# Using Cellular Automata to Analyze and Model Urban Growth.

A case study of the greater Copenhagen area

From1990 to 2010.

**By**

**Carolynn Amujal**

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This thesis is submitted to the Department of Planning, Aalborg University Copenhagen as a partial fulfilment for the requirements the degree of Masters of Science in Geo- informatics.

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# Abstract

The statistics suggest that by 2025 Copenhagen will have approximately 22,000 more young people and children and 33,000 more between the age of 18 and 29. However, with such soaring numbers in a small country like Denmark, this can certainly put a lot of pressure on the social services especially at the municipality level. Such growth in numbers calls for better planning and more social services like schools, daycare institution, and infrastructure to meet their needs (Copenhagen Municipality 2011). This calls for a scientific explanation of the complexity of urban growth patterns in order to understand the fast rate of urban growth that is taking place today.

This study therefore focuses on determining how much urban growth has taken place in the greater Copenhagen area in a period of only 20 years from 1990 to 2010. The key method used to model the urban growth is the cellular automata method, which has been used by several researchers and urbanists to measure urban growth. The differences between CA and other models are quite distinguishable. Some of them include its ability to produce a clear resolution spatially (White 1997), the ability to model urban complexities based on simple rules.

The challenge for this study was to design a cellular automata model that can be used to model and possibly predict future urban growth. For urban growth, modelling this would be applicable in answering questions raised in this study like: is the area urban or non-urban? How close the cell of interest is to features for example the core of Copenhagen city and other urban centers, protected areas like the green wedges in the finger plan and the camping or summer cottages? In addition, how the constraints applied will affect the urban growth pattern. The spatial patterns to visualize urban growth in the greater Copenhagen area is simulated using Cellular Automata by representing the Cell element of the city whereby the cell will represent the spatial and physical, set up of the city.

Acknowledgement

Being able to pursue this course has been both a fulfilling challenge and a motivation to myself however; the fact that I am even writing this page means that I did not give up. The support I got through this journey was tremendous and therefore I would firstly like to say thank you to my husband and son that have believed in me from day one and to my friends, your prayers and support kept me going.

Secondly, I would like to thank all my lectures and colleagues in the Geoinformatics Department at the Aalborg University in Copenhagen. The guidance and advice you provided in regards to this thesis was very helpful and highly appreciated.

I want to specially say thank you to my supervisor professor Henning Sten Hansen. I want to say thank you for the countless hours you spent supervising and this thesis. Your comments and knowledge in this field were a great help.

Last but definitely not least, to my parents and siblings in Uganda. The distance between us did not stop your encouragements and prayers. Thank you for believing in me.

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# 1. Introduction

This chapter attempts to define and summarize the term ‘urban growth’. Within which various views and concepts related on urban growth are hinted on. The aim of this section of the study is ideally to capture the reasons as to why it was necessary to carry out yet another study on urban growth analysis and modelling for the greater Copenhagen area for the past 20 years. The perspective for the study is centered on the metropolitan area of Copenhagen, which is the capital city of Denmark and therefore a focal point for urban growth.

## 1.1 The Background

What is urban? This question is key to understanding the rest of this study. The definition of this term varies from source to source and as such the need to elaborate further on it. Several writers and scholars have attempted to give a fitting description to this term however, one shoe does not fit all thus there are as many opinions as are the writers. Different countries have defined ‘urban’ to mean towns, cities, villages etc. and yet still this definition can also vary within the same country from time to time mainly based on three categories thus economic, geographic or administrative (United Nations 1974)a

According to Batty and Longley the first planned urban settlements both organic and irregular become clearly distinguished in the Grecian and Roman period where by the growth of these urban centers was influenced by decisions of several individuals coupled with the rules and regulations of that time. In the bid to colonize new territories, the Greeks and romans forged some kind of plan like the gridiron plan with its first appearance in the present day region of Asia-Minor (Batty and Longley 1994).

Unlike today, the growth of the towns in the Grecian and Roman times was looked at in terms of straight geometric features like buildings and streets, which later changed to circular and then square pattern revolving around places of value like markets and churches. However, the grid plans where later adopted or copied by the new forms of civilizations all over Europe and America. Batty and Longley, further assert that in the early Roman civilizations, growth was minimal and not measured in terms of population numbers compared to the some of the world's large metropolis with dense populations like London. One of the examples cited was from the Circleville town in southern Ohio where the circular plans where modified to suit the modern times growth trends thus the grid or square format (Batty and Longley 1994). This is illustrated in figure 1 below.

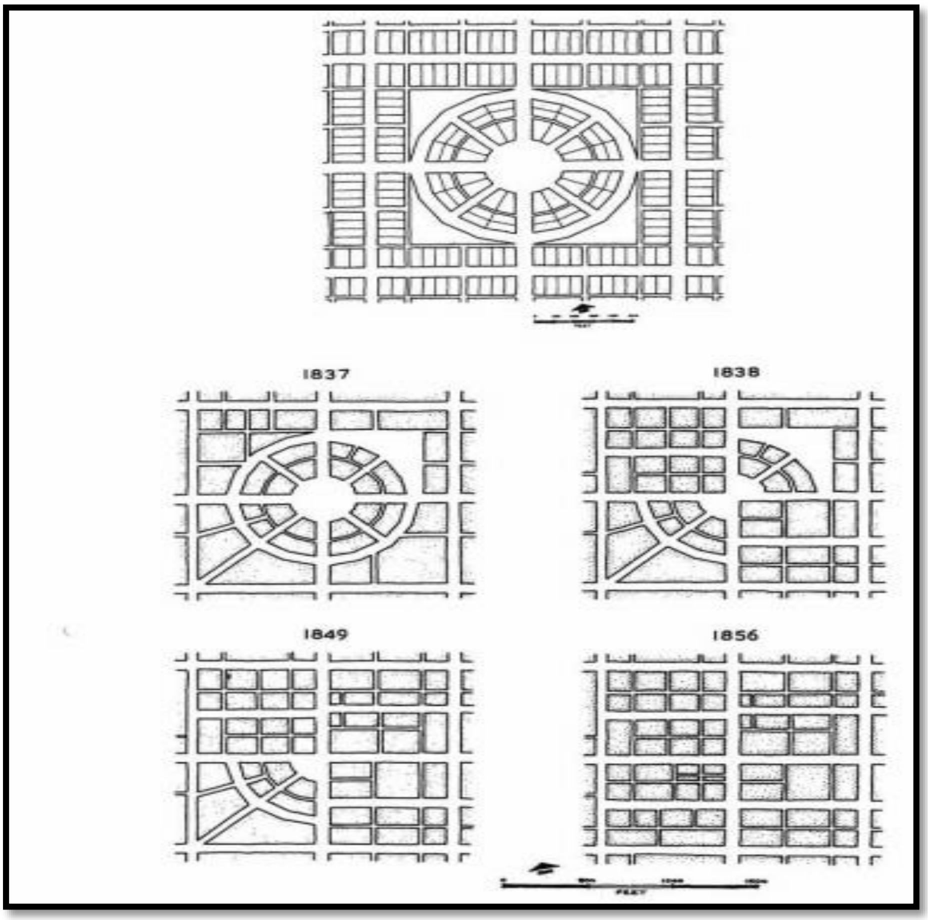



Figure 1: The pattern transformation of Circleville between 1810 and 1856. Source: (Batty and Longley 1994, p26).

