systems. Another option is to use absorption cooling systems (an efficient use of excess heat) instead of the usually less energy-efficient compressing cooling. It has also been recommended to us the district cooling system instead of the local cooling system (Schauser et al., 2010). Efficient air conditioning systems not only use less energy, but also lower electricity costs, providing an economical impact as well. A simulation study (Kikegawa et al., 2006) in Tokyo (Japan) showed that the use of air conditioners, plus increased vegetation on the side walls of a building could also decrease air temperature of UCL by 0,2 – 1,2°C.

Efficient thermal storage systems

Based on construction materials, thermal storage is an important factor of urban energy balance. Efficient thermal storage systems enable a slower energy release and lowers the UHI effect during the night (Schauser et al., 2010).

Rebuild to lower density or environmental friendly zones

The density of abandoned densely built areas should be reduced by designing more spacious buildings with higher height/width ratio which also would increase daylight to the buildings. Meanwhile the unused industrial zones could be converted to environmental friendly commercial or office buildings (Lenzholzer, 2015).

Use of coastal winds

The coastal cities can use the benefit of coastal winds to improve ventilation during the day. But at night, the same coastal winds bring warm air into the city. If there are dunes or obstacles between the coast and the city, the effect of coastal winds is greatly reduced (Lenzholzer, 2015), and does not prevent people from leaving the city to find relief in the coastal areas.

Use of urban winds

According to Ghiaus et al. (2006) the street orientation, height and density of the buildings can affect natural ventilation and lower the UHI intensity. A city built in a valley and surrounded by forests, can use this advantage by establishing the corridors of wind which bring cool air from the forests to the city during the night. These corridors can be established by lining up the streets, avoiding barriers and constructing buildings on slopes along the wind corridors (Lenzholzer, 2015). It’s practically impossible to change already build environments, but improved street orientation can be applied for any new developments (Yow, 2007).

The green adaptation options/measures address approaches that use vegetation and bodies of water to reduce the effects of heat wave:

Development of parks (green areas)

One of the ways to lower temperatures in urban areas is to develop parks which cool surroundings via shading and evapotranspiration (Spronken-Smith et al., 2000; Yu and Hien, 2006). Additionally, green areas improve biodiversity and animal species within the urban landscape (EEA, 2017). The development of parks often is addressed by urban planning. According to (Lenzholzer, 2015), a few small parks cool down surroundings much better than one large park. However, if the park does not have good ventilation, it does not lower the temperature in surrounding areas as well as it could. Therefore it is recommended to build well ventilated parks in higher areas, so that they can provide cool air to go down and lower the temperatures in the surrounding urban areas. The vegetation of the parks influences the cooling effect as well. Parks with more trees have better cooling effect than the parks with big lawns – the trees with big crowns provide shade, while the open areas in the parks with a big sky view factor allows the surface to cool down at night much faster and supply the cold air to the surroundings. The downside of the big lawns, however, is limited water in the soil, which causes lower evapotranspiration and a cooling effect. The best solution is to mix the park with trees and lawns (Lenzholzer, 2015). Additional vegetation in urban areas not only reduce the UHI intensity, but also provide habitats for wildlife, improves air quality and reduces the flood runoff (Wilby and Perry, 2006).

Geometry of green areas

The geometry of parks can have a great impact as well. From a landscape ecological perspective the different shapes of green areas can be identified as different elements of green infrastructure, such as corridors, patches or matrix. The corridor has the greatest flood storage, but low infiltration capacity, with cooling via an evapotranspiration effect and shading. Patches have average capabilities in all roles, but their strength is higher evapotranspiration. The matrix has a low flood storage and average evaporative cooling effect, but does have high shading and infiltration capacity (Gill et al., 2007). In order to lower the surroundings through evapotranspiration, it is recommended to develop green areas as small patches close to residential areas.

Combination of bodies of water and trees

Although bodies of water seem to be a good solution to cool down surroundings, their cooling effect is not as efficient, because water absorbs solar radiation during the day and releases it during the night, effectively warming up surrounding areas at night. A much more efficient solution is to combine bodies of water with densely grown plants. Plants provide shade which keeps the soil and water cooler and evaporation through stomata gives a much better cooling effect. Residential and water combined areas can be easily converted to recreational zones that are easily accessible to people. Such zones would have many positive effects: flat water surfaces and air corridors along rivers cause greater ventilation, shade from trees and opportunities to swim provide relief to people during heat waves. Green areas also encourage people to walk and cycle (Lenzholzer, 2015).

The soft options and measures consider population activities and efforts to increase adaptation toward heat hazards:

Implementing Heat Health Warning System

Warning systems improve preparedness of decision makers and individuals. Often a warning system is implemented on scientific, technical and social basis. Effective warning systems should also address knowledge of risk, monitoring and warning services, dissemination and communication of information, and response capability. The logical sequence of these elements and their interaction encompass a comprehensive warning system (EEA, 2017). One example of such a warning system is Heat Health Warning System (HHWWS). It was implemented on the national level in France, Hungary, Portugal, UK and Spain, as well as many cities around the world as an adaptation option. The HHWWS includes the following measures (Matthies et al., 2008; Schauser et al., 2010):

- Agreement and coordination between bodies and institutions in the case of emergency;
- Trigger mechanism of heat-health alerts, thresholds for action and risk communication;
- Public recommendations to reduce indoor heat exposure as short- and medium-term strategies;
- Special care for vulnerable population groups;
- Preparedness of the health and social care system in staff training, planning and infrastructure;
- Real time surveillance and evaluation.

Under the umbrella of the HHWWS, each stakeholder has a certain protocol and activities and are mandated to carry them out in the case of a heat wave (Schauser et al., 2010).

Awareness campaigns for behavioral change

Public awareness increases public support and motivation, and mobilizes local knowledge and resources. The awareness campaigns address groups of people, and share the knowledge of individuals and organizations. They are especially effective if following ways of communications are employed: public meetings and training, social and mass media, dissemination of printed materials, professional consultation and informal networks. Raising awareness helps to manage the impacts of climate change, to enhance adaptive capacity and to reduce vulnerability (EEA, 2017).

Climate knowledge integration into urban planning

According to Mills et al. (2010) climate knowledge should be integrated into planning and design more often. Today, only a limited number of urban planning projects includes climate scientists. The scientific support from the early beginning might help to avoid problems.

Knowledge transfer to and from less developed regions

A high knowledge gap exists between the areas where the research has been done and where it is required. A lot of research has been done in mid-latitude, temperate climate cities, while tropical cities and less developed regions often suffer from lack of knowledge and experience. It should be a simple solution to increase the knowledge transfer from developed to developing countries (Mills et al., 2010).

Broadcasting via mass media

Another adaptation option is provided by mass media. It has a great effect of risk communication by broadcasting guidelines on TV or radio on how to minimize the risk of hyperthermia and dehydration, explain an effective dress code, offer locations of air conditioned buildings as well as provide further forecasts if the situation could get worse (Schauser et al., 2010) .

Monitoring, modeling and forecasting systems

Successful climate adaptation requires reliable climate information which can be monitored, modeled or forecasted by specific complex systems. The monitoring system provides real-time climate information. When the data cannot be monitored, it is modeled. The combination of monitoring and modeling enables forecasts to be produced to warn the population of coming climate change and its impact (EEA, 2017).

GIS and decision support systems

Various GIS related decision support system help to plan, organize and implement various adaptation possibilities with higher efficiency (Yow, 2007). A system developed by Randall et al. (2003) helps to assess various greening strategies and their effects, such as the effect of planting trees along the streets. Another system, designed by Shashua-Bar et al. (2006), addresses thermal effects of street forms and vegetation. Meanwhile other implementations (Roaf et al., 2009) help to design more climate friendly buildings.

Extreme heat register

Paris established an extreme heat register, called CHALEX, and motivated elderly and disabled people to register. Such a system helps to encourage sensitive people to receive essential guidelines on how to deal with the heat impact during heat waves. Additionally, such a system helps to send social welfare or medical staff, if there is a need (Schauser et al., 2010).

Crisis and disaster management

Disaster management includes prevention, protection, preparedness, response and recovery. These activities include planning process, development of the strategies and various procedures in the case of emergency, warning systems, emergency operations and plans which are typically managed by civil protection services, but other actors are also involved: from individuals, teams, organizations to communities (EEA, 2017).

Emergency water supply

During heat waves in Barcelona (Spain) in 2007, in Belle-Ille (France) in 2005 and in Istanbul and Ankara (Turkey) the local municipalities supplied people with emergency water in the form of water tanks or bottled water (Schauser et al., 2010).

Mitigation of water scarcity

It is very important to educate citizens to manage water resources better during heat waves. Additionally, governments have to improve water supply systems, reduce the leakage probability, initiate better water pricing and taxation mechanisms, reuse waste water and limit water usage in agriculture and industry (Schauser et al., 2010).

Some of the adaptation solutions employ both grey and green adaptation measures which include engineering's precision and nature's vitality. Lenzholzer (2015) published a list of illustrative examples which can be applied on the local scale:

- Spaces beneath the buildings provide cool shade, are often ventilated and do not require additional energy. However, such areas can be dark in the winter and the establishment costs are high.

- Arcades are an alternate, but traditional option to provide shade along buildings. The arcades can be oriented in such way that it would allow the sunrays during the winter, but would block the sun in the summer time.

- Loggias are a similar, but simpler solution which protects people from the weather and the high summer sun, but allows the winter or evening sun to warm up the living quarters.

- Canopies, louvres and flexible awnings are add-on construction which can provide shade, protect from dust and rain, but might block the sun in the winter. The costs are below average.

- Planted pergolas, screens and green facades are mixed engineering and vegetation measures. Pergolas and screens can be attached to buildings and provide the same function as green facades, just with higher costs. All measures have an advantage in that they are blocking the sun in the summer and letting it through in the winter. Additionally they provide extra cooling via evapotranspiration and protection from the rain. The green facades even decrease heat loss during the winter by approximately 6%, because of the air layer between the vegetation and the building's surface. But the downside of such implementations is that vegetation attracts birds and insects, plants may require irrigation and water supply and self climbing plants can damage walls or frames.

- Colonnades, pavilions and shaded roofs are open built objects, providing fixed or flexible shade. They do not allow any sunrays to go through by absorbing them and increasing surrounding air temperature. Therefore such structures have a good potential to be covered by photovoltaic elements (Golden, 2006).

- Trees in squares, along streets and buildings intercept incoming solar radiation and provide shade to the surfaces beneath which absorb and emit less heat. Trees also increase evapotranspiration which cools down temperature, block heavy winds, give protection from rain, improve water management, reduce noise and pollution, attract birds and enliven surroundings. The deciduous trees are more preferable, because of their ability to allow the winter sun to come through and provide more water content in the leaves which give better evapotraspiration. The costs of such options are very light.

- Roofs, facades and surfaces with high albedo reflect more solar radiation. The high albedo can be produced by using light-colored materials or "cool coatings" (Akbari et al., 2005). During summer, a black roof can be heated to 80°C, while white colored surface can be 17°C cooler by average. The downside is that albedo decreases if surfaces become dirty. However, the reflected solar radiation can be diverted not to the upper canopy layers, but to the other objects on the surface.

- "Cool", heat-emitting walls and surfaces are produced from lower mass materials which emit absorbed solar radiation and provide good insulation.

- Green roofs are considered as a good solution to lower urban heat. However, the cooling effect depends on the level of irrigation, thickness of the substance and surface of vegetation. Compared to regular roofs, green roofs lower the temperature by 20°C (average). Such roofs lower indoor temperatures beneath the roof by 5°C which can reduce energy costs for air conditioning by 25% annually. Additionally the green roofs can greatly reduce rainfall run-off. The higher water content can also increase the cooling effect. Green roofs serve also as roof gardens for recreation and food supply. The implementation of green roofing is a no-regret adaptation option. It mitigates UHI effect, reduces pollution and protects biodiversity in urban areas (Schauser et al., 2010). The obstacle to the construction of such roofs is the high pressure load. In 2013, the roof of the Zolitude shopping center in Riga, Latvia, collapsed because of the construction of the green roof. The weight was too heavy and the roof collapsed and more than 50 people lost their lives. A change in roof types can have a high financial benefit. A simulation study (Akbari and Konopacki, 2004) in Toronto (Canada) showed that implementation of "cool roof" technology and vegetation on the roofs would reduce annual electricity consumption by 150 GWh (worth in 2004 over US$11 million).

- Water roofs and walls were used in old Indian palaces to keep surfaces and roofs moist and cool. The cool water was stored and covered on the roof. Falling water allowed the cooled air to access and cool indoors. Such technique can be used today, although it can be costly to implement. Storing water on the roofs can lower surface temperatures by 10 – 20°C and inside temperatures by 5°C. Additionally such water management implementations can increase water runoff capacities during heavy precipitation events.

- Low plants, such as lawns, grass, flowers, vegetables, moss and gardens increase evapotranspiration and cool down the surroundings. Additionally they provide food and shade, increase biodiversity and can be used for recreational purposes.

Urban agriculture is a growing trend today which can not only reduce UHI effect, but also provide social and educational functions.

- Ponds and fountains are bodies of water which are not very effective in lowering air temperature, but they can refresh people or provide water to the surrounding plants which cool down surroundings by evapotranspiration. Moreover, ponds can collect rain water, increase biodiversity and produce algae during hot periods.

- Water mist installations and sprinkling are quite expensive adaptation measures. Both are used to cool down the surfaces or the air. The water mist installations, similar to fountains can be used to provide cooling effects to the people, while sprinkling is used to cool down and clean street surfaces.

The list of the above presented grey, green and soft adaptation measures and options consist from typical approaches which support the development of policies, strategies and approaches from decision makers on the local, national and international level. New ways to adapt are developed with every successful application, so there are no reasons not to incorporate one or several of these measures into the surroundings.

IV. Discussion and conclusions

In the last part of the thesis I presented the synthesis of the study outcome. The discussion part addresses many important issues which, due to the strict structure of the thesis, were not covered in part III. This chapter summarizes the thesis by providing answer to research questions, informs the reader of future work possibilities and wraps up the entire study by identifying the main conclusions and, finally, delivers a “take away” message.

10 Discussion

This chapter explains the validity of the research, discusses the results and their possible consequences. Additionally, it lists my interpretations which might be different than common understanding, difficulties and challenges of the study, uncertainties and explanations of my questionable decisions and future work.

10.1 Validity of the research

The goal of this study is to assess future population’s vulnerability to heat waves in Greater Hamburg, but the major finding is the future population’s vulnerability to heat waves modeling framework and how it can be applied for the Greater Hamburg case study. The modeling framework consists of a set of methods and approaches, used in Greater Hamburg case study area, but could be applied in any other case study in the world.

Compared to past and recent future vulnerability assessments, this study includes not only the current, but also future conditions: future climate, future population and future landscape data. The future population’s vulnerability to heat waves is composed of indicators of future monthly average minimum and maximum temperatures, distance to the nearest hospital, relative number of people over 65 years old, degree of soil sealing, and the relative nmber of welfare recipients. The first three indicators were modeled in other studies and served as auxiliary data, while the other were unknown and were modeled via UVCZ proxy cell-based indicator. Based on future urban development scenarios, the four UVCZ cell sets representing Greater Hamburg in 2050, were developed using cellular automata model.

The vulnerability assessment’s results produced in this study do not pretend to represent the future, but intend to show how different urban development scenarios can shift population’s vulnerability to heat waves. Therefore the credibility of the results cannot be verified - the future will show itself. However, the model’s sensitivity analysis have shown that changing the most sensitive vulnerability indicator, the relative population over 65 years old by 0,5 of its standard deviation, the average vulnerability changes by 18%. That might be a big difference, but it only says that the indicator of relative population over 65 years old has a significant impact on vulnerability index. A much more interesting outcome was produced by using other climate data into the model. The climate data of monthly average temperatures was not modeled in this study, but acquired from the downscaled global climate models. Specifically the MPI-ESM-LR climate model has been chosen. But other climate models were considered reliable as well, therefore I added the climate data from these models and analyzed how it would affect average vulnerability in Greater Hamburg. Surprisingly the HadGEM2-AO climate model with the highest monthly average temperatures increased average vulnerability in Greater Hamburg by 225% from the vulnerability, using the baseline MPI-ESM-LR model data, the RCP 4.5 and BaU urban development scenario in 2050. Meanwhile the climate model INMCM4 with the lowest monthly average temperatures decreased average vulnerability only by 16%. Because the uncertainty of the population’s vulnerability to heat waves is lower than the uncertainty between global climate scenarios, it can be concluded that the vulnerability assessment's results of the study are acceptable.

The validity and reliability of this case study could be improved by improving the data quality and model itself. If local authorities could give more accurate information and develop more realistic scenarios, the results might be different and more reliable. This process would not only increase the validity of the research, but also would cause greater cooperation between scientists and local authorities of Hamburg city and surrounding districts. Both sides would win – researchers would get better data and develop better models, and the local decision makers would make better decisions.

10.2 Results

Although most of the results have been discussed in details in part III of this thesis, it is worthwile to summarize them and to overview what kind of impact they could have. The results are based on the case study data, but also could be used as examples for other studies.

UVCZ scheme

The idea of modeling future population's vulnerability was based on modeling a proxy parameter which would contain properties of urban climate, landscape and population. The Stewart and Oke's (2012) LCZ classification was missing the socio-economic component, therefore it was decided to enhance the LCZ by adding the subclasses of the Germany energy-based planning scheme, developed by Erhorn-Kluttig et al. (2011). The combination was called Urban Vulnerability Climate Zones which contained 24 classes. Compared to LCZ, the UVCZ scheme has a more detailed representation of the potential housing classes. For instance the zones of open mid rise, compact mid rise and open low rise contained not one, but two classes each. The UVCZ scheme can be applied in any country in the world, but might be the most suitable for German cities. From 24 UVCZ classes, the 21 were identified in Greater Hamburg case study area. The UVCZ classification was used to classify the historical topographical maps of Greater Hamburg, in order to know how the UVCZ have changed during the years.

Historical urban development in Greater Hamburg

In order to model future urban development, the historical urban development trends have to be identified. This study considers the urban development as the change of UVCZ classification-based areas. The UVCZ classification was applied to topographical maps of Greater Hamburg, produced around the years of 1960, 1990 and 2000. The UVCZ differences between 1960 – 1990 and 1990 – 2000 reflected various urban changes, typical for these time periods. Despite the fact that the 1960 – 1990 time period is three times longer than the second one, it still experienced many more urban changes. One of the reasons for more active urban development in 1960 – 1990 was the high economical, industrial and residential development after the Second World War. During this time period most of the urban development took part in the central parts of the Hamburg city-state. In 1990 – 2000, because of the limited space, the central area experienced densification and the urban development mainly occurred in the suburbs. Both of these trends, as the UVCZ changes, were employed into the model for calibration in order to model future urban development scenarios.

Future urban development scenarios

The future urban development scenarios for Greater Hamburg were crafted by local experts during the workshop. In total four scenarios were developed: business as usual, uncontrolled urban sprawl, de-central concentration and concentration. The scenarios of uncontrolled urban sprawl and concentration were not realistic, but rather extreme. They were created in order to see how such extreme urban development would affect the population's vulnerability. The outputs of these scenarios could be used in other fields, such as urban planning, transportation infrastructure, healthcare, socio-economical development etc.

The development of scenarios was an easy task, but it was much more complicated to implement them into the model. Each scenario has specific neighborhood, zoning, accessibility and conversion functions and population fractions which were framed by the local experts as well. The outputs of future urban development scenarios as sets of UVCZ cells, dated for the year 2050, served as a proxy parameter and later on were assigned to modeled vulnerability indicators. Although the future urban development scenarios used very different functions, the outputs they generated have been very similar. As the main reason I identified the limited population growth. In 1960 – 1990 intense urban development was driven by high population growth, but the projected population growth in the future is rather low.

Future socio-economic scenario

Because of higher future socio-economic uncertainty, lack of expertise in socio-economic development and limited number of available local projections, this research employed only one socio-economic scenario. The pattern of future economical scenario was identical to commercial UVCZ pattern in 1990 – 2000 (business as usual scenario). Meanwhile the future social scenario considered future population projections and aging factor. The main difficulty was that three types of population projections were available for different parts of Greater Hamburg. The statistical analysis was used to match projections together. Afterwards the actual and projected population data were extrapolated till 2050, considering that the trend will not change over time. Based on the actual, projected and extrapolated data, the total population number in Hamburg city should not reach two million by 2050 and the number of population in whole Greater Hamburg should be between 3,6 – 3,7 million in 2050. Such an amount of population would be only 13% higher than it was in the year 2000 which means only a 0,26% annual increase of population.

Alternate history scenarios

The idea of alternate history was raised after it was identified that the differences between extreme urban development scenarios were low. This was the case because there was a limited future population increase which caused lower urbanization degree and fewer changes. The solution was to use historical population growth and employ the extreme urban development scenarios in the model, starting in 1960. This time the results of alternate history using extreme urban development scenarios showed a high difference. The concentration scenario would cause a lot of densification in the central areas and emergence of the new mid rise zones in the sub-centers. The de-central concentration scenario focused on high growth of mid rise zones within the sub-centers and with limited densification within the central areas, while the uncontrolled urban sprawl scenario would cause a significant increase in low rise housing along the roads outside the city. Additionally the dense clusters of commercial areas would be established in the Southeast of Hamburg city-state. That kind of representation of alternate history does not have any scientific meaning, but is a great way to extrapolate the results in order to verify the model's properties and sensitivity. Moreover, the visualization of alternate history could serve as a great example of how past decisions could change the present and why there is the need to change the present in order to avoid certain consequences in the future.

Socio-economic discretization

The main hypothesis of this research suggested that the population groups of different age, income and density are unevenly distributed among different potential housing UVCZ. In order to verify the hypothesis, the statistical analysis of the baseline (year 2000) census data was conducted. The Census data contained population indicators, defining the population's vulnerability for Greater Hamburg case study: population density, relative number of population over 65 years old (elderly) and relative number of welfare recipients.

Based on disaggregation of 2000 data the lowest population densities were among open low rise and dense open low rise UVCZ classes. Meanwhile the highest population density was typical for perimeter open mid rise. Open high rise takes the third place, just after compact mid rise. Surprisingly, dense compact mid rise has the third lowest population count. This is because the inner city of Hamburg is full of public, service and commercial buildings and often the residential use in these areas is quite limited. Comparing the perimeter open mid rise and open high rise, the mid rise has greater population density, even though the open high rise are much higher and should host more residents. The reason for this could be that the open high rise has more space between the buildings, while the perimeter mid rise is more packed. The coefficient of variation is highest for dense open low rise, terraced open mid rise and dense compact mid rise and exceeds. It means that among all classes, these three classes have the highest inner heterogeneity of population density. The lowest coefficient of variation is for the open high rise class, and the second lowest is for the perimeter open mid rise. The dense open low rise and terraced open mid rise are quite common cells in Greater Hamburg, therefore the heterogeneity of population density is high (it varies from 2 to 800 persons per cell). Meanwhile the high heterogeneity of dense compact mid rise could be because of commercial, service and public space, and limited residential use. Such high differences give higher coefficient of variation. The number of compact mid rise and open low rise cells, comparing to dense open low rise, is low, but the coefficient of variation is higher as expected. In general, the three classes of population density by UVCZ can be distinguished: the perimeter open mid rise, compact mid rise and open high rise have the highest population density, the terraced open mid rise have an average, the low rise classes have low population density. The dense compact mid rise is a rather special case.

The results of the elderly indicator are slightly different. The highest percentage of elderly was identified among the open low rise UVCZ. The second place is shared by terraced open mid rise and dense open low rise. Meanwhile the lowest concentration of elderly is in compact mid rise. The reason could be that the older people prefer to live in open low rise housing in the outskirts of the city and in terraced open mid rise in the higher density urban areas, while the compact mid rise housing are more typical in the central areas which attract younger people. The coefficient of variation of elderly, compared to population density, is smaller, because of the smaller internal variation: the population density varies from 1 to more than a 1000 per cell, while the elderly varies from 0 to 97. The lowest variation is in the dense compact mid rise class and the highest is among the terraced open mid rise and the compact mid rise. Although the differences between average elderly among the UVCZ classes are low, three classes of elderly can be identified: the low rise UVCZ and terraced open mid rise are the "oldest" classes. The average concentration of elderly is among perimeter open mid rise and the least “old” classes are the compact mid rise, dense compact mid rise and open low rise.

The last population indicator is the number of welfare recipients which indirectly measures income and education. The highest average of welfare recipients was found in the class of open high rise, while the lowest is in dense open low rise (poor people usually live in social open high rise housing, while wealthy residents live in spacious low rise dwellings). The compact mid rise takes the second place by the number of welfare recipients.. The coefficient of variation is low for open high rise, dense compact mid rise and compact mid rise. Meanwhile the highest variation was identified in dense open low rise. Concerning classification by poverty, four poverty classes among UVCZ can be seen: the dense open low rise are among the “wealthiest”, the perimeter open mid rise and open low rise have the second lowest number of welfare recipients, terraced open mid rise and dense compact mid rise share the third place and the poorest people live within open high rise and compact mid rise UVCZ classes.

The coefficient of variation for all population properties varies from low (elderly) to high (welfare recipients), because there always will be an internal class variation and some population groups will have preference to live in one or another, not the dominant type of housing. There is probably no city in which only old people live in single home housing, while the young live in apartment blocks. The results of the statistical analysis done in this study, therefore, are acceptable. Moreover, because the UVCZ classification is based not only on population, but also landscape and climate properties, the higher variance inside the classes instead of between the classes is fully understandable and acceptable.

Impact of refugee settlements

Because of the refugee crisis in Europe in 2015, Germany accepted many people seeking asylum from Syria and other countries. The refugees were sheltered in refugee camps throughout Germany. Hamburg, as the second largest city in Germany, accepted refugees as well. However, Hamburg did not have enough housing, so it was decided to establish refugee settlements around the central part of Hamburg. The decision to address the development of refugee settlements was made because they affect future urban development. This study considered only the settlements indending to host more than 1000 people. In the official plans of Hamburg city administration, 10 places were allocated to such settlements, but only the locations of 7 have been identified. These 7 settlements had to be built in 2016 and provide shelter to more than 25 000 refugees. The typical UVCZ of settlements are open low rise or terraced open mid rise. All settlements were implemented in the model through zoning. Although the 25 000 refugees in one year is almost the total increase of the annual population in Greater Hamburg, they were not added to the population pool developed by population projection because their status of residence in Germany is unknown. However, the housing that was built for refugees may be used for social housing later. If such an amount of refugees, however, would arrive in Hamburg each year, the population scenario should be revised.

Future population’s vulnerability to heat waves in Greater Hamburg

Though the strength of this research is to develop the framework of future population’s vulnerability modeling, the vulnerability assessment is necessary to accomplish the goal of the study – where the heat impact will be highest and the heat-vulnerable people will live in the future in Greater Hamburg. This study conducted two types of population’s vulnerability assessments: relative and absolute. The relative vulnerability, also simply called vulnerability, considers heat impact, population’s sensitivity and its adaptive capacity, while the absolute vulnerability additionally addresses the population density. The absolute vulnerability shows higher population concentrated areas with higher vulnerability. This information is important during discrete extreme events, such as heat waves.

Population's vulnerability has been modeled for four extreme urban development scenarios. The both vulnerabilities (absolute and relative) are strongly affected by the randomness factor and a high variance of vulnerability indictors. However, taking into account the average vulnerability for all cells, the concentration scenario has the lowest relative vulnerability, because population is more concentrated and fewer areas are vulnerable. In contrast, the uncontrolled urban sprawl scenario has the highest average vulnerability, because of the highest amount of cells, especially in the countryside where the adaptive capacity, due to higher distance to the healthcare facilities, is lower. The increase of adaptive capacity by building more healthcare facilities or implementing additional healthcare measures in the smaller towns and less urbanized areas would help to reduce vulnerability if uncontrolled urban sprawl scenario would occur. Meanwhile the average absolute vulnerability is highest for the concentration scenario, because the higher concentrated areas with high vulnerability has a greater impact. In order to reduce absolute vulnerability, if it is not possible to reduce population's concentration, risk awareness education, social-care services and green and grey adaptation measures would reduce vulnerability. The additional healthcare facilities or improvements of healthcare infrastructure would be required only if the existing one is overcrowded or inefficient. The least vulnerable (absolute) urban development scenario is the business as usual. It means that the population's concentration and vulnerability are spread equally among the whole area of Greater Hamburg.

Spatially, the relative vulnerability in the central area, in the North of the Elbe river is low, mainly due to lower number of elderly people and limited numbers of welfare recipients, although the degree of soil sealing is high. However, few areas in the central part have low vulnerability, because of the low population density. The areas surrounding the central Hamburg, have significantly high absolute and relative vulnerabilities, especially in the East and Northeast, although the far West and far Southeast sides have high vulnerability as well. These areas experience higher vulnerability because of the higher concentration of elderly people and their lower adaptive capacity, as well as the higher number of welfare recipients. In order to reduce vulnerability, the heat impact should be lowered or additional social-care measures for the elderly should be implemented. In addition, the reduction of poverty would decrease vulnerability, as well as the implementation of grey and green adaptation options. The hospitals have good coverage in the entire Hamburg city-state area, therefore no future actions should be taken, if the healthcare system functions quite well during the extreme heat wave events. The stronger focus should be placed on isolated high vulnerability areas. Such areas are typically filled with homes of elderly people or a population of with a high level of poverty. Isolation and limited mobility can cause difficulties for healthcare and social services to reach these people. This is also the case for lonely elderly, who are vulnerable during heat waves, even if they live in a wealthy area. The surrounding districts of Hamburg city-state experience different vulnerabilities. Vulnerability in North and West varies between low and average, while the South and East have moderate and very high vulnerabilities. Because the population living outside of Hamburg city-state have similar properties (most of them are living within dense open low rise UVCZ), one would think vulnerability should be distributed equally as well. However, the differences between North, West and South, East represents the pattern of future monthly average minimum and maximum temperatures: South and East will probably experience about 2°C higher temperatures than the areas in the North and West. Such a difference can have a significant impact on population's vulnerability. Therefore, the settlements in South and East of Greater Hamburg should be prioritized by implementing adaptation measures and options, lowering the heat impact. Additionally it would be interesting to compare the historical mortality between these areas during heat waves. If the mortality is higher, then adaptation should be implemented as soon as possible.

10.3 Interpretations

Each researcher has his own interpretations, emerging from observations and analysis. Below I listed my interpretations which show my critical view of some aspects covered in this research.

Population density

In biophysical, socio-economic and climate change vulnerabilities, the population often is reflected by its sensitivity to certain hazards. The population density is considered as well, but it does not say anything about how sensitive the population is. For instance, if there are 1000 people in the area which is affected by hazard, but no one is sensitive to this hazard, there will be no harm from that hazard, and thus no vulnerability exists. However, in the same case, the 50% of sensitivity would make 500 people vulnerable. The same degree of sensitivity in the area of 100 people would cause vulnerability only to 50 people. That kind of difference would have a different impact in emergency response applications which focus on the higher concentration of victims during the discrete extreme events. Therefore, the population density is important and should be considered in population's vulnerability as well. Instead of being a part of sensitivity, (for instance in the study done by Lissner et al., 2012), I defined the population density as a part of exposure. From my personal view, the exposure defines not only the location and the type of hazard to which the assets are exposed, but also the number of people exposed to that hazard. In chapter 4.2 I presented that exposure for this case study consists of physical exposure (hazard), territorial exposure (area/environment) and social exposure (population density). Although the social exposure is not composed into potential impact, as physical, territorial exposures and sensitivity are, it is used in the end by calculating absolute vulnerability.

Adaptive capacity

Adaptive capacity in climate change, disaster and risk sciences does not exactly mean adaptive capacity, but more like adaptation. IPCC names adaptation as an act of adapting to the changing conditions (IPCC, 2014a). In other words, adaptation is an act to become accustomed to or to cope with changing conditions. Ongoing adaptation would cause a lesser impact on changing conditions. Ongoing adaptation would cause lower impact by changing conditions. Meanwhile, according to IPCC (IPCC, 2014a), the adaptive capacity is "*the ability of systems… to adjust to potential damage, to take advantage of opportunities, or to respond to consequences*". But I understand the adaptive capacity, not as ability, but as a space of adaptation. If there is no space of adaptation, the adaptation cannot be applied. Using the verb "to be" the adaptation would mean "is" and the adaptive capacity would mean "could". If all adaptation measures are used, no adaptive capacity would need to exist and no additional adaptation would be needed or used. Also the high adaptive capacity does not mean that all adaptation measures will be applied ("could" does not mean "is" or "will"). So, from my personal perspective, adaptive capacity defines how much adaptation can be applied. I think both terms, adaptation and adaptive capacity are important, but the difference between their meanings should be emphasized more. I found that, even when the studies address adaptation, they often have in mind the adaptation options, or the possibilities of adaptation, which are the concepts of adaptation, rather than the actual measures of adaptation. In general this problem of adaptation, adaptive capacity and adaptation options exist because of a lack of clarity, an uncertainty and a lack of a systematic framework for adaptation. I also found that adaptation in quantitative approaches were addressed, but not quantified. Despite my personal interpretation of the adaptive capacity term, in this study I decided to leave the IPCC term and considered that adaptive capacity is the ability to respond to consequences.

Land use

The landscape can be classified by many factors. One of the common factors is the land use. Land use data is important in order to analyze environmental processes and to understand problems if the living conditions and standards have to be improved or maintained at current levels (Anderson, 1976). However, the term "land use" is frequently a mixture of land use, land cover and other properties. Therefore, a more appropriate naming and explanation should be used, in order to bring more clarity into the field of modeling, GIS and environmental science (Kaveckis et al., 2017). It is not clear, however, exactly how to name the land entity, to describe not only the land use but also the land cover, the morphology and other properties. It depends on what is the need to be distinguished and represented. If it is only one property, it's easy. If there are more than one, then it should be decided how the land will be described and what the set of the properties means. For instance, if one crop type and its productivity have to be defined, a proper name should be given to it, similar to "crop productivity zones". If heterogeneous properties are building density and population count, a convenient name would be "urban zones". Notwithstanding all of this, when the term is mentioned, it is very important to name exactly what properties it means. And if possible, examples have to be given. This will help the reader to more easily understand the land entity and its properties. If the set of various types of land properties does not allow the assigning of an appropriate name, it's recommended to give it a general name, such as "land zones" or "landscape".

However, even a consistent naming doesn't always mean a consistent interpretation. The residential zones where people reside and live, is the focus of this study. But these zones are not uniform: some areas are more populated, and others less. In order to describe higher and lower density residential zones, it is common to classify them as low and high residential. But density can also mean the building density or even the building height. Therefore it should be clarified in the classification scheme on what criteria the classification is based. The classification also depends on the number and the thresholds of classes. That is an issue, because low density residential area in China might be a very high density residential area in Iceland. Therefore each classification scheme should explain the classes in detail in order to avoid misinterpretation.

If the populated areas can be easily quantified for easier interpretation and classification, natural areas can be a much more complicated issue. For instance, the forest in Australia probably would be interpreted as a bush in Northern Europe. There are no international standards on naming an area as a forest, based on how much it is covered with trees (Kaveckis et al., 2017) – the forest is defined as a large area, covered with trees (Oxford University Press, 2015), but a large tree covered area can be interpreted very differently among the countries or even individuals. Therefore, classes should be clearly defined each time, or interpreted with caution.

Local Climate Zones

Despite the land use classification problems, one of the successful classifications of local climate within cities was done by Stewart and Oke (2012). Instead of using the land use classification, they developed a local climate zones' (LCZ) scheme. The authors declared that the major motivation to develop a LCZ scheme was the lack of a complete set of surface climate properties, such as urban structure, fabric, land cover and land use, in the existing urban climate classifications. This raised the question of whether or not the urban microclimate is limited only by these factors? Of course, some climatologists might keep it simple and would use only a few indicators, such as urban morphology and surface material, while others would prefer to have a very complex representation reflecting dominant wind speed, surface material, albedo coefficient, sky-view, buildings orientation or other factors. The word "complete" is quite relative. From the climatic perspective, the list of surface climate properties, represented by LCZ is appropriate, but not complete. However, Stewart and Oke are correct, considering the urban structure, fabric, land cover and land use are the main characteristics of the urban climate. But if more climatic characteristics are required, the LCZ scheme is not complete and has to be extended.

10.4 Difficulties

Each study experiences difficulties and limitations. This list of difficulties in this sub-chapter explains the challenges experienced during the research. Some of the difficulties were successfully solved while some were identified as limitations.

Landscape similarity

The UVCZ is a classification of spatial areas containing similar land use, land cover, urban morphology, housing and population properties. Again a question is raised as to what the limits of "similarity" are the limits of similarity? For instance, is the coverage by grass similar to coverage by crops? Or is the 40% coverage by grass similar to 80% coverage? If the objective is urban areas, then it does not matter if the area is covered by bush, scrub or grassland. The differences between the urban areas, especially the potential housing UVCZ, are less notable than the differences between natural areas. Of course, it is easy to distinguish open high rise and perimeter open mid rise, but much more difficult to see the differences between open low rise and dense open low rise. Based on the UVCZ classification, the open low rise class contains larger buildings with more space in between them, while the dense open low rise has a higher building density with less vegetation. However, because the UVCZ were acquired not by remote sensing, but by historical topographic maps and interpreted by one person, some of the cells might belong to a class different from which it was assigned.

The subjective interpretation in the primary steps of the research can have great influence on the final results. The UVCZ data was acquired by vectorizing historical maps which might be not as accurate as the soil sealing data produced by EEA using the remote sensing technologies. But in the end these two datasets must be merged (soil sealing is aggregated to the potential housing UVCZ cells). Even if the soil sealing data is quite accurate, the misinterpretation of UVCZ cell can drastically affect the final results. For instance, if a certain area with average degree of soil sealing of 90% is incorrectly interpreted as dense open low rise, but in reality it is a compact mid rise, then the false data which are used to model the indicators afterwards, is perceived. It is acceptable if there are many dense open low rise cells, because this false information would have little effect, but if the compact mid-rise class has only a very limited number of cells with Greater Hamburg, there may be a valuable record that is lost to its statistics. The result is that the classes have a high variance ad the modeled indicators are not modeled properly.