However, the term "Urban growth" today is commonly used when referring to the transformation of non-urban spaces thus the development of a space for commercial or other purposes thus the landscape change brought about by urban growth can be temporal or spatial in nature.

The purpose of modelling these dimensions aims at abstracting and representing the piece of land in question. There are various modelling procedures thus mathematical, symbolic, or conceptual depending on what the data extracted from the model is going to be used for

(Cheng 2003).This process of urban growth is very dynamic and is usually modelled using Cellular Automata and Complex systems theories.

However (Andersen and Engelstoft 2004) argue that it is also not easy to define what an urban area is, based on the economic status and population of any given city. They further add that cities in the mid-20th century started losing people because of shortages in spaces for expansion whereas the surrounding areas, which were virgin were gaining in numbers.

In addition, report by the United Nations, states that the population in the urban areas is growing much faster than the world population thus putting the total number to approximately three billion urban dwellers in small urban areas and less than five per cent of the world's population dwelling in mega cities like Mexico, Tokyo and New York. (United Nations 2004a).

The use of GIS in calibration and the construction of models makes this an indispensable and effective system. The models produced by a GIS system assist the public to understand the effects of urban growth. Several studies have shown that there is a steady increase in the growth rate of urban areas and the use of systems like GIS, digitalized maps, and remote sensing have been used to monitor and record the on-start and the growth patterns of big cities also termed as megalopolises in South America, Asia, California and also in Europe. These mega cities have been also termed as gigalopolis a term that, was coined to refer to the 21st century world cities with billions of people (Clarke and Gaydos 1998)

## 1.2 Problem statement.

With the fact that the population of Copenhagen is ever growing, can the greater Copenhagen area contain this growth and if yes, then how or if not then what are the possible solutions? Municipalities within the greater Copenhagen area are currently faced with this scenario. This has therefore prompted the problem statement for this study, which states as follows:

***How can the use of GIS be beneficial in the assessment of urban growth and planning for the greater Copenhagen area?***

## 1.3 Objectives of the study.

1. To analyze the urban growth trends of the greater Copenhagen area from 1990 to 2010.
2. To investigate the various factors contributing to this urban growth.
3. To evaluate the effectiveness of GIS as a tool for assessing urban growth.

## 1.4 Research Questions.

1. How has the five-finger plan model influenced spatial planning in the greater Copenhagen?
2. How can potential urban growth factors be incorporated into a cellular automata model for the greater Copenhagen area?
3. How can neighbourhood window size and threshold influence the Cellular Automata model calibration?
4. How can Cellular Automata (CA) help in modelling urban growth in the area?

## 1.5 Scope of study area.

The area study for this project is the Copenhagen metropolitan area. Copenhagen being the capital city of Denmark has a population of approximately 510,000 people. The functional metropolitan area where people live, work and spend their leisure time is larger with a population of approximately 2.39 million people thus 44% of the national population of Denmark (OECD 2009).

Located in the Oresund region of Denmark, Copenhagen is located to the east of Zealand one of the main islands that make up the country. Characterized by an oceanic climate, with

Latitude of 55°40′33″ N and Longitude of 12°33′55″ E, the city is elevated above sea level at 5 m, which is approximately 16 feet and a size of 88.25sq.km (Statistics Denmark 2013).

The 2011 municipal plan for the Copenhagen area states that “*By 2025, Copenhagen and Malmö will be an integral metropolis in which growth and quality of life go hand in hand” and with this in mind”*, (Copenhagen Municipality 2011, p7). Furthermore, it is important to note that just like most cities around the world, the Copenhagen metropolitan area is vital to the economic well-being of Denmark as a whole. This project is about urban growth effects and factors with the focus on Denmark five-finger plan, which covers the Copenhagen metropolitan area. This plan has under gone several alterations since it was first introduced in 1947. Therefore, the study analyses the urbanization process from 1970 to 2010 within the greater Copenhagen area, which is ideally covered by the five- finger plan. The factors that will be considered include the population and its influence on urban growth and the infrastructure like roads, railways and housing, effectiveness and the challenges posed by this plan in the urbanization process of the greater Copenhagen area (Østergård 2007).

There are several ways to analyze and model the rate of the urban growth, the study will look at some of the modelling systems available. The study area for this thesis is shown in figure 2 below.