Aggregation and disaggregation

The aggregation operation was done in this study for soil sealing data and monthly average temperatures which were transferred from the greater spatial resolution to the UVCZ cells simply by defining the average value of the cell. The disaggregation, meanwhile, was done by transferring the population data to greater spatial resolution UVCZ cells. In both cases the target data was only the potential housing UVCZ classes. This method was chosen because it was assumed that people only live in residential areas. A problem can arise if some of the potential housing UVCZ areas are missing. This could lead to an outcome of the disaggregation analysis that is misleading, because it would never be known that there is missing, or misleading data. One of the ways to avoid such a problem is to review the data (both source and target) and the disaggregation results, especially the extreme values. Such a method could help to reduce the number of errors. That might be not a big problem in aggregation. In aggregation the potential housing UVCZ cells are assigned by the average value of the source data. If there was a mistake in identifying the UVCZ data (target data), this data is simply not included in the set.

Land use discretization

People used to live in single dwelling homes or apartment buildings which by land use are classified as residential areas - the areas where people reside and rest. However, today, as well as many years ago, people occupy abandoned industrial areas and create lofts, live in old town buildings where the first floor usually is occupied by shops and restaurants and/or build their homes in between commercial buildings. The heterogeneity of the land use within the city districts or even building blocks is high, but a land use area is often defined by the majority. This highlights a problem of discretization. Land use must to be assigned to each building block by the dominant land use in the area. However, such cases of generalization can cause a misunderstanding by combining land use with additional attributes, like population. If people are registered and statistically assigned to a building block that is not classified as residential, then these people are seen as living in industrial, commercial or other land use areas instead of living in a residential area. This could happen if a building is classified according to the dominant land use, which might be commercial, industrial or any other. This will happen in mixed use buildings, in which some of the building is used for commercial (for instance) and other smaller parts are almost “trapped” between the other uses. The use of generalization to classify a building by its dominant use can lead to some errant information. This was the case for this study. In the process of disaggregation which used the census tracts as a source data and the UVCZ as a target data, some of the people were accounted to be living in parks, commercial or industrial areas. But based on the assumptions, people should live in the potential housing UVCZ and any other cases, because of the generalization, should be ignored. The solution was to assign such population to the neighborhood potential housing UVCZ classes. However, the class of the dense compact mid rise was an exception. Although its dominant land use is between residential, commercial and public and it has low population count, it was decided to consider it as a potential housing UVCZ. This UVCZ class is mainly located in the city center of Hamburg. First floors are occupied by public services, shops, practitioners and restaurants, while the upper floors are dedicated for offices or residential spaces.

Temporal discretization

The historical UVCZ, used as an input data for the model in Metronamica, have been identified from the historical topographical maps by one interpreter. For this research the set of topographical maps, dated in 1960, 1990 and 2000, was acquired. A comparison of UVCZ interpretations between the years enabled the identification of the degree of change in Greater Hamburg during the last half of the century. Based on these changes, the Metronamica model was calibrated. By identifying the changes between the two time periods, it is clear that the change happened during a specific time period (for instance 1960 – 1990), but it is not known when exactly. It is possible that most of the development happened between 1960 – 1980, while there was stagnation between 1980 – 1990. Unfortunately this cannot be reflected in the model which captures an overall increase in urban development in 1960 – 1990. If this change is reflected in the BaU scenario in the future as well, it will show a constant slow increase of urban development, but no accelerated expansion or stagnation will be represented.

Missing data

Although the historical urban areas were vectorized from the topographical maps, the natural lands, such as agriculture, forests, wetlands, bush/scrub/grasslands, bare rock and waters are not as well reflected in historical topographical maps. Therefore, all these natural areas had to be acquired in a different way. The only available data was the CORINE dataset of the year 1990. It was assumed that the natural lands which were not affected by urban development and did not change much in 30 years. Even if there would be a change, it would not affect the model, because all the natural areas in the Metronamica model were defined as vacant cells, which means that these cells can be occupied by the function cells which are actually modeled by Metronamica. Simply put, the model used in this study is not sensitive to the vacant classes – it is does not matter if the area is forest, agriculture or wetland, except if one of them is restricted by zoning. Therefore, method that was chosen to fill the missing data gap is considered appropriate.

Issues of model calibration

The kappa was used as a measure to judge the model's calibration and the agreement between actual and modeled data. Although the high kappa shows good cells' allocation agreement, it does not always represent the accurate urban development pattern. This was the case in this study as well and is analyzed in detail in chapter 5.3. During the benchmarking which used the initial rules (IR), it was noticed that although the modeled pattern was quite different than the actual urban development pattern, the kappa values were quite high. This might have occurred because the IR rules cause less randomness and less dispersion which on a cell basis might be similar to actual development. But the aim of this study is not to reproduce authentic cell-to-cell development, but to develop a realistic urban development pattern. Moreover, the kappa reflects agreement between all the cells of the case study, but not between the changed cells. If the actual changes were only 10%, the model can represent any changes, the kappa will show 90% agreement. Therefore, in that case it is better to trust kappa simulation which shows agreement only between changed cells.

The calibration of the UVCZ changes experienced different difficulties among the various UVCZ classes. One of such cases was the calibration of the urban park (dense trees) for the year 1990 – 2000. Of course, the kappa value was 0,773 which shows a very good agreement, but the kappa simulation received the value of 0,013 which is quite close to zero. Although only a limited number of cells matched, the trend of urban parks' development was quite similar to the actual development in 1990 – 2000. The cell mismatch could possibly happen because the urban parks are quite strictly managed and special zoning is applied. Unfortunately this zoning was not available for Greater Hamburg study and neighborhood factor had been used to model urban parks. Because there are no clear relationships between other UVCZ, transportation infrastructure and urban parks, their allocation can be hardly projected. Although the calibration did not show good results of urban parks' calibration, the modeled trend was quite acceptable.

The other calibration's issue was with the most common dense open low rise UVCZ for the years 1990 – 2000. The kappa simulation value for that time period was 0,097, which is about seven times higher than the value for the urban parks, but two times lower than kappa simulation for dense open low rise in 1960 – 1990 which was 0,256. In general, it was noted that the calibration results for 1960 – 1990 were better than for the 1990 – 2000, even though the latter period is three times shorter. The reason for this is unknown. The greater magnitude of urban development in 1960-1990 may have made it easier to identify the urban development trend and improve calibration, or some other factors not included in the model may have caused this situation. But in the end, for the time frame 1960 – 1990 the kappa simulation was 0,306 and for the time frame 1990 – 2000 the kappa simulation was 0,113. According to RIKS (2013), the values of kappa simulation over 0,1 are fine. The calibration of the latter time frame might be not as comprehensive, but that is fine, knowing that the urban changes during that time period were not as intense as it was in 1960 – 1990. Moreover, in calibration done by Daneke (2013) for the time frames of 1960 – 1990 and 1990 – 2005 with greater study area and different classes, the kappa simulation received corresponding values of 0,222 and 0,148. Therefore, it can be concluded that the calibration performed in this study was well done.

Model randomness

Even if projected urban development scenario is done in the future, the outcome could be quite different from the modeled one for many reasons: the different than projected population growth, changed zoning and urban plans, different allocation of new population among new potential housing UVCZ, changed migration, national and local politics, different economical and industrial development etc. However, another challenge is to recognize if the specific scenario is occurring. Even the model cannot guarantee that in 2050 the urban sprawl scenario in Greater Hamburg will give the exact cells' allocation, although the pattern should not change.

10.5 Uncertainties

Uncertainties are common in many studies, especially dealing with future events. Knowing the uncertainties increases the awareness of the study's credibility and validity. Below I listed the most important uncertainties of this research.

Future scenarios

Objective of future scenarios is not the exact reproduction of the future situation, but to represent a possible urban development trend. And according to the local experts who developed the future urban development scenarios, the different urban development trends for Greater Hamburg are represented well by the four scenarios with certain population fractions, UVCZ demands and rules: the extrapolated business as usual (BaU) scenario, concentration (compact city), uncontrolled urban sprawl and de-central concentration, as a middle scenario. Previous land modeling study in Greater Hamburg, done by Daneke (2013), used very similar scenarios: basic trend, compact city, de-central concentration and de-centralization. All the scenarios are driven by population growth and its projections are affected by certain rules (more details in chapter 7.4). But if these drivers would be exactly as projected, the urban development can also be affected by development of new transportation infrastructure, commercial and industrial zones, landfills, airports and many other factors which are not accounted for this study. But the aim is to project the exact allocation of urban development in the future, but to assess the impact of certain urban development trends on population's vulnerability to heat waves. However, if one of the four defined urban development scenarios would follow, there is no guarantee that the UVCZ demands, neighborhood potential and accessibility rules would represent the actual future urban development.

Vulnerability indicators

The idea of modeling vulnerability indicators was based on the UVCZ proxy parameter which would be modeled by Metronamica. The historical vulnerability indicators would be transferred via aggregation and disaggregation to the potential housing UVCZ. Afterwards the new or converted UVCZ cells and patches of cells would be "unpacked" by assigning the average values of historical vulnerability indicators related to each potential housing UVCZ class. However, this would cause a low variance among the cells (different value to each seven classes). The development of the new cell does not mean that it will have the exact properties as the average cell of that class. Therefore, it was decided to involve a factor of randomness. This means that each new/converted cell or patch of cells will receive not the average value of degree of soil sealing, relative elderly, relative number of welfare recipient, but the random values within the certain range. The suitable range of the values' randomization was selected as +/- 0,5 of the standard deviation from the mean. The standard deviation was used to define the ranges, because of the normal distribution among all vulnerability indicators. The range of 0,5 of the standard deviation was selected in order to reduce the variance between the values, although the statistics have shown that the variance inside the group was higher than between the groups. But in order to keep the heterogeneity of the vulnerability indicators within the potential housing UVCZ classes, it was decided to use only half range of the standard deviation.

The assignation of the random values is done not to the individual cells, but to the clusters of cells which are called patches. The patch is defined as a cluster of adjacent, same potential housing UVCZ type cells. All cells within the patch receive the same values via the "unpacking" operation. This affects only new cells. Such an approach aggregates socially and physically similar cells into the areas which represent the city more realistically than the stack of heterogeneous cells. However, this approach does not consider the maximum size of the patch. For instance, if patch is large, the size of the small town emerges and the model identifies it as a homogenous patch and assigns the same vulnerability indicators to each cell. Although it is possible, it is not realistic that a large area contains the same properties as a smaller one. But even if the size of the patch is limited, the question arises about how big the patch can be? One of the ways to deal with this is to randomize the patches within the large patch. That is technological a solution which could be implemented later on. For this time, the modeling of future vulnerability indicators is based on the assumption that all new cells of the same UVCZ type contain the same or nearly the same vulnerability properties which are assigned via random allocation. Another issue with the patches is that if a new patch emerges near the existing patch, the new one receives the average vulnerability properties of the existing one.

Unfortunately, the Hamburg city-state surrounding districts contain only population density and distance to the closest hospital, and soil sealing, but not the number of elderly or the number of welfare recipients, which are very important population's vulnerability indicators for this study. This is because the statistics of these indicators for the surrounding districts of Hamburg city-state was not collected at the very local scale, as it was done in Hamburg city-state at the statistical tract level. Therefore, the gap of missing data must be filled. During one of the workshops the local experts were told that the vulnerability indicators classified by potential housing UVCZ should not differ between Hamburg city-state and surrounding districts. It was decided to use the approach of the random values which has been used for the new cells as well. In addition, although the data of the degree of soil sealing for surrounding districts has quite good resolution, it was also randomized in order to keep operational consistency. The population density was also randomized, because the rough scale of the population data was not enough to reach good results via disaggregation. The distance to the nearest healthcare facility as the spatial indicator, based on proximity, was not randomized. Although the high variance of vulnerability indicators creates high uncertainty, the gap of missing data had to be filled.

Normalization

Another great issue within this research was the selection of data normalization method. The data normalization is used to normalize the different values in order to combine them. The normalization method used to process the data was the minimum-maximum normalization. This method simply transfers the scale, limited by minimum and maximum values, to the range of 0 – 1 or 0 – 100 as desired. The advantage of this method is that if the value is normalized to the scale of 0 – 1 or 0 – 100, the different values can be added, multiplied and more easily compared. However, the downside is that the extremes of the original data, the minimum and maximum values, are emphasized. The alternative to the minimum and maximum values is to define the threshold. The threshold identifies the range of the values used for vulnerability indicators. For instance, if the full range of the temperature data is from 0 – 100 °C, but if the minimum threshold is 60 °C, then only the temperature within the range 60 – 100 °C will be aggregated into vulnerability. Thus, the 60 °C will be low, the 80 °C will be average and 100 will be high temperature, although for other cases, the 60 °C might be a very high temperature. This issue is the case for this study as well. It can be clearly seen by analyzing the sensitivity indicator which is represented by the people over 65 years old (elderly). The data of elderly persons ranges from 0 – 97%. The same range is used for vulnerability – the 0 means a low concentration of elderly and 97 means high percentage of elderly. Meanwhile, if the threshold would be applied, the results could be quite different. For instance, if 40% would be the highest threshold, the 0% would have a meaning of low elderly and 40% would be high elderly. All values over 40% would be identified as high elderly as well. This shows that the thresholds can have a great effect on final vulnerability index. However, for this case study, it was decided to not apply the threshold approach, because there are no guidelines to identify thresholds for population density, high soil sealing level, percentage of elderly and number of welfare recipients.

10.6 Decisions

The vulnerability modeling is not framed by any strict rules and is therefore quite flexible. Thus, some of the decisions which I made during the research might be questionable. This sub-chapter explains why the certain decisions or choices have been made.

Software

The software selected to model the UVCZ as a proxy parameter, is Metronamica which is based on cellular automata (CA). Metronamica and CA were chosen because the CA acts similarly to the urban development – it is based on new cells' demands and is strongly affected by neighborhood. Metronamica adds additional functions, such as changing neighborhood potential, factors of suitability, randomness, accessibility and zoning. Although the Metronamica does not fully represent an ideal future vulnerability modeling tool, it was proven as the most suitable approach. Looking at it from the modeling side, the agent based modeling, instead of the CA, could have a good outcome. But in my opinion, agent based modeling is more suitable for a population which is more dynamic. Although the population is the great interest in this research, the urban landscape (UVCZ) is more important, because it represents not only population properties, but also the territorial exposure and is easier to model because environment is more static and easier to project.

Cell size

The cell size does not only define the spatial resolution, but also the distance of the neighborhood effect. Technically, in Metronamica the neighborhood effect influences all the cells around by an 8 cells radius. The cell size for this case study was set to 250 x 250 meters because this size is close to the size of the building block in Greater Hamburg. The smaller cell size would give greater spatial resolution and the data aggregation might be unnecessary, but the greater data heterogeneity and greater computation time would be a problem. In addition to this, the greater cell size would be helpful when trying to disaggregate data, but it would also be too difficult to represent spatial heterogeneity of the UVCZ. The most important effect would be the different distance of the neighborhood effect. The 250 x 250 meters cell size gives a neighborhood effect of two kilometers, which in Greater Hamburg, is an appropriate distance affecting the cell by the surrounding UVCZ classes.

Vulnerability indicators

The number of indicators does not always cause a higher quality of composite index. This study is not an exception. In the early stages of this study, common population's vulnerability assessment studies were analyzed. The large set of identified indicators was a promising input into the vulnerability assessment framework. However, because this study has not only to assess vulnerability, but also model the missing indicators, it was decided that a high number of indicators could not be considered because of high complexity and uncertainty. Therefore, the decision was made to keep the model as simple as possible and to have a clear process of modeling and a possibility to apply realistic scenarios. In the end only eight vulnerability indicators were chosen: monthly average minimum and maximum temperatures, degree of soil sealing, population density, relative number of elderly over 65 years old, relative number of welfare recipients and distance to the nearest healthcare facility. The decision of choosing these indicators was based on future data availability, possibility to model, and their effect on heat-related mortality.

The indicator having the highest impact on the population's vulnerability to heat waves and the only indicator of population's sensitivity in this study is the relative population over 65 years old. It means that only the people over 65 years old are sensitive to the heat within this study, but that does not mean that only the elderly are sensitive to heat in general. Much more factors affect the population's sensitivity to heat (more details in chapter 6.1), however the elderly has the weight among all the other indicators and is easiest to model. That is why it was selected as a strong sensitivity indicator. The other factors, such as diseases, people working outside etc. are very complex and hardly can be used in the indicator-based quantitative assessments. But this study, as well as many other common assessments, does not consider the heat impact to people who do not belong to any sensitive social group or who do not have any illness which could cause a sensitivity to heat. In other words, this study does not include ordinary people who do not have a high risk of being affected by heat. Looking at real life examples, however shows that even the healthy young person, who would ordinarily sustain high heat, can suffer from heat related situations: dehydration caused by a short heat exposure, limited use of liquids, heat stroke, etc. It's well known that there is always a possibility that there will be victims of heat stroke, regardless of age, and the number of those victims will be more than what was projected. From another perspective, however, it does not mean that all elderly people are susceptible to heat during a heat event. Thus, the probability of young people to be sensitive might be equal to the probability of old people to be less sensitive, resulting in the probabilities compensating each other out. There may be some who will disagree because the probability of an older person being more sensitive to heat than a younger person is high. This would be why the elderly population was selected as a sensitivity indicator. These statements are only assumptions based on historical heat impact studies, research and statistics. It may well be that the elderly today might be less sensitive than the average teenager. Another important issue which was not covered in this research is the heat threshold for the other younger people. This study models and identifies the most vulnerable areas, but does not say what will happen if the maximum temperature is extreme, when all people, no matter what age, is sensitive to the heat. In such an event, the elderly might die sooner than younger people, maybe by days or weeks. If everyone dies, however, there's no need for a vulnerability assessment. Assuming that some people are more susceptible to extreme heat than others, the need for a vulnerability assessment is real.

10.7 Future work

This study has a lot of future potential. Future vulnerability's modeling framework can be used not only to assess vulnerability to heat waves, but also to other hazards. The indicators used in this study could be used to assess vulnerability for floods, for instance. The higher population concentration is a very important measure to plan emergency response and evacuation activities regardless of a disaster type. The degree of soil sealing shows the percentage of soil sealed by the impervious surfaces which have a great impact to heat susceptibility and flood runoff – the water infiltrates into the unsealed soil, but cannot penetrate the sealed soil and collects at lower locations and causes flooding by inundating valuable assets (DG Environment, European Commission, 2011; EEA, 2009; Pitt, 2008; Scalenghe and Marsan, 2009; Schauser et al., 2010). The number of welfare recipients is also a universal indicator – it is common that poor households experience a higher impact from disasters, regardless of what kind of disaster it is. Such households have very limited financial capacity to mitigate disaster effects. One of the main required steps is to determine if, when used for other hazards, the proxy parameter can be revised for other indicators. In addition, a different UVCZ classification that is based on case study and selected hazard should be required if used for a different hazard. Any new study addressing a new hazard should be required to set new assumptions and verify a new hypothesis, as the hazard data would vary, based on the disaster type. For instance, in the case of flood, the hazard data might be future precipitation; in the case of earthquakes, the earth's shaking intensity; in the case of wind storm, the wind intensity, etc. Although the indicators would be different, the same modeling approach could be used.