STUDY AREA

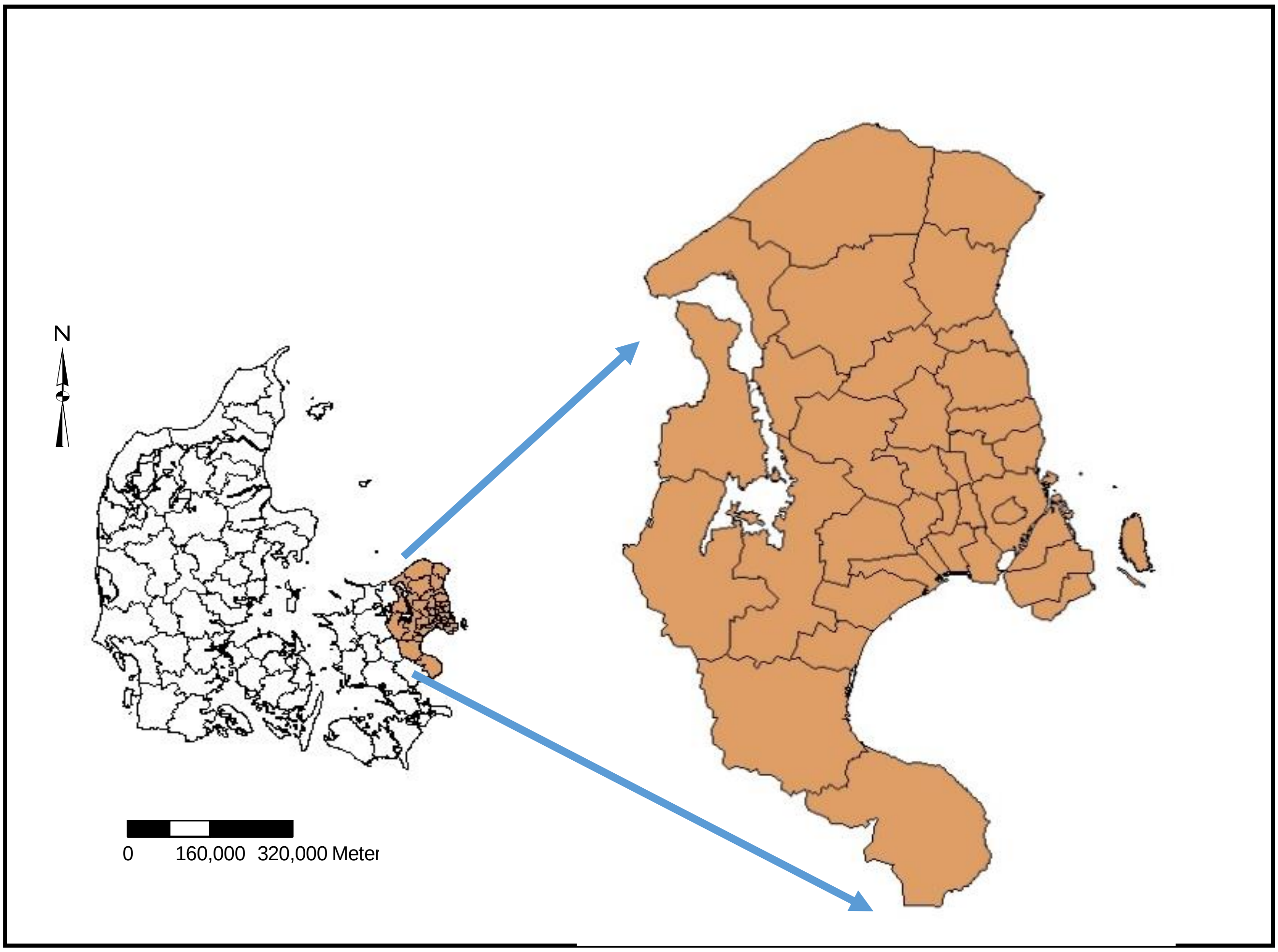


Figure 2: Map of the study area.

The Copenhagen greater area currently covers 18 municipalities in the Zealand region, which is the main island of Denmark. These municipalities are Copenhagen, Frederiksberg, Ballerup, Brøndby, Gentofte, Gladsaxe, Glostrup, Herlev, Greve, Rudersdal (former Sølrod), Furesø, Vallensbæk, Tårnby, Ishøj, Rødovre, Hvidovre, Albertslund and Lyngby (Statistiksbanken 2014)

Based on the data from statistics Denmark, the table below further elaborates on the population status for the core Copenhagen city excluding the suburban municipalities that make up the greater Copenhagen as shown in the table below:

| | Population | % of national population |
|---|---|---|
| **Copenhagen municipality** | 569,557 | 10.1% |
| **Frederiksberg municipality** | 102,717 | 1.8% |
| **Greater Copenhagen area** | 1,246,611 | 22.1% |
| **Total national population** | 5,634,437 | |

Table 1: Population status of Copenhagen in 2014. Source: Statistics Denmark, 2014

# 2. Structure of the thesis.

This thesis consists of the following chapters: the theory, methodology and discussion of the results and the perspectives. Within these chapters, the research questions and the objectives of the study are covered. The chapters are broken down as follows:

**Chapter 1** gives the background on urban growth and introduces various examples and definitions of urban growth from other parts of the world. In this section, the study states what the objectives and purpose of the thesis is. It also defines the extent of area of study.

**Chapter 2** discusses the theoretical makeup of urban growth, analysis of urban growth as a system, and the complexes therein. In this chapter, various patterns and processes (spatial and temporal) of urban growth in Copenhagen are also reviewed. This chapter also delves into the various modelling methods.

**Chapter 3** deals with the data collection and preparation process and modelling requirements necessary for the case study area. Particular emphasis will be on the five-finger plan of the Copenhagen metropolitan area, which covers the study area.

**Chapter 4** offers the methodology used to interpret and represent the data from the previous chapter. This will further explore Cellular Automata modelling and how it can be applied for interpreting the spatial and temporal patterns in urban growth for the study area.

**Chapter 5** will evaluate and discuss the findings of the study with reference to the research objectives stated in chapter one.

**Chapter 6** draws conclusions of the study based primarily on the results from the previous chapters.

**Chapter 7** provides various perspectives for further evaluation of the study.

# 3. Theoretical framework

Within this chapter, various theories of urban growth systems, models and complexities are elaborated upon. It also further explores various aspects in regards to the urbanization of the greater Copenhagen area.  This gives a wider understanding to the subject at hand and provides a background for the methodology chapter that follows.

## 3.1 Definitions of urban growth.

There are several definitions and meanings of urban growth. This section of the report discusses some of them.

In one of the 2012 UNICEF reports. Urban growth was defined as *“The (relative or absolute) increase in the number of people who live in towns and cities. The pace of urban population growth depends on the natural increase of the urban population and the population gained by urban areas through both net rural-urban migration and the reclassification of rural settlements into cities and towns”* (UNICEF 2012, p10).

Urbanization which is also a result of urban growth defines how much “proportion of the country is urban” (UNICEF 2012, p10). This process said to have originated from what is now termed as the developed countries of the world has half of its population living in urban areas. In 2003, the levels of urbanization had accelerated to more than 80 percent in some parts of the world including North America, Australia, and Europe by 73 percent. These levels are expected to go even higher in the coming years. (United Nations 2012).

However, urbanization also happens with industrialization and modernization of areas. From the start of the twentieth century, it was predicted that there were about 150 million people living in urban areas. The industrialization and modernization of areas is like a magnet, attracting the people searching for new opportunities like jobs and better living standards thus abandoning the rural areas. This migration process has also been termed as rural flight. (Galen 2004).

Despite the soaring numbers of people dwelling and relocating to cities and urbanized areas as previously mentioned by Galen, a survey that was carried out by the European

Commission in 2012, reported that a large number of these city dwellers approximately 80% in the European cities were satisfied with the quality of their lives in these cities with Aalborg in Denmark topping the list at 99% satisfaction.  (European Commission 2013). The survey results supporting are as seen in the figure 3 below