The methods approaches presented in this study are not limited by applicability of Greater Hamburg. It is encouraged to be used in other case studies as well. The most major obstacle would be the availability of the data. It would be a time consuming effort to develop the UVCZ scheme and model with data analysis and calibration of the model. The other steps could be somewhat simple: a new set of case study specific future urban development scenarios, the climate RCP scenarios or models. It might also require different indicators with different weights. Although the vulnerability modeling in another case study might not bring as much of a novelty as this study, it could improve the modeling's framework and methods.

This study has used the Metronamica software to model the proxy parameter. However, for local scale applications, other CA-based software or model could be used as well. Additionally, the population's vulnerability has a great potential to be modeled using the agent-based modeling. But instead of the landscape (UVCZ) as a grid of cells, the population as agents, could be used. Such modeling would be very complex, because of the population's dynamicity and mobility, but would be possible.

The effect of aging population was addressed in this study. However, it was quite simply applied – based on aging projections, the population over 65 years old was adjusted in all cells. But that might not fully represent the real aging process. Because when people die, often their apartment or house is sold for the new family (although it is not always a case). In order to implement such process, the more complex approaches are required. One of the ways is the attributes' count – each year the age of each individual living within the cell is counted and when the age of the individual reaches the average maximum age, the individual is replaced with 1-3 new individuals of young age. But then such approach has to consider the births as well, and should be related to the population growth. But this is where the system is getting more complex and would require additional research.

Because of the high focus on Greater Hamburg, the reliability of the study could be improved by continuously adding current information. Additional scenarios developed by local authorities could easily be implemented into the model and could generate more realistic results which could be a great help to local decision makers, not only in the vulnerability modeling but also in urban planning, transportation infrastructure, population migration, heating demands, economical development and many other areas.

11 Conclusions

This study was conducted to assess future population's vulnerability to heat waves in Greater Hamburg. It found that recent future vulnerability and heat-related mortality assessments addressed future climate conditions only and did not study other future conditions such as future urban development and future population. This study overcame this problem by introducing the proxy parameter (UVCZ) which represented urban landscape, climate and population. The modeling of future UVCZ enabled us to fill the gap and obtain future urban landscape and population conditions which are required to assess future population's vulnerability to heat waves. Such an approach answered the main research question "How can future vulnerability be modeled, considering not only today's conditions but also future conditions?", which helped me reach the goal of the study and answer the question "Where will the heat impact be highest and where will heat vulnerable people live in Greater Hamburg in the future?".

However, in order to answer the main research question, the study has raised and answered the following research questions:

1. What are the definitions of vulnerability?

The study collected and analyzed 50 vulnerability definitions, dating from 1974 to 2004. Most of these definitions addressed three main topics: risk, hazard and resilience. There were only 3 out of 49 vulnerability definitions that directly related to climate change. This finding indicates that the definition of vulnerability has developed from dealing with the risk, hazard and resilience disciplines to being used in the climate sciences in the last few decades.

2. What are the main aspects of vulnerability?

Because vulnerability is a complex topic, the aspects of vulnerability were analyzed in great details. The study gave an overview of how vulnerability can be identified via a vulnerable situation, what the common vulnerability concepts, frameworks and interpretations are, and how vulnerability can be quantified and measured. Additionally the study reviewed the common understanding of future vulnerability, the IPCC vulnerability assessment approach and presented detailed step-by-step guidelines on how vulnerability should be assessed. All of these aspects helped to identify vulnerability for case study of Greater Hamburg.

3. What factors affect a future population's vulnerability to heat waves in Greater Hamburg?

The identification of a vulnerable situation in Greater Hamburg helped to formulate that future population's vulnerability to heat waves is affected by future conditions of urban landscape, climate and population.

4. How can the properties of urban landscape, climate and population be combined into a proxy parameter?

The existing local climate zones' scheme (developed by Stewart and Oke,2012), addressing urban landscape and climate, was expanded to form a new classification called "urban vulnerability climate zones" (UVCZ) which also included the socio-economic properties of population. The UVCZ was used as a proxy parameter to model future conditions and future population's vulnerability indicators.

5. What is the conceptual setting and operational options required to model vulnerability?

The formulated future conditions required the establishment of a conceptual setting which could give a rough overview of three domains addressing a population's vulnerability to heat waves: urban landscape, climate and population and their relationship to one another. The operational options reviewed the most comprehensive modeling and data processing techniques that were required to model vulnerability.

6. How can future proxy parameter (UVCZ) be modeled?

The cellular automata-based land use modeling software "Metronamica" was chosen as the most appropriate tool. This software required historical UVCZ data to calibrate the model.

7. How have UVCZ changed in the past in Greater Hamburg?

Many more changes in UVCZ happened between 1960 and 1990 than between 1990 and 2000, even ignoring the difference in the length of time for the two time periods. In regard to the spatial patterns, the development occurring between 1960 and 1990 was found in the central areas of Hamburg city-state, while in 1990 to 2000 most of the development was identified to be occurring in suburbs. Because of lack of space in Greater Hamburg city-state, development occurred as expansion into the suburbs as well as increasing the densification of the city-core.

8. What indicators could measure future population's vulnerability in Greater Hamburg?

The indicators which were selected were based on data availability, the ability to model the data and the literature research on heat-related mortality studies. A total of eight indicators were selected: the monthly average minimum and maximum temperatures, degree of soil sealing, population density, the relative population of persons over 65 years old, the relative population receiving welfare and the distance to the nearest hospital.

9. What is the minimum mortality temperature in Greater Hamburg and how can it be related to future monthly average minimum and maximum temperatures?

Based on an analysis of available literature, the minimum mortality temperature in areas, similar to Hamburg, varies from 16,5°C to 22°C. In this study I decided to use 20°C as a threshold of minimum mortality temperature in Greater Hamburg. This means that days with daily average temperature over 20°C (I called it "heat days") would cause greater heat-related mortality. The statistical analysis of historical temperatures in Hamburg showed a good correlation between daily average temperature and monthly average minimum and maximum temperatures. The number of heat days increases when the monthly minimum average temperature exceeds 12°C and the monthly maximum average temperature exceeds 20°C. This means that people living in the areas where the monthly average minimum temperature exceeds these thresholds will probably experience much more heat than other areas.

10. What future scenarios could shift future conditions affecting the population's vulnerability to heat waves in Greater Hamburg?

During workshops which were held, it was decided that one social-economic (BaU) scenario, four urban development scenarios (BaU, uncontrolled urban sprawl, concentration and de-central concentration) and one climate change scenario (RPC 4.5 from MPI) would be used.

11. If extreme urban development scenarios had been applied in 1960, how would Greater Hamburg look today?

The high historical population growth shows many differences between extreme urban development scenarios. The concentration scenario would cause very high densification in central areas and development of mid rise buildings in sub-centers. The urban sprawl scenario would increase low rise housing sprawl along the roads in throughout the entire study area, while the de-central concentration would have mixed results.

12. How can future conditions be modeled using future UVCZ?

Future conditions have been developed via modeled UVCZ for each urban development scenario using the assumption that the conditions of each UVCZ class will not experience much change from the baseline (2000 data) in the future. Through statistical analysis, each new or converted UVCZ has been assigned a random value ranging +/-0,5 of the standard deviation from the mean of each vulnerability indicator for each potential housing UVCZ class.

13. How can the future population's vulnerability to heat waves in Greater Hamburg be assessed?

The future population's vulnerability indicators, modeled via UVCZ, were transformed, rescaled and normalized. Then they were combined into vulnerability elements based on the IPCC concept and assigned certain weights to define their importance to each other. Lastly, the combinations of indicators were aggregated using geometric or arithmetic aggregation's methods to develop a relative vulnerability index. This index was multiplied by the population density to develop an absolute vulnerability index.

14. What are the common adaptation options and measures to reduce population's vulnerability to heat waves?

The list of grey, green and soft adaptation options/measures, listed in chapter 9, presents many possible ways reduce the impact of heat on those most vulnerable to heat waves.

In addition to the research questions, this study partly confirmed the main hypothesis which stated that population groups of different age, income and density are unevenly distributed among different potential housing UVCZ. Although the variance of socio-economic properties is higher with each class than between different classes, the results showed that socio-economic properties are more or less unevenly distributed among different potential housing UVCZ classes. This outcome shows that there is the potential to classify cities not only by local climate and landscape, as the LCZ classification was intended to do, but also by socio-economic properties.

The successful answers to the research questions and the confirmation of the hypothesis did not eliminate one of the limitations of this research: the uncertainty. Uncertainty cannot be avoided in any modeling study, especially when the future is being modeled. With that being said, however, the sensitivity analysis that was conducted has shown that the uncertainty between different global climate models is even higher. The monthly average temperature obtained by HadGEM2-AO model caused a 225% increase in the populations vulnerability to heat wave, while the standard deviation of 0,5 of the most vulnerability affecting indicator would cause a change in average vulnerability by only 18%. This does not conclude that this research is reliable, it just states that its results of vulnerability assessment are more reliable than the global climate models.

The strong reliability of the entire study gives an acceptable plausibility of the study's final outcome – the population's vulnerability to heat waves assessment. If the urban development patter continues, the central areas of Hamburg City will probably experience a low vulnerability for the population compared to the clusters circling around the central areas. An especially higher vulnerability could be a dangerous threat in the Northeast, East and Southeast areas of Hamburg city-state. This would be the result of a high proportion of the elderly and poor population. The population in the surrounding districts should be less affected by poverty, but the Eastern and Southern districts would experience higher temperatures than their counterparts in the North and West. The communities farther from the center will also be more vulnerability because of the lack of a healthcare infrastructure.

If the government of Greater Hamburg would decide to change the existing urban development pattern, it would not have much effect on vulnerability – the effects were minimal, mainly because of the limited population increase in the future. The sensitivity analysis has shown that scenarios with greater greenhouse gas emissions could cause higher vulnerability than the most unfavorable urban development scenario. What this means is that even the best efforts to change the pattern of urban development would not help if Greater Hamburg would experience higher temperatures than expected. Only if the population projections would drastically change, the impact of extreme urban development scenarios would be higher. Nevertheless, if non BaU urban development trends would be considered, the concentration scenario would result in the lowest average relative vulnerability and the urban sprawl scenario would cause a higher than average relative vulnerability, mainly because of the longer distance to the nearest healthcare facilities.

The vulnerability assessment delivered interesting results, but they are not the strength of the study. The results can be very uncertain, due to its complexity and various decisions not addressed within this research. But the future scenarios give room that could be used to shift future decisions to experience the lowest possible population's vulnerability to heat waves. The case of Greater Hamburg was used as a good example of how future vulnerability could be modeled using not today's but future conditions. The extensively described methods and data examples form comprehensive guidelines for other studies which could use the same approach to not only model future vulnerability but also heating demands, energy consumption, pollution or even GDP.

Although this study does not discover a fundamental scientific breakthrough do to the topic's complexity, it does develop a methodological basis which will support future environmental modeling studies by addressing future conditions. At one time forecasting the weather was thought to be impossible and today it's used by everyone. I would like to picture a similar picture for this study – that today there may be many uncertainties about it which will one day be taken away with new ideas to give a more accurate projection.

References

Ackerman, B., 1985. Temporal march of the Chicago heat island. J. Clim. Appl. Meteorol. 24, 547–554.

Adams, W.C., 1986. Whose lives count? TV coverage of natural disasters. J. Commun. 36, 113–122.

Adebayo, Y.R., 1987. A note on the effect of urbanization on temperature in Ibadan. J. Climatol. 7, 185–192.

Adger, W.N., 2000. Institutional adaptation to environmental risk under the transition in Vietnam. Ann. Assoc. Am. Geogr. 90, 738–758.

Adger, W.N., Kelly, P.M., 1999. Social Vulnerability to Climate Change and the Architecture of Entitlements. Mitig. Adapt. Strateg. Glob. Change 4, 253–266. doi:10.1023/A:1009601904210

Akbari, H., Konopacki, S., 2004. Energy effects of heat-island reduction strategies in Toronto, Canada. Energy 29, 191–210.

Akbari, H., Levinson, R., Rainer, L., 2005. Monitoring the energy-use effects of cool roofs on California commercial buildings. Energy Build. 37, 1007–1016.

Alcoforado, M.-J., Andrade, H., 2006. Nocturnal urban heat island in Lisbon (Portugal): main features and modelling attempts. Theor. Appl. Climatol. 84, 151–159.

Alexander, D.E., 1993. Natural disasters. Springer Science & Business Media.

Ali-Toudert, F., Djenane, M., Bensalem, R., Mayer, H., 2005. Outdoor thermal comfort in the old desert city of Beni-Isguen, Algeria. Clim. Res. 28, 243–256.

Allen, A., Milenic, D., Sikora, P., 2003. Shallow gravel aquifers and the urban “heat island”effect: a source of low enthalpy geothermal energy. Geothermics 32, 569–578.

Alwang, J., Siegel, P.B., Jorgensen, S.L., 2001. Vulnerability: a view from different disciplines. Social protection discussion paper series.

Anderson, B.G., Bell, M.L., 2009. Weather-related mortality: how heat, cold, and heat waves affect mortality in the United States. Epidemiol. Camb. Mass 20, 205.

Anderson, J.R., 1976. A land use and land cover classification system for use with remote sensor data. US Government Printing Office.

Armstrong, B., 2006. Models for the relationship between ambient temperature and daily mortality. Epidemiology 17, 624–631.

Arnds, D., Böhner, J., Bechtel, B., 2015. Spatio-temporal variance and meteorological drivers of the urban heat island in a European city. Theor. Appl. Climatol. 1–19. doi:10.1007/s00704-015-1687-4

Arnfield, A.J., 2003. Two decades of urban climate research: a review of turbulence, exchanges of energy and water, and the urban heat island. Int. J. Climatol. 23, 1–26. doi:10.1002/joc.859

Assemblee Nationale, 2004. N° 1455 - 01 - Rapport de la commission d’enquête sur les conséquences de la canicule (MM. Claude Evin, François d’Aubert) (tome I) [WWW Document]. URL http://www.assemblee-nationale.fr/12/rap-enq/r1455-t1.asp (accessed 1.22.14).

Auer, A.H., 1978. Correlation of Land Use and Cover with Meteorological Anomalies. J. Appl. Meteorol. 17, 636–643. doi:10.1175/1520 0450(1978)017<0636:COLUAC>2.0.CO;2

Auerbach, F., 1913. Das Gesetz der Bevölkerungskonzentration. Petermanns Geogr. Mitteilungen 74–76.

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., Anderson, H.R., Bisanti, L., D’Ippoliti, D., Danova, J., Forsberg, B., Medina, S., Paldy, A., Rabczenko, D., Schindler, C., Michelozzi, P., 2008. Heat Effects on Mortality in 15 European Cities: Epidemiology 19, 711–719. doi:10.1097/EDE.0b013e318176bfcd

Baird, B.F., 1989. Managerial decisions under uncertainty: An introduction to the analysis of decision making. John Wiley & Sons.

Balchin, W.G.V., Pye, N., 1947. A micro-climatological investigation of bath and the surrounding district. Q. J. R. Meteorol. Soc. 73, 297–323. doi:10.1002/qj.49707331706

Bankoff, G., 2003. Vulnerability as a measure of change in society. Int. J. Mass Emergencies Disasters 21, 30–50.

Barnett, A.G., Tong, S., Clements, A.C.A., 2010. What measure of temperature is the best predictor of mortality? Environ. Res. 110, 604–611.

Bärring, L., Mattsson, J.O., Lindqvist, S., 1985. Canyon geometry, street temperatures and urban heat island in Malmö, Sweden. J. Climatol. 5, 433–444.

Batty, M., 2007. Cities and complexity: understanding cities with cellular automata, agent-based models, and fractals. The MIT press.

Batty, M., 1997. Cellular automata and urban form: a primer. J. Am. Plann. Assoc. 63, 266–274.

Baxter, J.W., Pickett, S.T., Dighton, J., Carreiro, M.M., 2002. Nitrogen and phosphorus availability in oak forest stands exposed to contrasting anthropogenic impacts. Soil Biol. Biochem. 34, 623–633.

Bechtel, B., 2012. Robustness of annual cycle parameters to characterize the urban thermal landscapes. IEEE Geosci. Remote Sens. Lett. 9, 876–880.

Bechtel, B., Schmidt, K.J., 2011. Floristic mapping data as a proxy for the mean urban heat island. Clim. Res. 49, 45–58. doi:10.3354/cr01009

Bell, M.L., O'Neill, M.S., Ranjit, N., Borja-Aburto, V.H., Cifuentes, L.A., Gouveia, N.C., 2008. Vulnerability to heat-related mortality in Latin America: a case-crossover study in Sao Paulo, Brazil, Santiago, Chile and Mexico City, Mexico. Int. J. Epidemiol. 37, 796–804.

Benson, C., 2004. Macroeconomic concepts of vulnerability: dynamics, complexity and public policy. Earthscan Publishers, London.

Benzie, M., Harvey, A., Burningham, K., Hodgson, N., Siddiqi, A., 2011. Vulnerability to heatwaves and drought: case studies of adaptation to climate change in south-west England. Joseph Rowntree Found. York.

Birkmann, J., 2006. Measuring Vulnerability to Natural Hazards: Towards Disaster Resilient Societies. United Nations University Press, Tokyo ; New York.

Birkmann, J., 2005. Measuring Vulnerability - Expert Workshop in Kobe, UHU-EHS Working Paper. UHU-EHS, Bonn.

Birkmann, J., Flacke, J., 2006. Monitoring und Controlling einer nachhaltigen Raumentwicklung–Indikatoren als Werkzeuge im Planungsprozess. Berichte Zur Dtsch. Landeskd. 80, 485.

Bjornas, C., 2015. A guide to Representative Concentration Pathways.

Blaikie, P., 2004. At risk: natural hazards, people's vulnerability and disasters. Routledge.

Blaikie, P., Cannon, T., Davis, I., Wisner, B., 1994. At risk. Nat. Hazards People's Vulnerability Disasters.

Blesl, M., 2002. Räumlich hoch aufgelöste Modellierung leitungsgebundener Energieversorgungssysteme zur Deckung des Niedertemperaturwärmebedarfs.

Bluemap.de, 2014. HVV Network [website]. URL http://www.hvv.de/pdf/plaene/hvv_geoplan_gesamt.pdf (accessed 7.19.16).

Boeing, G., Church, D., Hubbard, H., Mickens, J., Rudis, L., 2014. LEED-ND and Livability Revisited. Berkeley Plan. J. 27.

Bogard, W.C., 1989. Bringing Social Theory to Hazards Research Conditions and Consequences of the Mitigation of Environmental Hazards. Sociol. Perspect. 31, 147–168.

Bohle, H.G., Downing, T.E., Watts, M.J., 1994. Climate change and social vulnerability: toward a sociology and geography of food insecurity. Glob. Environ. Change 4, 37–48.

Böhm, R., 1998. Urban bias in temperature time series–A case study for the city of Vienna, Austria. Clim. Change 38, 113–128.

Bojariu, R., Wendlová, V., Cica, R.-D., 2014. Changing risks in changing climate (SeeRisk Report). Budapest, Hungary.

Bolin, R., Stanford, L., 1998. The Northridge Earthquake: Community-based Approaches to Unmet Recovery Needs. Disasters 22, 21–38.

Bosselmann, P., Arens, E., Dunker, K., Wright, R., 1995. Urban form and climate: case study, Toronto. J. Am. Plann. Assoc. 61, 226–239.

Bourbia, F., Awbi, H.B., 2004. Building cluster and shading in urban canyon for hot dry climate: Part 1: Air and surface temperature measurements. Renew. Energy 29, 249–262.

Braga, A.L., Zanobetti, A., Schwartz, J., 2002. The effect of weather on respiratory and cardiovascular deaths in 12 US cities. Environ. Health Perspect. 110, 859.

Brazel, A.J., Fernando, H.J.S., Hunt, J.C.R., Selover, N., Hedquist, B.C., Pardyjak, E., 2005. Evening transition observations in Phoenix, Arizona. J. Appl. Meteorol. 44, 99–112.

Breheny, M., 1992. The Compact City: An Introduction. Built Environ. 18.

Brooks, N., 2003. Vulnerability, risk and adaptation: A conceptual framework. Tyndall Cent. Clim. Change Res. Work. Pap. 38, 1–16.

Brooks, N., Adger, W.N., 2003. Country level risk measures of climate-related natural disasters and implications for adaptation to climate change. Tyndall Centre for Climate Change Research Norwich.

Bruegmann, R., 2006. Sprawl: A Compact History. University Of Chicago Press.

Bryant, C.D., 2003. Handbook of death and dying. Sage Publications.

Buckle, P., Mars, G., Smale, S., others, 2000. New approaches to assessing vulnerability and resilience. Aust. J. Emerg. Manag. 15, 8.

Burgess, E.W., 1925. The growth of the city in Park, RE, Burgess EW and McKenzie RD (eds), The city. Chicago: University of Chicago Press.

Burgess, R., Jenks, M., 2002. Compact cities: Sustainable urban forms for developing countries. Routledge.

Burton, I., Huq, S., Lim, B., Pilifosova, O., Schipper, E.L., 2002. From impacts assessment to adaptation priorities: the shaping of adaptation policy. Clim. Policy 2, 145–159.

Burton, I., Kates, R.W., White, G.F., 1993. The Environment as Hazard. N. Y. Guilford Press.

Büttner, K., Jensen, C., 1938. Physikalische bioklimatologie: Probleme und methoden. Akademische Verlag.

Cadwallader, M., 1995. Urban Geography: An Analytical Approach, 1 edition. ed. Prentice Hall, Upper Saddle River, N.J.

Cannon, T., 1994. Vulnerability analysis and the explanation of "natural"disasters. Disasters Dev. Environ. 13–30.

Cardona, O.D., 2004. The need for rethinking the concepts of vulnerability and risk from a holistic perspective: a necessary review and criticism for effective risk management. Mapp. Vulnerability Disasters Dev. People 17.

Carpenter, S., Walker, B., Anderies, J.M., Abel, N., 2001. From metaphor to measurement: resilience of what to what? Ecosystems 4, 765–781.

Carter, T.R., Mäkinen, K, 2011. Approaches to climate change impact, adaptation and vulnerability assessment: towards a classification framework to serve decition-making. MEDIATION Technical Report No. 2.1. Finnish Environment Institute (SYKE), Helsinki, Finland.

Chambers, R., 1989. Editorial Introduction: Vulnerability, Coping and Policy. IDS Bull. 20, 1–7. doi:10.1111/j.1759-5436.1989.mp20002001.x

Chandler, T.., 1965. The climate of London. London: Hutchinson, 292 pp. Prog. Phys. Geogr. 33, 437–442. doi:10.1177/0309133309339794

Chandler, T.J., 1960. Wind as a factor of urban temperatures - a survey in North East London. Weather 15, 204–213.

Chang, C.H., Goh, K.C., 1999. The relationship between height to width ratios and the heat island intensity at 22: 00 h for Singapore.

Chase, T.N., Pielke Sr, R.A., Kittel, T.G.F., Nemani, R.R., Running, S.W., 2000. Simulated impacts of historical land cover changes on global climate in northern winter. Clim. Dyn. 16, 93–105.

Chaudhry, Q. uz Z., Rasul, G., Kamal, A., Mangrio, M.A., Mahmood, S., 2015. Technical Report on Karachi Heat wave June 2015. Government of Pakistan, Ministry of Climate Change.

Cheng, C.S., Campbell, M., Li, Q., Li, G., Auld, H., Day, N., Pengelly, D., Gingrich, S., Klaassen, J., MacIver, D., others, 2008. Differential and combined impacts of extreme temperatures and air pollution on human mortality in south–central Canada. Part II: future estimates. Air Qual. Atmosphere Health 1, 223–235.

Clarke, K.C., Gaydos, L.J., 1998. Loose-coupling a cellular automaton model and GIS: long-term urban growth prediction for San Francisco and Washington/Baltimore. Int. J. Geogr. Inf. Sci. 12, 699–714.

Couclelis, H., 1997. From cellular automata to urban models: new principles for model development and implementation. Environ. Plan. B 24, 165–174.

CRED, 2014. Database | EM-DAT [website]. URL http://www.emdat.be/database (accessed 1.22.14).

Crichton, D., 1999. The Risk Triangle. Nat. Disaster Manag. 102–103.

Cross, J.A., 2001. Megacities and small towns: different perspectives on hazard vulnerability. Glob. Environ. Change Part B Environ. Hazards 3, 63–80.

Curdes, G., 1993. Spatial organisation of towns at the level of the smallest urban unit: plots and buildings. 1993 Urban Landsc. Dyn. Multi-Level Innov. Process Avebury Aldershot 281–94.

Curriero, F.C., Heiner, K.S., Samet, J.M., Zeger, S.L., Strug, L., Patz, J.A., 2002. Temperature and Mortality in 11 Cities of the Eastern United States. Am. J. Epidemiol. 155, 80–87. doi:10.1093/aje/155.1.80

Cutter, S.L., 2006. Hazards Vulnerability and Environmental Justice. Routledge, London.

Cutter, S.L., 1996. Vulnerability to environmental hazards. Prog. Hum. Geogr. 20, 529–539.

Cutter, S.L., 1993. Living with risk: the geography of technological hazards. Edward Arnold London.

Cutter, S.L., Boruff, B.J., Shirley, W.L., 2003. Social vulnerability to environmental hazards. Soc. Sci. Q. 84, 242–261.

Cutter, S.L., Boruff, B.J., Shirley, W.L., 2001. "'Indicators of Social Vulnerability to Hazards.'" Unpublished paper.

Cutter, S.L., Mitchell, J.T., Scott, M.S., 1997. Handbook for conducting a GIS-based hazards assessment at the county level. Univ. S. C. Columbia SC.

Cutter, S.L., Solecki, W.D., 1989. The national pattern of airborne toxic releases. Prof. Geogr. 41, 149–161.

Daneke, C., 2013. Modellierung von Stadtentwicklungsprozessen am Fallbeispiel Hamburg: unter Berücksichtigung stadtklimatologischer Aspekte.

Daneke, C., Bechtel, B., Böhner, J., Langkamp, T., Oßenbrügge, J., 2011. Conceptual Approach to Measure the Potential of Urban Heat Islands from Landuse Datasets and Landuse Projections, in: Murgante, B., Gervasi, O., Iglesias, A., Taniar, D., Apduhan, B.O. (Eds.), Computational Science and Its Applications - ICCSA 2011, Lecture Notes in Computer Science. Springer Berlin Heidelberg, pp. 381–393.

Daneke, C., Ossenbrügge, J., 2012. Evaluating axial growth in Hamburg using a Cellular Automata Model and landscape metrics, in: Planning Support Tools: Policy Analysis, Implementation and Evaluation. Presented at the 7th International Conference on Informatics and Urban Regional Planning INPUT 2012, Francoangeli, Caglari, Italy, pp. 659–670.

Dantzig, G.B., Saaty, T.L., 1974. Compact City: A Plan for a Liveable Urban Environment. W.H.Freeman & Co Ltd, San Francisco.

Davis, G., 2002. Scenarios as a Tool for the 21st Century, in: Probing the Future Conference, Strathclyde University, Glasgow, Scotland.

Davis, R.E., Knappenberger, P.C., Novicoff, W.M., Michaels, P.J., 2003. Decadal changes in summer mortality in US cities. Int. J. Biometeorol. 47, 166–175.

Davis, R.E., Knappenberger, P.C., Novicoff, W.M., Michaels, P.J., 2002. Decadal changes in heat-related human mortality in the eastern United States. Clim. Res. 22, 175–184.

Dawson, R.J., Hall, J.W., Barr, S.L., Batty, M., Bristow, A.L., Carney, S., Dagoumas, A., Evans, S., Ford, A., Harwatt, H., others, 2009. A blueprint for the integrated assessment of climate change in cities. Tyndall Cent. Clim. Change Res. Work. Pap. 129.

de Chenay, C., 2003. Les industries quittent aussi l'Ile de France. Le Monde.

De Sherbinin, A., Schiller, A., Pulsipher, A., 2007. The vulnerability of global cities to climate hazards. Environ. Urban. 19, 39–64.

Dessai, S., 2003. Heat stress and mortality in Lisbon Part II. An assessment of the potential impacts of climate change. Int. J. Biometeorol. 48, 37–44.

DG Environment, European Commission, 2011. Methods for the Improvement of Vulnerability Assessment in Europe, Project MOVE. European Comission.

DG Environment, European Commission, 2007. EC DGEnv European Commission, DG Environment (2007).Water Scarcity and Droughts. In - depth assessment, Second Interim report. European Comission.

Dodge, Y., Cox, D., Commenges, D., Solomon, P.J., Wilson, S., others, 2003. The Oxford dictionary of statistical terms. Oxford University Press.

Dousset, B., Gourmelon, F., Laaidi, K., Zeghnoun, A., Giraudet, E., Bretin, P., Mauri, E., Vandentorren, S.,

2011. Satellite monitoring of summer heat waves in the Paris metropolitan area. Int. J. Climatol. 31, 313–323.

Dow, K., 1992. Exploring differences in our common future (s): the meaning of vulnerability to global environmental change. Geoforum 23, 417–436.

Dow, K., Downing, T.E., 1995. Vulnerability research: where things stand. National Emergency Training Center.

Downing, T., 2004. What have we learned regarding a vulnerability science, in: Science in Support of Adaptation to Climate Change. Recommendations for an Adaptation Science Agenda and a Collection of Papers Presented at a Side Event of the 10th Session of the Conference of the Parties to the United Nations Framework Convention on Climate Change, Buenos Aires. pp. 18–21.

Downing, T.E., 1991. Vulnerability to hunger and coping with climate change in Africa. Glob. Environ. Change 1, 365–380.

Downing, T.E., Patwardhan, A., Mukhala, E., Stephen, L., Winograd, M., Ziervogel, G., 2003. Vulnerability assessment for climate adaptation. Adapt. Policy Framew. Guide Policies Facil. Adapt. Clim. Change UNDP.

Duncan, O.D., Lieberson, S., 1959. Ethnic segregation and assimilation. Am. J. Sociol. 364–374.

DWD, 2016. Deutscher Wetterdienst - Glossary [website]. URL http://www.dwd.de/DE/service/lexikon/Functions/glossar.html?lv2=102672&lv3=102802 (accessed 10.4.16).

Eakin, H., Luers, A.L., 2006. Assessing the vulnerability of social-environmental systems. Annu. Rev. Environ. Resour. 31, 365.

EEA, 2017. European Climate Adaptation Platform [website]. Eur. Clim. Adapt. Platf. URL http://climate-adapt.eea.europa.eu/knowledge/adaptation-information/adaptation-measures (accessed 2.21.17).

EEA, 2016. Urban soil sealing in Europe [website]. URL http://www.eea.europa.eu/articles/urban-soil-sealing-in-europe (accessed 7.21.16).

EEA, 2013. Cities of the future — how will European cities adapt to new climate conditions? — European Environment Agency [website]. URL http://www.eea.europa.eu/articles/cities-of-the-future-2013-how-will-european-cities-adapt-to-new-climate-conditions (accessed 7.11.16).

EEA, 2008. Impacts of Europe’s changing climate - 2008 indicator-based assessment (No. EEA Report No 4/2008).

EEA, 2004. Criteria for the Selection of the EEA Core Set of Indicators. EEA.

EEA, O., 2009. Water resources across Europe—confronting water scarcity and drought (EEA Report No. 2). Eur. Environ. Agency EEA Off. Off. Publ. Eur. Communities OPOCE Cph. Den.

Eicher, C.L., Brewer, C.A., 2001. Dasymetric mapping and areal interpolation: implementation and evaluation. Cartogr. Geogr. Inf. Sci. 28, 125–138.

Ellefsen, R., 1991. Mapping and measuring buildings in the canopy boundary layer in ten US cities. Energy Build. 16, 1025–1049.

Engelen, G., Geertman, S., Smits, P., Wessels, C., 1999. Dynamic GIS and strategic physical planning support: a practical application, in: Geographical Information and Planning. Springer, pp. 87–111.

Erell, E., Pearlmutter, D., Williamson, T., 2012. Urban microclimate: designing the spaces between buildings. Routledge.

Erhorn-Kluttig, H., Jank, R., Schrempf, L., Dütz, A., Rumpel, F., Schrade, J., Erhorn, H., Beier, C., Sager, C., Schmidt, D., 2011. Energetische Quartiersplanung. Fraunhofer IRB Verlag, Stuttgart.

ETC-CCA, 2016 [website]. URL http://cca.eionet.europa.eu/ (accessed 6.27.16).

Fan, H., Sailor, D.J., 2005. Modeling the impacts of anthropogenic heating on the urban climate of Philadelphia: a comparison of implementations in two PBL schemes. Atmos. Environ. 39, 73–84.

Fanger, P.O., 1972. Thermal comfort analysis and applications in environment engineering. McGraw Hill New York.

FAO, U., 1999. Terminology for Integrated Resources Planning and Management. Food Agric. Organ. Nations Environ. Programme Rome ItalyNairobi Kenia.

Field, C.B., Barros, V.R., Mastrandrea, M.D., Mach, K.J., Abdrabo, M.-K., Adger, N., Anokhin, Y.A., Anisimov, O.A., Arent, D.J., Barnett, J., others, 2014. Summary for policymakers. Clim. Change 2014 Impacts Adapt. Vulnerability Part Glob. Sect. Asp. Contrib. Work. Group II Fifth Assess. Rep. Intergov. Panel Clim. Change 1–32.

Florida, R., 2002. Bohemia and economic geography. J. Econ. Geogr. 2, 55–71. doi:10.1093/jeg/2.1.55

Foley, J.A., DeFries, R., Asner, G.P., Barford, C., Bonan, G., Carpenter, S.R., Chapin, F.S., Coe, M.T., Daily, G.C., Gibbs, H.K., 2005. Global consequences of land use. science 309, 570–574.

Freeman, P., Warner, K., 2001. Vulnerability of infrastructure to climate variability: how does this affect infrastructure lending policies? World Bank, Disaster Management Facility, ProVention Consortium.

Freudenberg, M., 2003. Composite Indicators of Country Performance.

Fritzsche, A.F., 1992. Severe Accidents: Can They Occur Only in the Nuclear Production of Electricity? Risk Anal. 12, 327–329.

Füssel, H.-M., 2005. Vulnerability in climate change research: a comprehensive conceptual framework. Univ. Calif. Breslauer Symphosium.

Füssel, H.-M., Klein, R.J.T., 2006. Climate Change Vulnerability Assessments: An Evolution of Conceptual Thinking. Clim. Change 75, 301–329. doi:10.1007/s10584-006-0329-3

Gabaix, X., 1999. Zipf's law for cities: an explanation. Q. J. Econ. 739–767.

Gabor, T., Griffith, T.K., 1980. The assessment of community vulnerability to acute hazardous materials incidents. J. Hazard. Mater. 3, 323–333.

Gagge, A.P., 1971. An effective temperature scale based on a simple model of human physiological regulatory response. Ashrae Trans 77, 247–262.

Gallopin, G.C., 1997. Indicators and their use: information for decision-making. SCOPE-Sci. Comm. Probl. Environ. Int. Counc. Sci. UNIONS 58, 13–27.

Gencer, E.A., 2013a. Natural disasters, urban vulnerability, and risk management: a theoretical overview, in: The Interplay between Urban Development, Vulnerability, and Risk Management. Springer, pp. 7–43.

Gencer, E.A., 2013b. Natural Disasters, Urban Vulnerability, and Risk Management: A Theoretical Overview, in: The Interplay between Urban Development, Vulnerability, and Risk Management, SpringerBriefs in Environment, Security, Development and Peace. Springer Berlin Heidelberg, pp. 7–43. doi:10.1007/978-3-642-29470-9_2

German Environmental Ministry, 2016. Umweltbundesamt - Glossar [website]. Umweltbundesamt. URL http://www.umweltbundesamt.de/service/glossar (accessed 10.4.16).

Ghiaus, C., Allard, F., Santamouris, M., Georgakis, C., Nicol, F., 2006. Urban environment influence on natural ventilation potential. Build. Environ. 41, 395–406.

Gilbert, N., Troitzsch, K., 2005. Simulation for the social scientist. McGraw-Hill International.

Gill, S.E., Handley, J.F., Ennos, A.R., Pauleit, S., 2007. Adapting cities for climate change: the role of the green infrastructure. Built Environ. 33, 115–133.

Gillis, M., Shoup, C., Sicat, G.P., 2001. World development report 2000/2001-attacking poverty. The World Bank.

GIZ, 2014. Vulnerability Sourcebook: Concept and guidelines for standardised vulnerability assessments.

Golden, J.S., 2006. Photovoltaic canopies: thermodynamics to achieve a sustainable systems approach to mitigate the urban heat island hysteresis lag effect. Int. J. Sustain. Energy 25, 1–21.

Goodman, P.G., Dockery, D.W., Clancy, L., 2004. Cause-specific mortality and the extended effects of particulate pollution and temperature exposure. Environ. Health Perspect. 112, 179.

Google, 2014. Google Maps [website]. URL maps.google.com (accessed 11.22.14).

Gosling, S.N., Lowe, J.A., McGregor, G.R., Pelling, M., Malamud, B.D., 2009. Associations between elevated atmospheric temperature and human mortality: a critical review of the literature. Clim. Change 92, 299–341.

Green, C., 2004. The evaluation of vulnerability to flooding. Disaster Prev. Manag. 13, 323–329. doi:10.1108/09653560410556519

Grimmond, C.S.B., 2006. Progress in measuring and observing the urban atmosphere. Theor. Appl. Climatol. 84, 3–22.