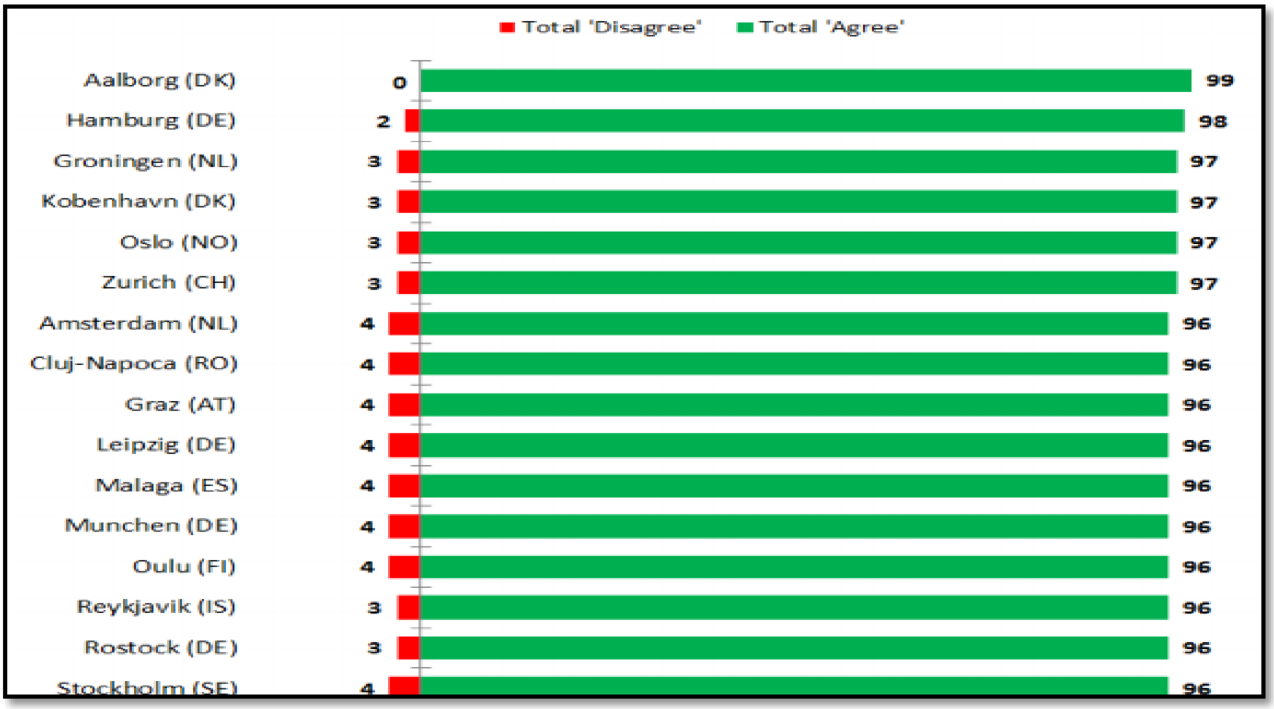


Figure 3: Percentage of satisfied city dwellers in Europe. Source: (European Commission 2013, p12)

There are several definitions (UNICEF 2012), (Yannis and Esteban ), (Wirth 1938) of what urban growth is, however Hansen points out that the growth of an economy solely encourages the expansion of urban areas. This expansion is seen in the sprouting of dwellings, road networks, businesses, shopping malls etc. As a result, urban sprawling which is a problem for metropolitan areas increases causing problems like loss of wildlife habitats and clearing of natural vegetation to create land for expanding cities (Hansen 2001).

According to the European Environment Agency(EEA), the key contributors to fast urban growth in Europe can be categorized into demographic, economic and social factors wherein lie several contributors like standards of living, the European integration, prices of land among others (European Environment Agency)

## 3.2 Theories on urban growth patterns and Trends.

Batty and Longley, argue that in order to define a city, the development process of that city provides the best definition. In a nutshell they describe the process of making a city as sequential procedure whereby hamlets become villages, villages grow into towns and towns transform into cities and several cities add up to create an urban region. A similar pattern of growth was synonymous with the towns that emerged before the post- industrial era characterized by concentric patterns usually around places like temples and markets (Batty and Longley 1994).

Furthermore, in some parts of Europe, it has also been noted that the processes of urbanization due to increased technologies in communication and mobility are on the rise thus birthing new types of urban configurations. More and more, the urban growth patterns prevalent in the cities of these countries are Mono-centric in nature as neighboring rural areas are taken on for further development (United Nations 2013). This kind of pattern depicted by Batty and Longley(1994) as one of the first patterns of urban settlers in Europe which was of Grecian and Roman origin copied from how they designed their first military camp also known as *castras.*

However, according to the European Union *Cities of tomorrow* report, in the last century Europe was able to grow from a rural to urban continent with more than 70% of its population living in urbanized settings. Characterized by a polycentric urban growth pattern, Europe's growth rate may have slowed down but it is still growing however compared to the populations of city inhabitants in the USA and China, only 7% of the European population dwell in the cities (European Union 2011b). However this growth is accompanied with some challenges of urbanizations like increased crime rates, socio-cultural differences among others thus in order to avoid or alleviate some of these problems instigated by urbanization on large scale, there is need for further research into dynamics and the structural set up of the population trends in Europe (Joint Programming Initiative 2010)

According to the United Nations (2010) report, high population increase in the developing countries with low rates of urbanization is linked to high fertility rates, whereas the many of the countries with lowest fertility rates are highly urbanized and former members of the communist nations like the Baltics, Russia and parts of Eastern Europe. In the Americas however, Cuba also a former communist nation has the lowest fertility rate (United Nations 2011). On the contrary, at the start of the 20th century, capitalist nations where experiencing a different kind of urbanism where the urban landscapes where distinguished between an urban family environment and a more complex urbanized setting with hotels, high-raised buildings and luxurious apartments (Wells 1902).

Furthermore, Andersen and Engelstoft interject that measuring of economic performance of an area due to urban growth by basing on population numbers can be sometimes misleading especially if the number of work force coming into the city is higher than the residential. They further point out that most metropolitan areas are administratively divided for example Copenhagen where majority of the work force is academic and residing outside the central municipality. Gauging economic growth based on just the population of the area is not sufficient (Andersen and Engelstoft 2004). This is further supported by (Wirth 1938), who argues that defining an area as urban based on population size alone can indeed have misleading outcomes adding that cities are administrative units and a such numbers like the census are vital for proper planning and management.

According to Wirth, "the influences which cities exert upon the social life of man are greater than the ratio of urban population would indicate for the city is not only in ever larger degrees the dwelling-place and the workshop of modern man, but it is the initiating and controlling center of economic, political and cultural life that has drawn the most remote parts of the world into its orbit and woven diverse areas, peoples and activities into a cosmos", (Wirth 1938) p.2. This indicates that as much as several theories and writers seem to point out the contribution of population (Copenhagen Municipality 2011) growth as key to urban growth, Wirth begs to differ from this phenomenon citing that the influences of urban areas on social settings is far more than just the population.

The urban growth trends are also more elaborate within the metropolitan areas of the OECD nations like Copenhagen and Seoul. In Copenhagen between 44 and 48% of the county's population lives in an urban area that are ideally located based on the size of the city. The population in these urban areas is usually between 100,000 and 500,000 and as a result, the annual growth rate is slower at an average of approximately 0.4%. However, despite all these various global trends, there is a notable difference regionally. The developing countries are now on a fast-paced growth rate whereas their counterparts in the developed regions of the world are continually growing but at a much slower rate. (OECD 2009).

## 3.3 The link between population and urban growth

According to Bertaud, the migration of people from other countries and cities could be one of the driving factors behind the growth of these cities as this group of migrants gets older and settles in these areas creating not only consumer driven retiree cities but also demand for young labor force in the market. Furthermore, the demands for social services like health facilities, retirement homes, and restaurants, from the retirees is high (Bertaud 2014).

In the European context just like all the other parts of the world, there is no defined model of what a city should look like rather cities are ideally defined by the culture of the people in it, values, strengths, weaknesses, opportunities and threats. However, there is a European model of urban development within which the growth of cities and sustainable development of their territories is very much a shared vision (European Union 2011a)

In addition, urban growth has not only been visible in Europe as a whole but also in Denmark's capital city of Copenhagen where the population has been steadily on the rise. According to the Danish statistics report, the growth in population is greatly been linked to the increase in the number of immigrants to the country since 1985 especially from other European countries. (Statistics Denmark 2013).

According to (Andersen and Engelstoft 2004)b the urbanization of Copenhagen and Denmark in general dates back to the medieval times between the 8$^{th}$ and 11$^{th}$ century where most of the infrastructures for the bigger cities like Copenhagen where built. The population of Copenhagen was approximately 10% of the national census just like all the other cities in Denmark at that time and this trend only changed in the 19$^{th}$ century when more and more migrants moved to Copenhagen in search of jobs.

Furthermore, (Stevens 2005) interjects that population increase usually creates a demand for more living area and social services. In order to meet these demands, cities are forced to expand outwards thus urbanizing virgin territories in their neighborhoods. The growth may be evident vertically or horizontally depending on the availability of land or lack thereof. Stevens' argument is further elaborated upon by the United Nations report, which suggests that whereas the rural population of the world is expected to reach its maximum at 3.4 billion people by the year 2021, the report further claims that this rise is expected to decline by 2050. It attributes the rise in population in the less developed regions to the high rates in fertility as shown in the figure 4 below (United Nations 2012).

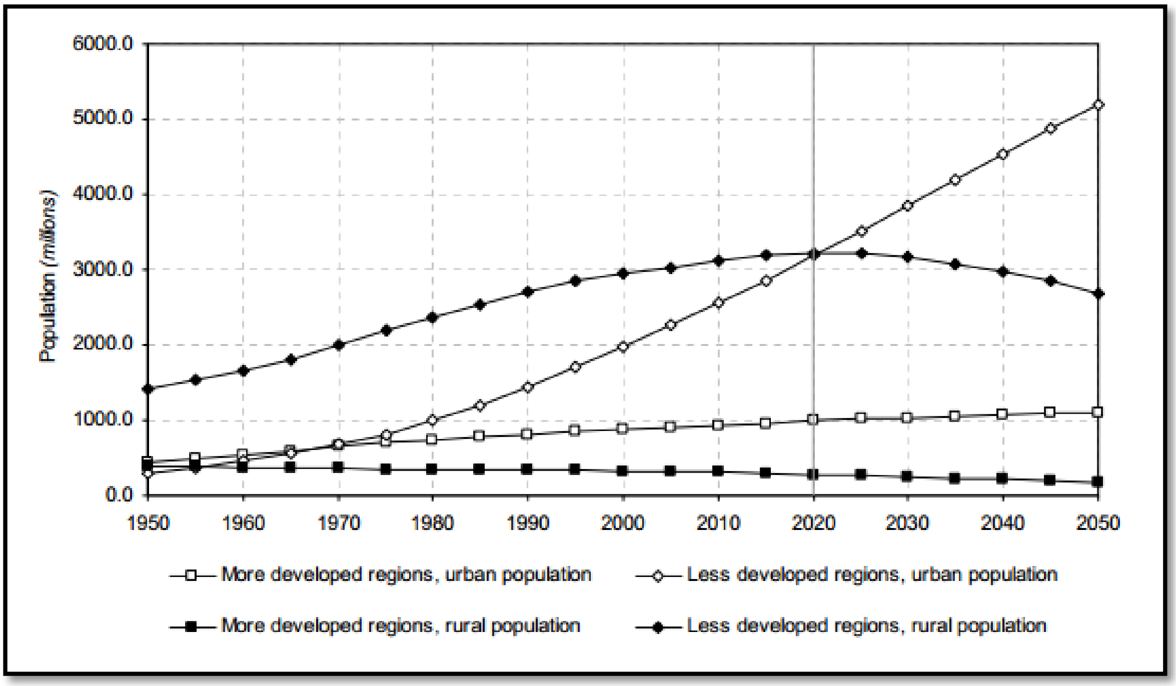



Figure 4: Urban and rural populations by development group, 1950-2050. Source: United Nations: *World Urbanization Prospects: The 2009 Revision*, pg. 3

In Denmark, high fertility rates may have not contributed to the population growth then, on the contrary, *Denmark in figures*, a report by Danish statistics department points out, in the 1980s the population growth of Denmark was very low due to because of the low birthrate and thus the term "small youth generations". This trend is however changing and the population has been on the rise. The population increase is greatly been attributed to immigration from mostly neighboring European countries like Romania, Germany, and Poland in pursuit of better jobs. With the increase in the immigration and the fact that the life span of the Danish people has increased averagely by six years compared to the 1970, the population has been slowly but steadily growing in Denmark. This steady population growth is also seen in Denmark's metropolitan city of Copenhagen as shown in the figure 5 below between 1970 and 2012, (Statistics Denmark 2013).