Guest, C.S., Willson, K., Woodward, A.J., Hennessy, K., Kalkstein, L.S., Skinner, C., McMichael, A.J., 1999. Climate and mortality in Australia: retrospective study, 1979-1990, and predicted impacts in five major cities in 2030. Clim. Res. 13, 1–15.

Guha-Sapir, D., Hargitt, D., Hoyois, P., 2004. Thirty years of natural disasters 1974-2003: The numbers. Presses univ. de Louvain.

Guzzetti, F., 2000. Landslide fatalities and the evaluation of landslide risk in Italy. Eng. Geol. 58, 89–107.

H. John Heinz III Center for Science Econ, White, G.F., 2000. The Hidden Costs of Coastal Hazards: Implications for Risk Assessment and Mitigation. Island Pr, Washington, D.C.

Hagen, A., 2003. Fuzzy set approach to assessing similarity of categorical maps. Int. J. Geogr. Inf. Sci. 17, 235–249.

Hajat, S., Armstrong, B.G., Gouveia, N., Wilkinson, P., 2005. Hajat. Epidemiology 16, 613–620. doi:10.1097/01.ede.0000164559.41092.2a

Hajat, S., Kosatky, T., 2010. Heat-related mortality: a review and exploration of heterogeneity. J. Epidemiol. Community Health 64, 753–760. doi:10.1136/jech.2009.087999

Hajat, S., Kovats, R.S., Atkinson, R.W., Haines, A., 2002. Impact of hot temperatures on death in London: a time series approach. J. Epidemiol. Community Health 56, 367–372.

Hajat, S., Kovats, R.S., Lachowycz, K., 2007. Heat-related and cold-related deaths in England and Wales: who is at risk? Occup. Environ. Med. 64, 93–100. doi:10.1136/oem.2006.029017

Hall, P., 1975. Urban and Regional Planning, 1 edition. ed. Pelican Books, Middlesex, England.

Hall, T., Barrett, H., 2012. Urban Geography, 4 edition. ed. Routledge, Milton Park, Abingdon, Oxon ; New York.

Hamburg.de, 2015. Flüchtlinge der Unterbringung in Hamburg [website]. Flüchtlinge Unterbring. Hambg. URL http://www.hamburg.de/fluechtlinge-unterbringung-standorte/

Hardi, P., ZDAN, T., 1997. Measurement and indicators program of the international institute for sustainable development. SCOPE-Sci. Comm. Probl. Environ. Int. Counc. Sci. UNIONS 58, 28–32.

Harman, I.N., Best, M.J., Belcher, S.E., 2004. Radiative exchange in an urban street canyon. Bound.-Layer Meteorol. 110, 301–316.

Harvey, A., 2009. Components influencing the vulnerability of European populations to heat waves (unpublished).

Harvey, R.O., Clark, W.A., 1965. The nature and economics of urban sprawl. Land Econ. 41, 1–9.

Hauer, M.E., Evans, J.M., Mishra, D.R., 2016. Millions projected to be at risk from sea-level rise in the continental United States. Nat. Clim. Change advance online publication. doi:10.1038/nclimate2961

Havlick, S.W., 1986. Third World cities at risk: building for calamity. Environ. Sci. Policy Sustain. Dev. 28, 6–45.

Hayhoe, K., Cayan, D., Field, C.B., Frumhoff, P.C., Maurer, E.P., Miller, N.L., Moser, S.C., Schneider, S.H., Cahill, K.N., Cleland, E.E., others, 2004. Emissions pathways, climate change, and impacts on California. Proc. Natl. Acad. Sci. U. S. A. 101, 12422–12427.

Hewitt, K., 1997. Regions of Risk: A Geographical Introduction to Disasters, 1 edition. ed. Routledge, Harlow.

Hewitt, K., Burton, I., 1971. Hazardousness of a place: a regional ecology of damaging events.

Hijmans, R.J., Cameron, S.E., Parra, J.L., Jones, P.G., Jarvis, A., others, 2005. Very high resolution interpolated climate surfaces for global land areas. Int. J. Climatol. 25, 1965–1978.

Hinkel, J., 2011. "Indicators of vulnerability and adaptive capacity": Towards a clarification of the science–policy interface. Glob. Environ. Change 21, 198–208.

Hinkel, K.M., Nelson, F.E., Klene, A.E., Bell, J.H., 2003. The urban heat island in winter at Barrow, Alaska. Int. J. Climatol. 23, 1889–1905.

Hogan, A.W., Ferrick, M.G., 1998. Observations in nonurban heat islands. J. Appl. Meteorol. 37, 232–236.

Höppe, P., 1999. The physiological equivalent temperature–a universal index for the biometeorological assessment of the thermal environment. Int. J. Biometeorol. 43, 71–75.

Houghton, R.A., Hackler, J.L., Lawrence, K.T., 1999. The US carbon budget: contributions from land-use change. Science 285, 574–578.

Howard, L., 1833. The climate of London: deduced from meteorological observations made in the metropolis and at various places around it. Harvey and Darton, J. and A. Arch, Longman, Hatchard, S. Highley [and] R. Hunter.

Huang, C., Barnett, A.G., Wang, X., Vaneckova, P., FitzGerald, G., Tong, S., 2011. Projecting future heat-related mortality under climate change scenarios: a systematic review. NIEHS, Detroit.

Hunt, A., Watkiss, P., 2013. Costs and Benefits for Adaptation: Health Sector Application in the Context of Heatwave risks.

IFRC, 1999. Vulnerability and Capacity Assessment. An International Federation Guide.

International Organization for Standardization, 2002. Risk management. Vocabulary. Guidelines for Use in Standards. Guide 73:2002. Geneva, Switzerland.

IPCC, 2014a. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panal on Climate Change. Geneva, Switzerland.

IPCC, 2014b. Climate Change 2013 - The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, New York.

IPCC, 2013. Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fith Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, UK ; New York, NY.

IPCC, 2007. Climate Change 2007 - Impacts, Adaptation and Vulnerability: Working Group II contribution to the Fourth Assessment Report of the IPCC, Auflage: 1 Pap/Cdr. ed. Cambridge University Press, Cambridge, U.K. ; New York.

ISDR, U., 2005. Hyogo framework for action 2005-2015: building the resilience of nations and communities to disasters, in: Extract from the Final Report of the World Conference on Disaster Reduction (A/CONF. 206/6).

Ishigami, A., Hajat, S., Kovats, R.S., Bisanti, L., Rognoni, M., Russo, A., Paldy, A., 2008. An ecological time-series study of heat-related mortality in three European cities. Environ. Health 7, 5. doi:10.1186/1476-069X-7-5

Isoard, S., 2010. Perspectives on Adaptation to Climate Change in Europe 51–68. doi:10.1007/978-94-007-0567-8_4

Isoard, S., Grothmann, T., Zebisch, M., 2008. Climate change impacts, vulnerability and adaptation: Theory and concepts, in: Workshop'Climate Change Impacts and Adaptation in the European Alps: Focus Water', UBA Vienna.

Jackson, J.E., Yost, M.G., Karr, C., Fitzpatrick, C., Lamb, B.K., Chung, S.H., Chen, J., Avise, J., Rosenblatt, R.A., Fenske, R.A., 2010. Public health impacts of climate change in Washington State: projected mortality risks due to heat events and air pollution. Clim. Change 102, 159–186.

Jacob Cohen, 1960. A Coefficient of Agreement for Nominal Scales. Educ. Psychol. Meas. Vol. 20, 37–46. doi:10.1177/001316446002000104

Jacobs, R., Smith, P. (Peter C.), Goddard, M.K., 2004. Measuring performance: an examination of composite performance indicators: a report for the Department of Health. Centre of Health Economics, University of York.

Jauregui, E., 1997. Heat island development in Mexico City. Atmos. Environ. 31, 3821–3831.

Jendritzky, G., Sönning, W., Swantes, H.J., 1979. Ein objektives Bewertungsverfahren zur Beschreibung des thermischen Milieus in der Stadt-und Landschaftsplanung (" Klima-Michel-Modell"). Schroedel.

Jones R, Boer R, 2003. Assessing current climate risks Adaptation Policy Framework: A Guide for Policies to Facilitate Adaptation to Climate Change.

Kalensky, Z.D., Latham, J.S., Claase, R. van D., 2002. Land cover mapping at global and regional levels. Backgr. Pap. Expert Consult. Strateg. Land Cover Mapp. Monit. Artimino Italy 6-8 May.

Kalkstein, L.S., Davis, R.E., 1989. Weather and Human Mortality: An Evaluation of Demographic and Interregional Responses in the United States. Ann. Assoc. Am. Geogr. 79, 44–64. doi:10.1111/j.1467-8306.1989.tb00249.x

Kasperson, J.X., Kasperson, R.E., Turner, B.L., 1995. Regions at risk: comparisons of threatened environments. U. N. Univ. Tokyo.

Kasperson, R.E., Kasperson, J.X., Turner, B.L., Dow, K., Meyer, W.B., others, 1995. Critical environmental regions: concepts distinctions and issues.

Kasperson, R.E., Turner, B.L., Schiller, A., Hsieh, W.H., 2002. Research and assessment systems for sustainability: Framework for vulnerability, in: AIACC Project Development Workshop on Climate Change Vulnerability and Adaptation, Trieste, Italy. pp. 3–14.

Kates, R.W., 1985. The interaction of climate and society. SCOPE.

Kaveckis, G., Bechtel, B., Pohl, T., Ossenbrügge, J., 2017. Land use modelling as new approach for future hazard-sensitive population mapping in Northern Germany, in: Planning for Community-Based Disaster Resilience Worldwide: Learning from Case Studies in Six Continents. Routledge, p. 470.

Kazmierczak, A., 2012. Heat and social vulnerability in Greater Manchester: a risk-response case study. EcoCities Univ. Manch.

Keatinge, W.R., Donaldson, G.C., Cordioli, E., Martinelli, M., Kunst, A.E., Mackenbach, J.P., Nayha, S., Vuori, I., 2000. Heat related mortality in warm and cold regions of Europe: observational study. BMJ 321, 670–673. doi:10.1136/bmj.321.7262.670

Kelly, P.M., Adger, W.N., 2000. Theory and practice in assessing vulnerability to climate change andFacilitating adaptation. Clim. Change 47, 325–352.

Kikegawa, Y., Genchi, Y., Kondo, H., Hanaki, K., 2006. Impacts of city-block-scale countermeasures against urban heat-island phenomena upon a building's energy-consumption for air-conditioning. Appl. Energy 83, 649–668.

Kim, Y.-H., Baik, J.-J., 2005. Spatial and temporal structure of the urban heat island in Seoul. J. Appl. Meteorol. 44, 591–605.

Kinney, P.L., O'Neill, M.S., Bell, M.L., Schwartz, J., 2008. Approaches for estimating effects of climate change on heat-related deaths: challenges and opportunities. Environ. Sci. Policy 11, 87–96.

Klein, R.J.T., Nicholls, R.J., 1999. Assessment of Coastal Vulnerability to Climate Change. Ambio 28, 182–187.

Klinenberg, E., 2015. Heat wave: A social autopsy of disaster in Chicago. University of Chicago Press.

Klugman, J., 2002. A Sourcebook for Poverty Reduction Strategies: Volume 2: Macroeconomic and Sectoral Approaches. World Bank.

Knowlton, K., Lynn, B., Goldberg, R.A., Rosenzweig, C., Hogrefe, C., Rosenthal, J.K., Kinney, P.L., 2007. Projecting heat-related mortality impacts under a changing climate in the New York City region. Am. J. Public Health 97, 2028–2034.

Knox, P., Pinch, S., 2000. Urban Social Geography: An Introduction, 4th Edition. ed. Prentice Hall.

Kropp, J., Holsten, A., Lissner, T., Roithmeier, O., Hattermann, F., Huang, S., Rock, J., Wechsung, F., Lüttger, A., Pompe, S., others, 2009. „Klimawandel in Nordrhein-Westfalen–Regionale Abschätzung der Anfälligkeit ausgewählter Sektoren ". Abschlussbericht Potsdam-Inst. Für Klimafolgenforschung PIK Für Minist. Für Umw. Naturschutz Landwirtsch. Verbraucherschutz Nordrh.-Westfal. MUNLV Potsdam Kylaars K2010 Umweltamt Stadt Duisburg Unveröff.

Kumar, S., Prasad, T., Sashidharan, N.V., Nair, S.K., 2001. Heat island intensities over Brihan Mumbai on a cold winter and hot summer night. Mausam 52, 703–708.

Kunst, A.E., Looman, C.W.N., Mackenbach, J.P., 1993. Outdoor Air Temperature and Mortality in the Netherlands: A Time-Series Analysis. Am. J. Epidemiol. 137, 331–341.

Kusaka, H., Kimura, F., 2004. Thermal effects of urban canyon structure on the nocturnal heat island: Numerical experiment using a mesoscale model coupled with an urban canopy model. J. Appl. Meteorol. 43, 1899–1910.

Kuttler, W., 2008. The urban climate–basic and applied aspects, in: Urban Ecology. Springer, pp. 233–248.

Kuznetsova, I.N., Khaikin, M.N., Kadygrov, E.N., 2004. Urban effect on the atmospheric boundary layer temperature from microwave measurements in Moscow and its suburbs. Izv. Atmospheric Ocean. Phys. 40, 607–616.

Lagouarde, J.-P., Moreau, P., Irvine, M., Bonnefond, J.-M., Voogt, J.A., Solliec, F., 2004. Airborne experimental measurements of the angular variations in surface temperature over urban areas: case study of Marseille (France). Remote Sens. Environ. 93, 443–462.

Lambin, E.F., Turner, B.L., Geist, H.J., Agbola, S.B., Angelsen, A., Bruce, J.W., Coomes, O.T., Dirzo, R., Fischer, G., Folke, C., others, 2001. The causes of land-use and land-cover change: moving beyond the myths. Glob. Environ. Change 11, 261–269.

Landesamt für Statistik Niedersachsen, 2015. Lebendgeborene, Gestorbene und Wanderungssaldo von 2014 bis 2060. 13. koordinierte Bevölkerungsvorausberechnung in Niedersachsen (Statistical report). Hamburg, Germany.

Landesamt für Statistik Niedersachsen, 2011. Bevölkerungsbewegungen während des Vorausberechnungszeitraumes in den kreisfreien Städten und Landkreisen Niedersachsens (Statistical report). Hamburg, Germany.

Landsberg, H.E., 1981. The urban climate. Academic press.

Langford, M., 2006. Obtaining population estimates in non-census reporting zones: An evaluation of the 3-class dasymetric method. Comput. Environ. Urban Syst. 30, 161–180.

Lavoie, C., Lachance, D., 2006. A new herbarium-based method for reconstructing the phenology of plant species across large areas. Am. J. Bot. 93, 512–516.

Lemonsu, A., Pigeon, G., Masson, V., Moppert, C., 2006. Sea-town interactions over Marseille: 3D urban boundary layer and thermodynamic fields near the surface. Theor. Appl. Climatol. 84, 171–178.

Lenzholzer, S., 2015. Weather in the City-How Design Shapes the Urban Climate. Nai 010 Uitgevers/Publishers.

Lewis, J., 1999. Development in disaster-prone places: studies of vulnerability. Intermediate Technology London.

Lewis, J., 1997. Development, vulnerability and disaster reduction: Bangladesh cyclone shelter projects and their implications, in: Reconstruction after Disaster: Issues and Practices. Ashgate Publishing, pp. 45–56.

Ley, D., 1983. A social geography of the city. Harper & Row New York.

Li, T., Pullar, D., Corcoran, J., Stimson, R., 2007. A comparison of spatial disaggregation techniques as applied to population estimation for South East Queensland (SEQ), Australia. Appl. GIS 3, 1–16.

Lissner, T.K., Holsten, A., Walther, C., Kropp, J.P., 2012. Towards sectoral and standardised vulnerability assessments: the example of heatwave impacts on human health. Clim. Change 112, 687–708. doi:10.1007/s10584-011-0231-5

Livada, I., Santamouris, M., Niachou, K., Papanikolaou, N., Mihalakakou, G., 2002. Determination of places in the great Athens area where the heat island effect is observed. Theor. Appl. Climatol. 71, 219–230.

Liverman, D.M., 1990. Vulnerability to global environmental change. Underst. Glob. Environ. Change Contrib. Risk Anal. Manag. 27–44.

Loveland, T.R., Zhu, Z., Ohlen, D.O., Brown, J.F., Reed, B.C., Yang, L., 1999. An analysis of the IGBP global land-cover characterization process. Photogramm. Eng. Remote Sens. 65, 1021–1032.

Luers, A.L., Lobell, D.B., Sklar, L.S., Addams, C.L., Matson, P.A., 2003. A method for quantifying vulnerability, applied to the agricultural system of the Yaqui Valley, Mexico. Glob. Environ. Change 13, 255–267.

Magee, N., Curtis, J., Wendler, G., 1999. The urban heat island effect at Fairbanks, Alaska. Theor. Appl. Climatol. 64, 39–47.

Malik, A., Qin, X., Smith, S.C., 2010. Autonomous adaptation to climate change: A literature review. Prelim. Draft Washinton DC Elliott Sch. Int. Aff.

Malte-Brun, V.A., 1880. Plan de Hamburg.

Matthies, A., Schartner, T., Leckebusch, G.C., Rohlfing, G., Névir, P., Ulbrich, U., 2008. Extreme weather events in southern Germany–Climatological risk and development of a nowcasting procedure, in: Geophys. Res. Abstr.

Matzarakis, A., Mayer, H., Iziomon, M.G., 1999. Applications of a universal thermal index: physiological equivalent temperature. Int. J. Biometeorol. 43, 76–84.

Mayer, H., 1993. Urban bioclimatology. Cell. Mol. Life Sci. 49, 957–963.

Mayer, H., Höppe, P., 1987. Thermal comfort of man in different urban environments. Theor. Appl. Climatol. 38, 43–49.

McCarthy, J.J., 2001a. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

McCarthy, J.J., 2001b. Climate change 2001: impacts, adaptation, and vulnerability: contribution of Working Group II to the third assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

McMichael, A.J., Wilkinson, P., Kovats, R.S., Pattenden, S., Hajat, S., Armstrong, B., Vajanapoom, N., Niciu, E.M., Mahomed, H., Kingkeow, C., others, 2008. International study of temperature, heat and urban mortality: the “ISOTHURM”project. Int. J. Epidemiol. 37, 1121–1131.

Melhuish, E., Pedder, M., 1998. Observing an urban heat island by bicycle. Weather 53, 121–128. doi:10.1002/j.1477-8696.1998.tb03974.x

Mennis, J., 2003. Generating Surface Models of Population Using Dasymetric Mapping∗. Prof. Geogr. 55, 31–42.

Mestayer, P.G., Durand, P., Augustin, P., Bastin, S., Bonnefond, J.-M., Bénech, B., Campistron, B., Coppalle, A., Delbarre, H., Dousset, B., others, 2005. The urban boundary-layer field campaign in Marseille (UBL/CLU-ESCOMPTE): set-up and first results. Bound.-Layer Meteorol. 114, 315–365.