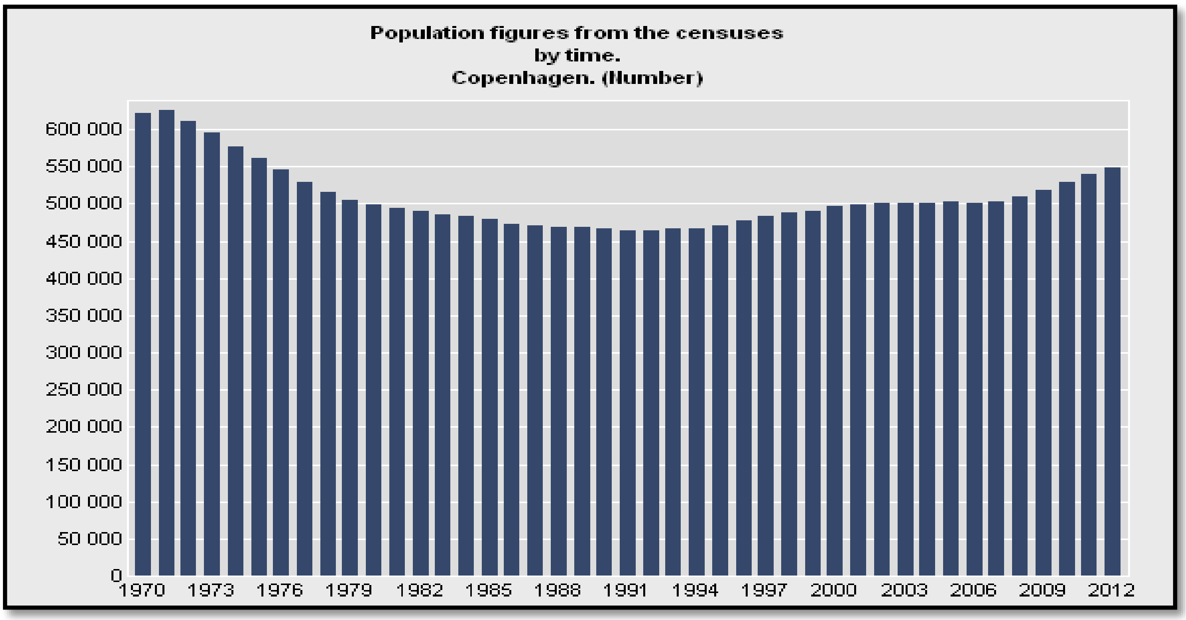



Figure 5: Population growth in Copenhagen from 1970 – 2012 .Source: (Statistics Denmark 2014)

## 3.4 Systems, Models and Complexities of urban growth.

Urban systems and models are as many as the theories and this chapter explores some of them and their applicability in understanding urban growth. *"Systems are often studied in terms of their statistics or their dynamics, the first implying structure, the second behavior usually in the context of changing structures",* (Batty and Longley 1994, p43).

Urban theories about cities have also transcended a period of time and change from the earlier theories thus from the mid-twentieth century, these theories have taken on a new meaning especially with the introduction of computers into the modeling world. These theories supported by the computer-based models are predominantly also known as location models. However, due to their tendency to model ideal locations for activities like services, housing areas, and industries, in order for these locations to suit the required activity, the economic aspect is highly considered thus issues like distance and accessibility in terms of travel costs to and from these areas are crucial deciding factors (Batty 2009).

Urs further mentions that Churchman, Ackoff and Arnoff provided a rough characterization of three types of models. These models were pictorial representations thus iconic in nature, in another; a set of properties are used in a system to represent another thus the analogue model and the symbolic model were symbols like equations in mathematics are assigned to properties in a system (Urs 1969).

Furthermore, several scholars have come up with various forms of urban growth systems and how it can modelled. For example (Makse, Havlin and Stanley 1995), describe the growth systems of cities to that of particles with two – dimensions further pointing out that this system of growth could be modelled with the help of statistical physics by clustering using a method like diffusion –limited aggregation (DLA). At varying degrees of correlation, the morphology of cities changes accordingly due to the population, density of the urban center that normally is the most densely populated as depicted in the figure 6 below showing the urban growth of a city with time. The simulation of the urban areas is shown in different degrees of correlation using a density gradient of ʎ= 0.0009 suggesting that the increase in correlations resulted into more compact clusters. However, this rough approximation of systems is far from the reality (Makse, Havlin and Stanley 1995).

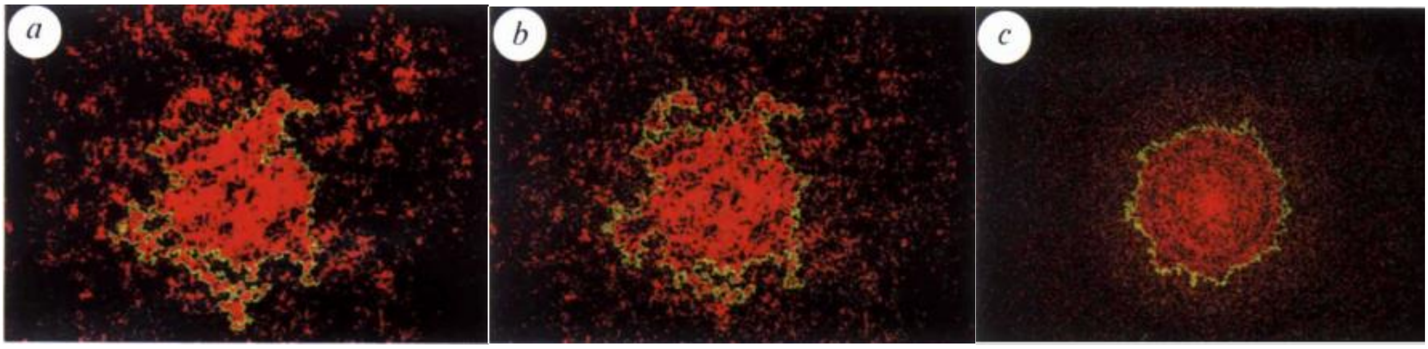



Figure 6: Time-series correlation of city growth. Source: (Makse, Havlin and Stanley 1995, p609)

As a system, urban growth influences trends, spatial patterns, growth rates that can be assessed to help in the planning process. (Ramachandra and Bharath 2013). The use of GIS in urban planning has been explored by various urban planners and authors like Batty and Torrens in several of their Urban modelling research papers, Heikkila, Kim and Moore in the journal *Sistemi Urbani,* among other researchers. However, its applicability has been clearly illustrated by Yeh as shown in figure 7 below

However, for a city to be referred to as a system there should be elements and relations that operate hand in hand whereby the relations in form of networks and or hierarchies describe the interaction of the components in the elements.

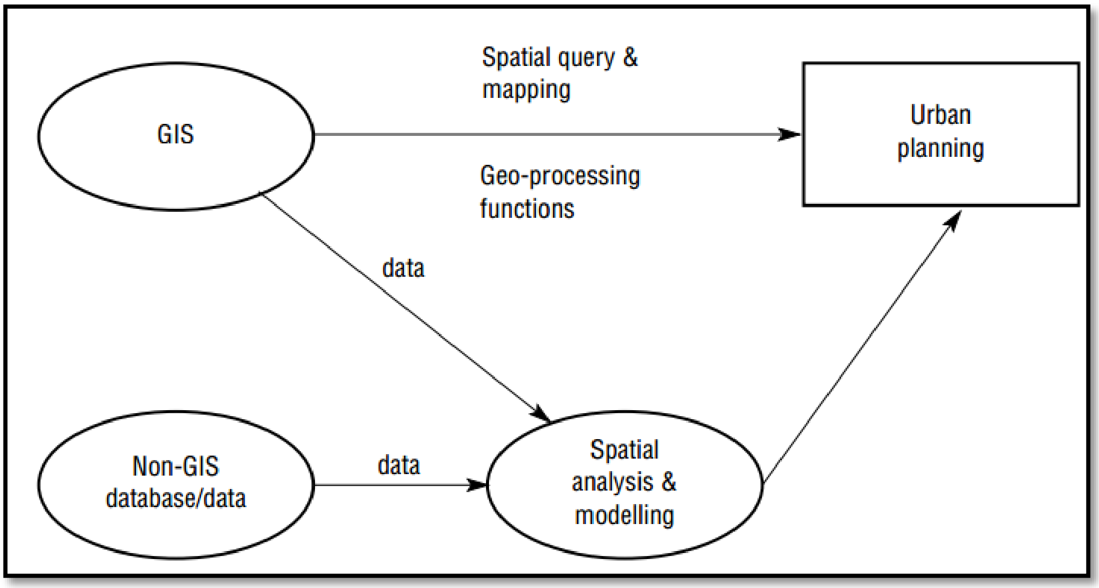



Figure 7: Urban planning using GIS. Source: (Yeh 1999, p878)

The elements of a city however usually are determined or restricted by the opinions of the theory in question.

A system is also subdivided into subsystems creating some form of hierarchy. Even more so many of the elements in a city possess a hierarchy that is spatial in nature.However, despite the growth of cities due to the idea of urban space hierarchy ideally a basic format of the elements seem to naturally manifest to promote growth and change (Batty and Longley 1994).

Having briefly defined what a city is, it is equally vital to understand what urban growth modelling is. Urban growth modelling in simple terms can be referred to as a way of translate the theoretical analysis of urban growth into a more tangible and visible format that can be applicable in actual representation of urban growth. Modeling of cities enables spatial planning, which optimizes the use of available land and for better environmental management.

However, looking at the study area for this project thus the Copenhagen Metropolitan area, the urban growth of cities like Copenhagen and Malmø in the Scandinavian region today is closely linked to the fact that since World War II, the highest population boom in these cities has only recently increased now. The boom in population figures suggests that people prefer to live, invest and work in the cities (Copenhagen Municipality 2011).

Batty and Longley, further acknowledge that cities do not only attract people and create a platform for businesses to flourish but also adding that even the largest cities started very small as hamlets driven by the size of its population and economic power to produce and consume (Batty and Longley 1994). The transition of Copenhagen from a small town to a metropolitan area follows the same pattern that Batty and Longley mention above as seen in the figure 8 below:

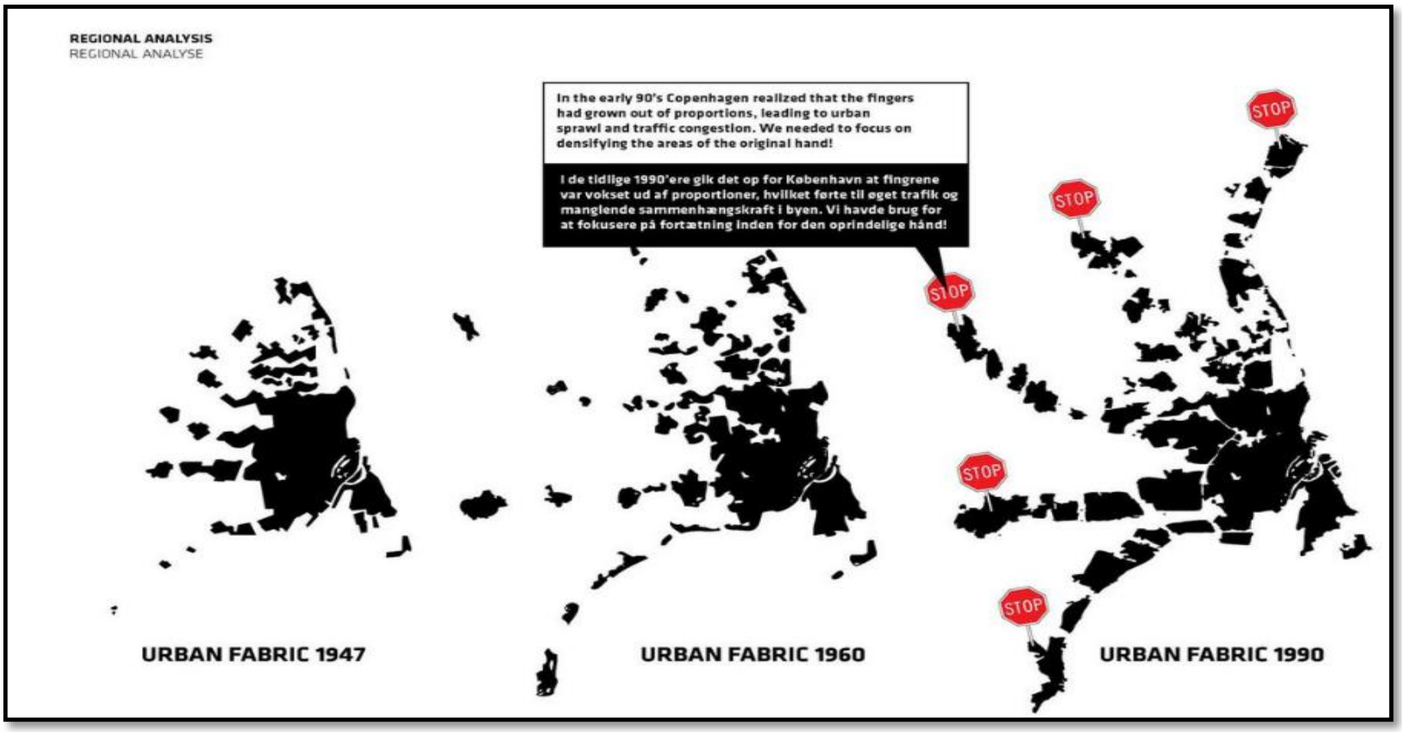



Figure 8: The Urban growth of Copenhagen from1947 to 1990. Source: (Realdania 2014, p20)

In the bid to improve the urban environment around Copenhagen and to manage the fast growing population, the Copenhagen municipality was offered several urban development proposal for example the 'Ringbyen' or Loop city vision.  The vision was coined and presented to the Danish parliament in 2010 with the idea to create a ring-like connection of Copenhagen to the suburb. One of the ideas included introducing a light rail to connect the inner city to the suburbs thus bettering the accessibility in the area. (Realdania 2014, p2).

When attempting to model urban growth, Batty explains that just like all science, theories need to be proven and tested, in order for them to become acceptable and applicable. He further adds that since urban growth theories cannot be tested in a laboratory, the use of computer technology to simulate the reality of these mathematical or logical models is important (Batty 2009). Furthermore, in an attempt to model urban growth, Forrester argues that when starting to model a system, modeling a general class of a system thus a model that represents the characteristics common to most urban settings makes the modeling process more realistic by focusing on the system components, which are directly linked to urban stagnation and growth (Forrester 1969).