Michelson, W., 1976. Man and his urban environment: A sociological approach. Addison-Wesley Reading, MA.

Mietus, M., Filipiak, J., 2004. The temporal and spatial patterns of thermal conditions in the area of the southwestern coast of the Gulf of Gdańsk (Poland) from 1951 to 1998. Int. J. Climatol. 24, 499–509.

Mileti, D., 1999. Disasters by Design:: A Reassessment of Natural Hazards in the United States. Joseph Henry Press.

Mills, G., Cleugh, H., Emmanuel, R., Endlicher, W., Erell, E., McGranahan, G., Ng, E., Nickson, A., Rosenthal, J., Steemer, K., 2010. Climate information for improved planning and management of mega cities (needs perspective). Procedia Environ. Sci. 1, 228–246.

Mitchell, J.K., Devine, N., Jagger, K., 1989. A contextual model of natural hazard. Geogr. Rev. 391–409.

Mitscherlich, A., 1965. Die Unwirtlichkeit unserer Städte: Anstiftung zum Unfrieden. Suhrkamp Frankfurt.

Montavez, J.P., Rodríguez, A., Jiménez, J.I., 2000. A study of the urban heat island of Granada. Int. J. Climatol. 20, 899–911.

Moshammer, H., Hutter, H.P., Gerersdorfer, T., 2009. Einfluss von Adaptationsmassnahmen auf das akutell Sterberisiko in Wien durch Temperaturextreme. Endbericht Von StartClim 2008.

Moss, R.H., Edmonds, J.A., Hibbard, K.A., Manning, M.R., Rose, S.K., van Vuuren, D.P., Carter, T.R., Emori, S., Kainuma, M., Kram, T., Meehl, G.A., Mitchell, J.F.B., Nakicenovic, N., Riahi, K., Smith, S.J., Stouffer, R.J., Thomson, A.M., Weyant, J.P., Wilbanks, T.J., 2010. The next generation of scenarios for climate change research and assessment. Nature 463, 747–756. doi:10.1038/nature08823

Moudon, A.V., 1997. Urban morphology as an emerging interdisciplinary field. Urban Morphol. 1, 3–10.

Murphy, D.J., Hall, M.H., Hall, C.A., Heisler, G.M., Stehman, S.V., Anselmi-Molina, C., 2011. The relationship between land cover and the urban heat island in northeastern Puerto Rico. Int. J. Climatol. 31, 1222–1239.

Musser, L., 2006. Vulnerability bibliography. Presented at the Security Symposium 2002, Citeseer, University of Colorado Boulder.

Mustow, S., 1995. Megacities: Reducing Vulnerability to Natural Disasters. London: Thomas Telford.

Nasrallah, H.A., Brazel, A.J., Balling, R.C., 1990. Analysis of the Kuwait City urban heat island. Int. J. Climatol. 10, 401–405.

Neddermeyer, F.H., 1832. Topographie der Freien und Hanse-Stadt Hamburg.

New Urbanism, 2016. New Urbanism [website]. URL http://www.newurbanism.org/newurbanism/principles.html

Nicholls, Klein, 2000. Some thoughts on impacts and adaptation to climate change in coastal zones, in: Proceeding of Survas Expert Workshop on European Vulnerability and Adaptation to Impacts of Accelerated Sea-Level Rise. Presented at the Survas Expert Workshop on European Vulnerability and Adaptation to impacts of Accelerated Sea-Level Rise, Flood Hazard Research Center, Hamburg, Germany.

NOAA, 2016. What is the difference between land cover and land use? [website]. URL http://oceanservice.noaa.gov/facts/lclu.html (accessed 2.16.16).

NOAA, 2002. Protecting Coastal Communities [website]. URL http://www.csc.noaa.gov/vata/intro2.html (accessed 2.16.16).

Noble, I., Apps, M., Houghton, R., Lashof, D., Makundi, W., Murdiyarso, D., Murray, B., Sombroek, W., Valentini, R., Amano, M., 2000. Implications of different definitions and generic issues. Land Use Land Use Change For. IPCC 2000, 55–126.

O'Brien, K., Eriksen, S., Schjolden, A., Nygaard, L., 2004. What's in a word? Conflicting interpretations of vulnerability in climate change research. Conflicting Percept. Vulnerability Clim. Change Res. CICERO Work. Pap. Oslo CICERO.

O'Brien, K., Eriksen, S., Sygna, L., Naess, L.O., 2006. Questioning complacency: climate change impacts, vulnerability, and adaptation in Norway. AMBIO J. Hum. Environ. 35, 50–56.

OECD and Joint Research Centre, 2008. Handbook on constructing composite indicators: methodology and user guide.

OECD-DAC, 1994. Guidelines for Aid Agencies on Disaster Mitigation. Paris.

Offerle, B., Jonsson, P., Eliasson, I., Grimmond, C.S.B., 2005. Urban modification of the surface energy balance in the West African Sahel: Ouagadougou, Burkina Faso. J. Clim. 18, 3983–3995.

Oke, T.R., 2004. Initial guidance to obtain representative meteorological observations at urban sites. World Meteorological Organization Geneva.

Oke, T.R., 1995. The heat island of the urban boundary layer: characteristics, causes and effects, in: Wind Climate in Cities. Springer, pp. 81–107.

Oke, T.R., 1988. The urban energy balance. Prog. Phys. Geogr. 12, 471–508.

Oke, T.R., 1987. Boundary layer climates. Routledge, London.

Oke, T.R., 1982. The energetic basis of the urban heat island. Q. J. R. Meteorol. Soc. 108, 1–24.

Oke, T.R., 1979. Review of urban climatology. Secretariat of the World Meteorological Organization Geneva.

Oke, T.R., 1977. The significance of the atmosphere in planning human settlements. Ecol. Biophys. Land Classif. Urban Areas Ecol. Land Classif. Ser. 3, 31–41.

Oke, T.R., 1976. The distinction between canopy and boundary-layer urban heat islands. Atmosphere 14, 268–277. doi:10.1080/00046973.1976.9648422

Oke, T.R., 1973. City size and the urban heat island. Atmospheric Environ. 1967 7, 769–779.

Oke, T.R., Johnson, G.T., Steyn, D.G., Watson, I.D., 1991. Simulation of surface urban heat islands under "ideal" conditions at night part 2: Diagnosis of causation. Bound.-Layer Meteorol. 56, 339–358. doi:10.1007/BF00119211

O'Neill, B.C., Kriegler, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2015. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. Glob. Environ. Change. doi:10.1016/j.gloenvcha.2015.01.004

O'Neill, M.S., Zanobetti, A., Schwartz, J., 2005. Disparities by race in heat-related mortality in four US cities: the role of air conditioning prevalence. J. Urban Health 82, 191–197.

Openshaw, S., 1984. Modifiable Areal Unit Problem, The. Geo Bks., Norwich Norfolk.

Oxford University Press, 2015. Oxford Dictionary [website]. URL http://www.oxforddictionaries.com/

Paddison, R., 2001. Handbook of Urban Studies, 1 edition. ed. SAGE Publications Ltd, London ; Thousand Oaks, Calif.

Palecki, M.A., Changnon, S.A., Kunkel, K.E., 2001. The nature and impacts of the July 1999 heat wave in the midwestern United States: learning from the lessons of 1995. Bull. Am. Meteorol. Soc. 82, 1353–1367.

Pannell, D.J., 1997. Sensitivity analysis of normative economic models: theoretical framework and practical strategies. Agric. Econ. 16, 139–152.

Park, H.-S., 1986. Features of the heat island in Seoul and its surrounding cities. Atmospheric Environ. 1967 20, 1859–1866.

Parris, K., Brouwer, E.F., Crabtree, B., others, 1999. Environmental indicators for agriculture: overview in OECD countries. Environ. Indic. Agric. Policy 25–44.

Parris, K.M., Hazell, D.L., 2005. Biotic effects of climate change in urban environments: The case of the grey-headed flying-fox (Pteropus poliocephalus) in Melbourne, Australia. Biol. Conserv. 124, 267–276.

Pavao-Zuckerman, M.A., Coleman, D.C., 2005. Decomposition of chestnut oak (Quercus prinus) leaves and nitrogen mineralization in an urban environment. Biol. Fertil. Soils 41, 343–349.

Pelling, M., Allen, K., 2003. Natural Disaster and Development in a Globalizing World. Psychology Press.

Pijawka, Radwan, 1985. The transportation of hazardous materials: risk assessment and hazard management. (No. 2–11), Dangerous Properties of Industrial Materials Report.

Pitt, M., 2008. The Pitt review: learning lessons from the 2007 floods. Lond. Cabinet Off.

Poumadère, M., Mays, C., Le Mer, S., Blong, R., 2005. The 2003 heat wave in France: dangerous climate change here and now. Risk Anal. Off. Publ. Soc. Risk Anal. 25, 1483–1494. doi:10.1111/j.1539-6924.2005.00694.x

Preston, B.L., Smith, T.., 2008. Mapping climate change vulnerability in the Sydney Coastal Councils Group. CSIRO and Sydney Coastal Councils Group.

Preston, B.L., Stafford-Smith, M., Flagship, C.A., 2009. Framing vulnerability and adaptive capacity assessment: Discussion paper. CSIRO Climate Adaptation National Research Flagship Australia.

Randall, T.A., Churchill, C.J., Baetz, B.W., 2003. A GIS-based decision support system for neighbourhood greening. Environ. Plan. B Plan. Des. 30, 541–563.

Reid, B., 1985. The new urbanism as a way of life: the relationship between inner city revitalization in Canada and the rise of the new middle class.

Research Institute for Knowledge Systems (RIKS), 2012. Metronamica Documentation.

Richard, G., Stevenson, D., Girardet, H., Stren, R., 1996. Making Cities Work: Role of Local Authorities in the Urban Environment. Routledge, Sterling, VA.

RIKS, 2013. Metronamica models and calibration - the Metronamica calibration course material.

RIKS, 2008. Assessment and scenarios of land use change in Europe. Natura 2000 Preparatory Actions, Lot 3: Developing new concepts for integration of the Natura 2000 network into a broader countryside.

Rinner, C., Patychuk, D., Bassil, K., Nasr, S., Gower, S., Campbell, M., 2010. The role of maps in neighborhood-level heat vulnerability assessment for the city of Toronto. Cartogr. Geogr. Inf. Sci. 37, 31–44.

Roaf, S., Crichton, D., Nicol, F., 2009. Adapting buildings and cities for climate change: a 21st century survival guide. Routledge.

Romero Lankao, P., Villafranco, H.L., Huerta, A.R., Gunther, G., Armenta, Z.C., 2005. Can cities reduce global warming. Urban Dev. Carbon Cycle Lat. Am.

Rosenfeld, A.H., Romm, J.J., Akbari, H., Pomerantz, M., Taha, H., 1996. Policies to reduce heat islands: magnitudes of benefits and incentives to achieve them, in: Proceedings of the 1996 ACEEE Summer Study on Energy Efficiency in Buildings. p. 177.

Roth, M., Oke, T.R., Emery, W.J., 1989. Satellite-derived urban heat islands from three coastal cities and the utilization of such data in urban climatology. Int. J. Remote Sens. 10, 1699–1720.

Roth, U., Häubi, F., Albrecht, J., 1980. Wechselwirkungen zwischen des Siedlungsstruktur und Wärmeversorgungssystemen.

Ruth, M., 2006. Smart growth and climate change: Regional development, infrastructure and adaptation. Edward Elgar Publishing.

Rylander, C., Odland, J.Ø., Sandanger, T.M., 2013. Climate change and the potential effects on maternal and pregnancy outcomes: an assessment of the most vulnerable – the mother, fetus, and newborn child. Glob. Health Action 6. doi:10.3402/gha.v6i0.19538

Saffi, P., 2013. People with vulnerabilities in disasters. Environmental scan and hap analysis of projects/programs for people with vulnerabilities in disasters 2013. Government of South Australia.

Santamouris, M., Papanikolaou, N., Livada, I., Koronakis, I., Georgakis, C., Argiriou, A., Assimakopoulos, D.N., 2001. On the impact of urban climate on the energy consumption of buildings. Sol. Energy 70, 201–216.

Sarewitz, D., Pielke Jr, R., 2001. Extreme events: a research and policy framework for disasters in context. Int. Geol. Rev. 43, 406–418.

Sarewitz, D., Pielke, R., Keykhah, M., 2003. Vulnerability and risk: some thoughts from a political and policy perspective. Risk Anal. 23, 805–810.

Sarrat, C., Lemonsu, A., Masson, V., Guedalia, D., 2006. Impact of urban heat island on regional atmospheric pollution. Atmos. Environ. 40, 1743–1758.

Satterthwaite, D., Tacoli, C., 2002. Seeking an understanding of poverty that recognizes rural-urban differences and rural-urban linkages. Urban Livelihoods People Centered Approach Reducing Poverty 52–70.

Scalenghe, R., Marsan, F.A., 2009. The anthropogenic sealing of soils in urban areas. Landsc. Urban Plan. 90, 1–10.

Schauser, I., Otto, S., Schneiderbauer, S., Harvey, A., Hodgson, N., Robrecht, H., Morchain, D., Schrander, J., Khovanskaia, M., Celikyilmaz-Aydemir, G., others, 2010. Urban Regions: Vulnerabilities, Vulnerability Assessments by Indicators and Adaptation Options for Climate Change Impacts. Eur. Top. Cent. Air Clim. Change ETCACC Bilthoven.

Scherer, D., Fehrenbach, U., Lakes, T., Lauf, S., Meier, F., Schuster, C., 2014. Quantification of heat-stress related mortality hazard, vulnerability and risk in Berlin, Germany. ERDE–Journal Geogr. Soc. Berl. 144, 238–259.

Schlünzen, K.H., Hoffmann, P., Rosenhagen, G., Riecke, W., 2010. Long-term changes and regional differences in temperature and precipitation in the metropolitan area of Hamburg. Int. J. Climatol. 30, 1121–1136. doi:10.1002/joc.1968

Schneiderbauer, S., Ehrlich, D., 2004. Risk, hazard and people's vulnerability to natural hazards. Rev. Defin. Concepts Data Eur. Comm. Jt. Res. Cent.

Schroeder, R.A., 1987. Gender vulnerability to drought: a case study of the Hausa social environment.

Shashua-Bar, L., Hoffman, M.E., Tzamir, Y., 2006. Integrated thermal effects of generic built forms and vegetation on the UCL microclimate. Build. Environ. 41, 343–354.

Simister, J., Cooper, C., 2005. Thermal stress in the USA: effects on violence and on employee behaviour. Stress Health 21, 3–15.

Smit, B., Burton, I., Klein, R.J., Street, R., 1999. The science of adaptation: a framework for assessment. Mitig. Adapt. Strateg. Glob. Change 4, 199–213.

Smith, K., 2004. Environmental hazards: assessing risk and reducing disaster. Routledge, London; New York.

Smith, K., 1992. Environmental hazards: assessing risk and reducing disaster. Routledge, London; New York.

Smith, K., Petley, D.N., 2009. Environmental Hazards: Assessing Risk and Reducing Disaster, 00005 ed. Routledge Chapman Hall, Milton Park, Abingdon, Oxon ; New York, NY.

Smoyer, K.E., Rainham, D.G., Hewko, J.N., 2000. Heat-stress-related mortality in five cities in Southern Ontario: 1980–1996. Int. J. Biometeorol. 44, 190–197.

Sofer, M., Potchter, O., 2006. The urban heat island of a city in an arid zone: the case of Eilat, Israel. Theor. Appl. Climatol. 85, 81–88.

Souch, C., Grimmond, C.S.B., 2004. Applied Climatology:"heat waves." Prog. Phys. Geogr. 28, 599–606.

Spronken-Smith, R.A., Oke, T.R., Lowry, W.P., 2000. Advection and the surface energy balance across an irrigated urban park. Int. J. Climatol. 20, 1033–1047.

Stafoggia, M., Forastiere, F., Michelozzi, P., Perucci, C.A., 2009. Summer temperature-related mortality: effect modification by previous winter mortality. Epidemiology 20, 575–583.

Statistisches Amt für Hamburg und Schleswig-Holstein, 2015a. Bevölkerungsenwticklung 2015 bis 2035 in Hamburg. Ergebnisse der 13. koordinierten Bevölkerungsvorausberechnung.

Statistisches Amt für Hamburg und Schleswig-Holstein, 2015b. Bevölkerungsentwicklung 2015 bis 2035 in Schleswig-Holstein. Ergebnisse der 13. koordinierten Bevölkerungsvorausberechnung (Statistical report No. AI8–j15SH). Hamburg, Germany.

Statistisches Amt für Hamburg und Schleswig-Holstein, 2011. Bevölkerungsentwicklung in den Kreisen und Kreisfreien Städten Schleswig-Holsteins bis 2025 (Statistical report No. AI8–2011S). Hamburg, Germany.

Statistisches Amt für Hamburg und Schleswig-Holstein, 2010. Bevölkerungsentwicklung 2010 bis 2030 in Hamburg. Ergebnis der 12. koordinierten Bevölkerungsvorausberechnung (KBV) (Statistical report No. AI8–2010H). Hamburg, Germany.

Steinnocher, K., Kaminger, I., Weichselbaum, J., Köstl, M., 2010. Gridded population - new datasets for an improved disaggregation approach.

Stewart, I.D., 2011. Redefining the urban heat island. PhD Diss.

Stewart, I.D., Oke, T.R., 2012. Local climate zones for urban temperature studies. Bull. Am. Meteorol. Soc. 93, 1879–1900.

Stone Jr, B., Rodgers, M.O., 2001. Urban form and thermal efficiency: how the design of cities influences the urban heat island effect. J. Am. Plann. Assoc. 67, 186–198.

Susan, S., 2007. Climate change 2007-the physical science basis: Working group I contribution to the fourth assessment report of the IPCC. Cambridge University Press.

Susman, P., O'Keefe, P., Wisner, B., 1983. Global disasters, a radical interpretation. Interpret. Calam. 263–283.

Svensson, M.K., Eliasson, I., 2002. Diurnal air temperatures in built-up areas in relation to urban planning. Landsc. Urban Plan. 61, 37–54.

Taha, H., Meier, A., Gao, W., Ojima, T., 1999. Mitigation of urban heat islands: meteorology, energy, and airquality impacts. J. Archit. Plan. Environ. Jpn. 529.

Tan, J., 2008. Commentary: People's vulnerability to heat wave. Int. J. Epidemiol. 37, 318–320.

Thesaurus, 2014. Thesaurus dictionary and encyclopedia [website]. URL http://www.thefreedictionary.com/ (accessed 1.22.14).

Thomsen, H., Mcintosh, C., 2015. Hamburg - Germany [website]. Encycl. Br. URL https://www.britannica.com/place/Hamburg-Germany (accessed 2.10.16).

Tide-forecast, 2016. Tide-forecast [website]. URL http://www.tide-forecast.com/locations/Hamburg-Germany

Timmerman, P., 1981. Vulnerability resilience and collapse ofsociety. Rev. Possible Clim. Appl. Tor. Can. Inst. Environ. Stud. Univ. Tor.

Tobler, W.R., 1979. Cellular geography, in: Philosophy in Geography. D.Reidel Publishing Company, Dordrecht, Netherlands, pp. 379–386.

Tolba, M., El-Kholy, O., 1992. The world environment 1972–1992: Two decades of challenge. Chapman & Hall, London.

Tong, H., Walton, A., Sang, J., Chan, J.C., 2005. Numerical simulation of the urban boundary layer over the complex terrain of Hong Kong. Atmos. Environ. 39, 3549–3563.

Torrens, P.M., O'Sullivan, D., 2000. Cities, cells, and complexity: developing a research agenda for urban geocomputation, in: 5th International Conference on GeoComputation, University of Greenwich, UK.

UNDESA, 2015. World Population Prospects: The 2015 Revision, Key Findings and Advance Tables (Working Paper No. ESA/P/WP.241). New York.

UNDESA, 2014. World Urbanization Prospects: The 2014 Revision, Highlights (Report No. ST/ESA/SER.A/352). United Nations, New York.

UNDESA, 2011. World Population Prospects. The 2010 Revision. United Nations, New York.

UNDRO, 1982. Natural disasters and vulnerability analysis.

UNEP, 2002. African Environmenal Outlook: Past, Present and Future Perspectives. DEWA/UNEP, Nairobi.

UNEP and South Pacific Regional Environment Programme, 1999. Pacific Islands environmental outlook.

Unger, J., 1999. Urban-rural air humidity differences in Szeged, Hungary. Int. J. Climatol. 19, 1509–1515.

UN-Habitat, 2009. Global report on human settlements 2009: Planning sustainable cities. Earthscan: for UN-Habitat.

UN-Habitat, 2003. The challenge of slums: Global report on human settlements 2003. U. N. Hum. Settl. Programme UN Habitat, Earthscan publications 352.

UN/ISDR, 2004. Living with risk: a global review of disaster reduction initiatives. UN Publ.

United Nations, 2014. World Urbanization Prospects 2014: Highlights. United Nations Publications.

United Nations, 2004. Living with Risk: A Global Review of Disaster Reduction Initiatives.

Unwin, D.J., 1980. The synoptic climatology of Birmingham's urban heat island, 1965–74. Weather 35, 43–50.

van Vliet, J., Hagen-Zanker, A., Hurkens, J., van Delden, H., 2013. A fuzzy set approach to assess the predictive accuracy of land use simulations. Ecol. Model. 261, 32–42.

Varley, A., 1994. Disasters, development and environment. J. Wiley.

Verburg, P.H., Schot, P.P., Dijst, M.J., Veldkamp, A., 2004. Land use change modelling: current practice and research priorities. GeoJournal 61, 309–324.

Vogel, C., 1998. Vulnerability and global environmental change. LUCC Newsl. 3, 15–19.

Vogel, C., O'Brien, K., 2004. Vulnerability and global environmental change: rhetoric and reality. Aviso 13, 1–8.

Von Neumann, J., 1951. The general and logical theory of automata. Cereb. Mech. Behav. 1–41.

Voogt, J.A., 2004. Urban heat islands: hotter cities. American Institute of Biological Sciences, Washington, D.C.

Wang, J.X., Gaffen, D.J., 2001. Trends in extremes of surface humidity, temperature, and summertime heat stress in China. Adv. Atmospheric Sci. 18, 742–751.

Ward, S., 2005. The Garden City: Past, present and future. Routledge.

Warmington, V., 1995. Disaster Reduction: a review of disaster prevention, mitigation and preparedness. Ottowa Reconstr. Rehabil. Fund Can. Counc. Int. Coop.

Watkiss, P., 2011. Review of Existing Impacts, Vulnerability and Adaptation MEDIATION Technical Report No. 1.3. Stockholm Environment Institute, Oxford, UK.

Watson, R.T., 2000. Land use, land-use change, and forestry: a special report of the intergovernmental panel on climate change. Cambridge University Press.

Watson, R.T., Zinyowera, M.C., Moss, R.H., 1997. The Regional Impacts of Climate Change: An Assessment of Vulnerability, New. ed. Cambridge University Press, Cambridge, UK ; New York, NY.

Watts, M.J., Bohle, H.G., 1993. The space of vulnerability: the causal structure of hunger and famine. Prog. Hum. Geogr. 17, 43–67.

WeAdapt, 2013. Project WeAdapt [website]. Online "open Space" Clim. Adapt. Issues. URL http://weadapt.org

Weng, Q., Lu, D., Schubring, J., 2004. Estimation of land surface temperature–vegetation abundance relationship for urban heat island studies. Remote Sens. Environ. 89, 467–483.

Westendorf, K.L., Leuthart, C.A., Howarth, D.A., 1989. A preliminary assessment of the Louisville urban heat island. Trans. Ky. Acad. Sci. 50, 86–93.

Weyant, J., Azar, C., Kainuma, M., Kejun, J., Nakicenovic, N., Shukla, P.R., La Rovere, E., Yohe, G., 2009. Report of 2.6 versus 2.9 Watts/m2 RCPP evaluation panel. Integr. Assess. Model. Consort.

White, G.F., 1974. Natural hazards research: concepts, methods, and policy implications. Nat. Hazards Local Natl. Glob. Oxf. Univ. Press N. Y. 3–16.

WHO, 2012. WHO | The top 10 causes of death [website]. WHO. URL http://www.who.int/mediacentre/factsheets/fs310/en/ (accessed 7.8.16).

WHO, 2009. Protecting health from climate change: Global research priorities.

Wichmann, E.H., 1896. Atlas zur Geschichte Hamburgs. Herold.

Wichmann, E.H., 1863. Heimatskunde: Topographische, historische und statistische Beschreibung von Hamburg und der Vorstadt St. Georg. Herausgegeben von EH Wichmann. Jowien.

Wilby, R.L., 2007. A review of climate change impacts on the built environment. Built Environ. 33, 31–45.

Wilby, R.L., Perry, G.L., 2006. Climate change, biodiversity and the urban environment: a critical review based on London, UK. Prog. Phys. Geogr. 30, 73–98.

Wilmers, F., 1991. Effects of vegetation on urban climate and buildings. Energy Build. 15, 507–514.

Wisner, B., 2004. At risk: natural hazards, people's vulnerability and disasters. Psychology Press.

WMO, 2017. METEOTERM [website]. URL https://www.wmo.int/pages/prog/lsp/meteoterm_wmo_en.html (accessed 3.13.17).

Wolfram, S., 1983. Statistical mechanics of cellular automata. Rev. Mod. Phys. 55, 601.

Woods, M., 2010. Rural, 1 edition. ed. Routledge, New York.

World Bank, 2016. Indicators of the World Bank [website]. URL http://data.worldbank.org/indicator (accessed 9.28.16).

WorldClim, 2016. WorldClim [website]. URL http://worldclim.org/

Wu, F., 1998. Simulating urban encroachment on rural land with fuzzy-logic-controlled cellular automata in a geographical information system. J. Environ. Manage. 53, 293–308.

Xinhuanet News, 2012. 25 dead due to intense cold in northern India [website]. 25 Dead Due Intense Cold North. India. URL http://news.xinhuanet.com/english/world/2012-12/26/c_132065304.htm

Yamada, K., Mimura, N., Machida, S., Yamamoto, M., 1995. Methodology for the assessment of vulnerability of South Pacific island countries to sea-level rise and climate change. J. Glob. Environ. Eng. 1, 101–125.

Yamashita, S., Sekine, K., Shoda, M., Yamashita, K., Hara, Y., 1986. On relationships between heat island and sky view factor in the cities of Tama River basin, Japan. Atmospheric Environ. 1967 20, 681–686.

Yow, D.M., 2007. Urban heat islands: observations, impacts, and adaptation. Geogr. Compass 1, 1227–1251.

Yu, C., Hien, W.N., 2006. Thermal benefits of city parks. Energy Build. 38, 105–120.

Yu, W., Mengersen, K., Wang, X., Ye, X., Guo, Y., Pan, X., Tong, S., 2011. Daily average temperature and mortality among the elderly: a meta-analysis and systematic review of epidemiological evidence. Int. J. Biometeorol. 56, 569–581. doi:10.1007/s00484-011-0497-3

Yu, W., Vaneckova, P., Mengersen, K., Pan, X., Tong, S., 2010. Is the association between temperature and mortality modified by age, gender and socio-economic status? Sci. Total Environ. 408, 3513–3518. doi:10.1016/j.scitotenv.2010.04.058

Yuan, Y., Smith, R.M., Limp, W.F., 1997. Remodeling census population with spatial information from Landsat TM imagery. Comput. Environ. Urban Syst. 21, 245–258.

Zipf, G.K., 1949. Human Behaviour and the Principle of Least Effort. Addison-Wesley, Cambridge.

Appendix A: list of vulnerability definitions

The following vulnerability definitions have been acquired by qualitative and quantitative analysis and have been discussed in chapter 1.1:

White (1974)

Vulnerability is the degree to which a system, subsystem, or system component is likely to experience harm due to exposure to a hazard, either a perturbation or stress/stressor.

Gabor and Griffith (1980)

Vulnerability is the threat (to hazardous materials) to which people are exposed (including chemical agents and the ecological situation of the communities and their level of emergency preparedness).

Timmerman (1981)

Vulnerability is the degree to which a system acts adversely to the occurrence of a hazardous event. The degree and quality of the adverse reaction are conditioned by a system's resilience (a measure of the system's capacity to absorb and recover from the event).

United Nations Disaster Relief Organization (UNDRO, 1982)

Vulnerability is the degree of loss to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude.

Susman et al., (1983)

Vulnerability is the degree to which different classes of society are differentially at risk.

Kates (1985)

Vulnerability is the capacity to suffer harm and react adversely.

Pijawka and Radwan (1985)

Vulnerability is the threat or interaction between risk and preparedness. It is the degree to which hazardous materials threaten a particular population (risk) and the capacity of the community to reduce the risk or adverse consequences of hazardous materials.

Schroeder (1987)

Gender vulnerability: the inability to prepare, adjust, or adapt due to constraints inherent in a particular form of gender relationship.

Bogard (1989)

Vulnerability is operationally defined as the inability to take effective measures to insure against losses. When applied to individuals vulnerability is a consequence of the impossibility or improbability of effective mitigation and is a function of our ability to detect the hazards.

Mitchell et al., (1989)

Vulnerability is the potential for loss.

Chambers (1989)

Vulnerability refers to exposure to contingencies and stress, and difficulty in coping with them. Vulnerability has thus two sides: an external side of risks, shocks, and stress to which an individual or household is subject: and an internal side which is defenselessness, meaning a lack of means to cope without damaging loss.

Liverman (1990)

Distinguishes between vulnerability as a biophysical condition and vulnerability as defined by political, social and economic conditions of society's vulnerability are defined both in geographic space (where vulnerable people and places are located) and in social space (who in that place is vulnerable).

Downing (1991)

Vulnerability has three connotations: it refers to a consequence (e.g., famine) rather than a cause (e.g., drought); it implies an adverse consequence; and it is a relative term that differentiates among socioeconomic groups or regions, rather than an absolute measure of deprivation.

Dow (1992)

Vulnerability is the differential capacity of groups and individuals to deal with hazards based on their positions within physical and social worlds.

Smith (1992)

Risk from a specific hazard varies through time and according to changes in either (or both) physical exposure or human vulnerability (the breadth of social and economic tolerance available at the same site).

Cutter (1993)

Vulnerability is the likelihood that an individual or group will be exposed to and adversely affected by a hazard. It is the interaction of the hazards of place (risk and mitigation) with the social profile of communities.

Alexander (1993)

Human vulnerability is a function of the costs and benefits of inhabiting areas at risk from natural disaster.

Watts and Bohle (1993)

Vulnerability is defined in terms of exposure, capacity and potentiality. Accordingly, the prescriptive and normative response to vulnerability is to reduce exposure, enhance coping capacity, strengthen recovery potential and bolster damage control (i.e., minimize destructive consequences) via private and public means.

Bohle et al., (1994)

Vulnerability is best described as an aggregate measure of human welfare that integrates environmental, social, economic and political exposure to a range of potential harmful perturbations. Vulnerability is a multi-layered and multidimensional social space defined by the determinate, political, economic and institutional capabilities of people in specific places at specific times.

Cannon (1994)

Vulnerability is a measure of the degree and type of exposure to risk generated by different societies in relation to hazards. Vulnerability is the a characteristic of individuals and groups of people who inhabit a given natural, social and economic space, within which they are differentiated according to their varying position in society into more or less vulnerable individuals and groups.

Organization for Economic Co-operation and Development (OECD-DAC, 1994)

Concerns the propensity of a society to experience substantial damage, disruption, and casualties as a result of hazard.

Varley (1994)

Vulnerability is characteristics of a person or a group and groups of people who habit a given natural, social and economic space, within which they are differentiated according to their varying position in society into more or less vulnerable individuals and groups. It is a complex characteristic produced by a combination of factors derived especially (but not entirely) from class, gender, and ethnicity.

Blaikie et al., (1994)

By vulnerability we mean the characteristics of a person or group in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural hazard. It involves a combination of factors that determine the degree to which someone's life and livelihood are put at risk by a discrete and identifiable event in nature or in society.

Warmington (1995)

A condition or set of conditions which adversely affect people’s ability to prepare for, withstand and/or respond to a hazard

Yamada et al., (1995)

The potential for attributes of a system to respond adversely to the occurrence of hazardous events.

Dow and Downing (1995)

Vulnerability is the differential susceptibility of circumstances contributing to Vulnerability. Biophysical, demographic, economic, social and technological factors such as population ages, economic dependency, racism and age of infrastructure are some factors which have been examined in association with natural hazards.

Kasperson et al., (1995)

Vulnerability in this sense is a product of three dimensions: exposure, resistance (the ability to withstand impacts), and resilience (the ability to maintain basic structures and to recover from losses).

Cutter (1996)

Vulnerability is conceived as both a biophysical risk as well as a social response, but within a specific areal or geographic domain. This can be geographic space where vulnerable people and places are located, or social space - who in those places is most vulnerable.

Lewis (1997)

Vulnerability is a pervasive socioeconomic condition; it is the reason why the poor and disadvantaged are the predominant victims of disasters.

Intergovernmental-Panel for Climate Change (IPCC), (Watson et al., 1997)

Vulnerability is defined as the extent to which a natural or social system is susceptible to sustaining damage from climate change. Vulnerability is a function of the sensitivity of a system to changes in climate and the ability to adapt to system to changes in climate. Under this framework, a highly vulnerable system would be one that is highly sensitive to modest changes in climate.

Bolin and Stanford (1998)

Vulnerability concerns the complex of social, economic, and political considerations in which peoples' everyday lives are embedded and that structure the choices and options they have in the face of environmental hazards. The most vulnerable are typically those with the fewest choices, those whose lives are constrained, for example, by discrimination, political powerlessness, physical disability, lack of education and employment, illness, the absence of legal rights, and other historically grounded practices of domination and marginalization.

Vogel (1998)

Vulnerability is perhaps best defined in terms of resilience and susceptibility including such dimensions as physical, social, cultural and psychological vulnerability and capacities that are usually viewed against the backdrop of gender, time, space and scale.

UNEP and South Pacific Regional Environment Programme (1999)

Vulnerability is a function of sensitivity to present climatic variability, the risk of adverse future climate change and capacity to adapt. The extent to which climate change may damage or harm a system; vulnerability is a function of not only the systems' sensitivity, but also its ability to adapt to new climatic conditions.

Lewis (1999)

Vulnerability is the product of sets of prevailing conditions within which disasters may occur.

International Federation of Red Cross and Red Crescent Societies (IFRC, 1999)

Vulnerability is a characteristic of a person or group of persons in terms of their capacity to anticipate, cope with, resist and recover from the impact of a natural or man-made hazard.

Adger (2000)

Individual and collective vulnerability and public policy determine the social vulnerability to hazards and environmental risks, defines here as the presence or lack of ability to withstand shocks and stresses to livelihood.

Buckle et al., (2000)

The degree of loss to a given element at risk or set of such elements resulting from the occurrence of a natural phenomenon of a given magnitude and expressed on a scale from 0 (no damage) to 1 (total loss) or in percent of the new replacement value in the case of damage to property.

Sarewitz and Pielke Jr, (2001)

Vulnerability refers to a system's susceptibility to change as a consequence of an extreme event.

Nicholls and Klein (2000)

Vulnerability is a function of system's ability to cope with stress and shock.

Carpenter et al., (2001)

Vulnerability defined as the opposite of resilience where resilience is "the capacity of a system to undergo disturbance and maintain its function and controls.

Intergovernmental-Panel for Climate Change (IPCC), (McCarthy, 2001a)

The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity.

Alwang et al., (2001)

The insecurity of the well-being of individuals, households or communities in the face of changine environment.

Kasperson et al., (2002)

Vulnerability is the degree to which a person, system or unit is likely to experience harm due to exposure to perturbations or stresses.

United Nations Environment Programme (UNEP, 2002)

Vulnerability is the interface between exposure to the physical threats to human well-being and the capacity of people and communities to cope with those threats.

National Oceanic and Atmospheric Administration (NOAA, 2002)

The level of exposure of human life, property and resources to damage from natural hazards.

The United Nations Office for Disaster Risk Reduction (UN/ISDR, 2004)

The conditions determined physical, social, economic and environmental factors or processes which increase the susceptibility of a community to the impact of hazards.

Downing, (2004)

A simple scheme is to label vulnerability with regard to the exposure unit (e.g., a livelihood or a sector), the threat (e.g., drought or floods) and the outcome (e.g., loss of life or depletion of assets).

Cardona (2004)

Vulnerability represents the physical, economic, political or social susceptibility or predisposition of a community to damage in the case a destabilizing phenomenon of natural or anthropogenic origin.

Green (2004)

Vulnerability is the relationship between a purposive system and its environment where that environment varies over time.

Appendix B: list of publications, delivered from this thesis

Peer reviewed papers in the conferences' proceedings:

Kaveckis, G., Bechtel, B., 2014. Land Use Based Urban Vulnerability to Climate Change Assessment, in: International Conference on Environmental Engineering (ICEE) Selected Papers. Presented at the 9th International Conference on Environmental Engineering, MAY 22-24, 2014 Vilnius, LITHUANIA, Vilnius Gediminas Technical University Press Technika, Vilnius, Lithuania.

Kaveckis, G., Bechtel, B., Ossenbrügge, J., Pohl, T., 2014. Land use modelling – a way of mapping future hazard-sensitive population, in: Proceedings of 5th International Disaster and Risk Conference IDRC. Presented at the Global Risk Forum Davos 2014, Davos Switzerland.

Peer reviewed publications as books' chapters:

Kaveckis, G., Bechtel, B., Pohl, T., Ossenbrügge, J., 2017. Land use modelling as new approach for future hazard-sensitive population mapping in Northern Germany, in: Planning for Community-Based Disaster Resilience Worldwide: Learning from Case Studies in Six Continents. Routledge, p. 470.