In many cases, urban growth is referred to as a complex system, which involves land use modifications from virgin territory to commercial uses. According to Cheng, "*Urban growth is in essence a complex subsystem; it involves multiple actors with differing patterns of behavior at various spatial and temporal scales. It centers on understanding the dynamic interactions between the socio-economic and built environments and major natural environmental impacts",* (Cheng 2003, p2).

The complexity of a city as a system has however been defined by its characteristics arguing that the ideology of what is complex and what is not is different from source to source. Lahti, cited Borredo *et.al* as mentioning the characteristics of a system to include the ability to self-organize and be self-similar thus they do not get more complex but instead create an orderly pattern like fractal patterns (Lahti 2008).

However, in the bid to better understand how these models work, it is important to be able to define what a model is. One relevant and simplified definition of a model for this study was given by Batty as follows: "*Models are simplifications of reality – theoretical abstractions that represent systems in such a way that essential features crucial to the theory and its application are identified and highlighted"* (Batty 2009, p52).

### 3.4.1 The Land-Use Scanner Model.

Some examples of the models used in land-use modeling include the Land-use scanner and the Environment Explorer developed by the Netherlands Environmental Agency. The Land-Use scanner used to forecast possible uses of a piece of land by integrating specific inputs from other models is part of a chain of many sector- specific models. The model bridges the gap between the different models by deriving its inputs from them and providing outputs specialized for hydrological, environmental or other specific purposes. The model does not factor in the changes in land-use but with the influence of external factors like land-use policies, current land-use, the model can be applied to extrapolate the best suitable use of a given piece of land (Koomen and Borsboom-Van Beurden 2011).The Land-Use scanner model as shown in figure 9 below:

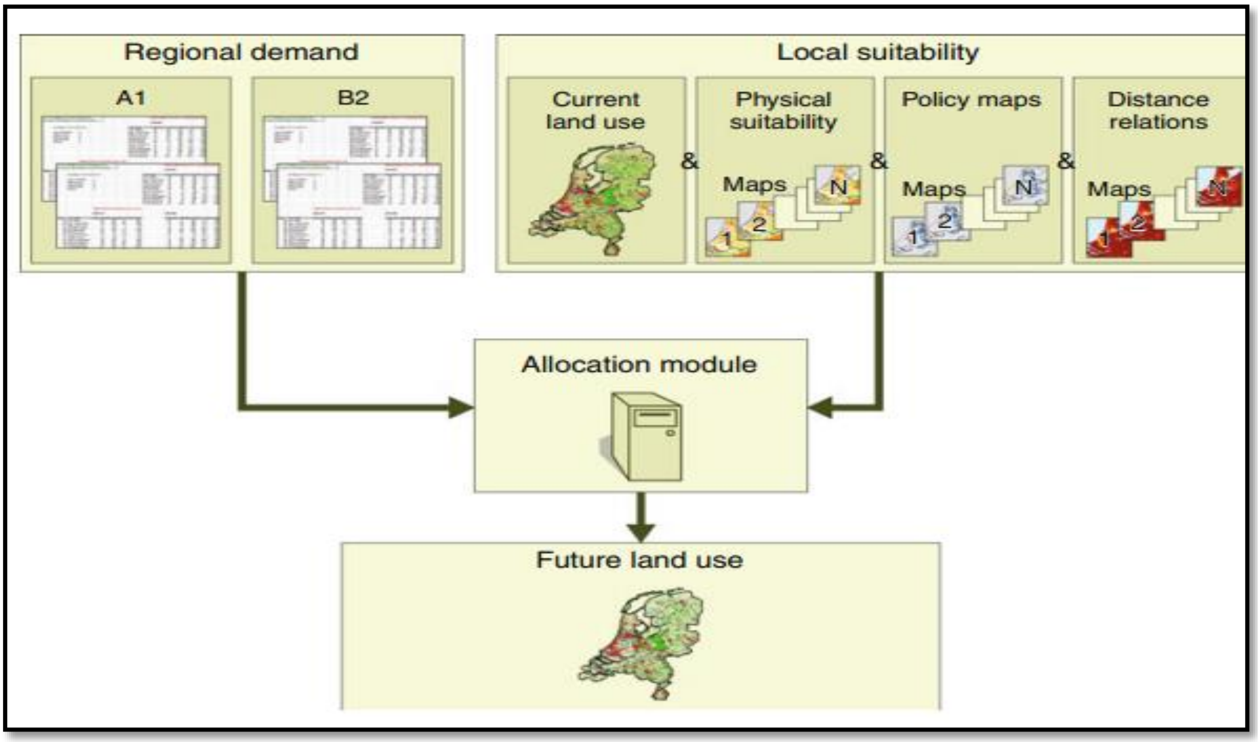



Figure 9: The land- use scanner model. Source: (Koomen and Borsboom-Van Beurden) 2011, p.9

### 3.4.2 The LUCIA model.

The LUCIA model has been used before in modelling various phenomena in land-use change and according to (Hansen 2007), the Land-Use Change Impact Analysis model (LUCIA) is a simulation grid based model. By incorporating socio-economic factors into the model, future land-use predictions can be made and analyzed. LUCIA, aims at helping in the decision making process by involving the public through the public participation phase where they get to contribute to the region plans. One of the main areas where the model can be applied is in the modeling of land-use change in the coastal areas.

LUCIA for coastal areas is able to simulated land-use by categorizing the land into three types namely, the active land-use, passive land-use and static land-use accordingly. Depending on what the simulation is used for, the common driving factors for LUCIA are economic and population growth (Hansen 2007). The other factor can include specific areas of interest like the soil fertility, environment services, biomass, forests, watershed analysis or coastal zones whereby the model is used to gauge the land-use changes in these areas (Marohn and Cadisch 2011). In Denmark, coastal zones are facing a threat from the on-going encroachment by the expanding need for land to build summer cottages. The LUCIA model has been used to simulate the effects of this behavior (Hansen 2007).

Hansen further elaborates that like most modeling systems, LUCIA applies four main elements namely, the accessibility factor thus what is the level of accessibility to the land in question. The proximity factor thus considering the neighborhood of the land (cell) of interest. There is a tendency that their neighbors affect cells, LUCIA applies the similar principle. The other elements are suitability and the attractiveness of the area.

Since the model is also cell-based, the procedure is in steps. In step one: the weighted linear method is used to combine the factors used. Step two: the creation and multiplication of constraints with the expression factor from the Boolean maps with only permitted and excluded areas. This is calculated as shown below (Hansen 2007, p160).

$$P^L(\mathrm{t+1}) = C^L 1(\mathrm{t}) * C^L 2 * \ldots C^L \mathrm{n} * \sum(W^L \mathrm{i} * F^L \mathrm{i}) \qquad (1)$$

Whereby:

P = Transition potential

C = Constraints (0 or1)

F = Factors (values between 0.0 and 1.0)

w = individual weight factor between 0 and 1

L = land-use type

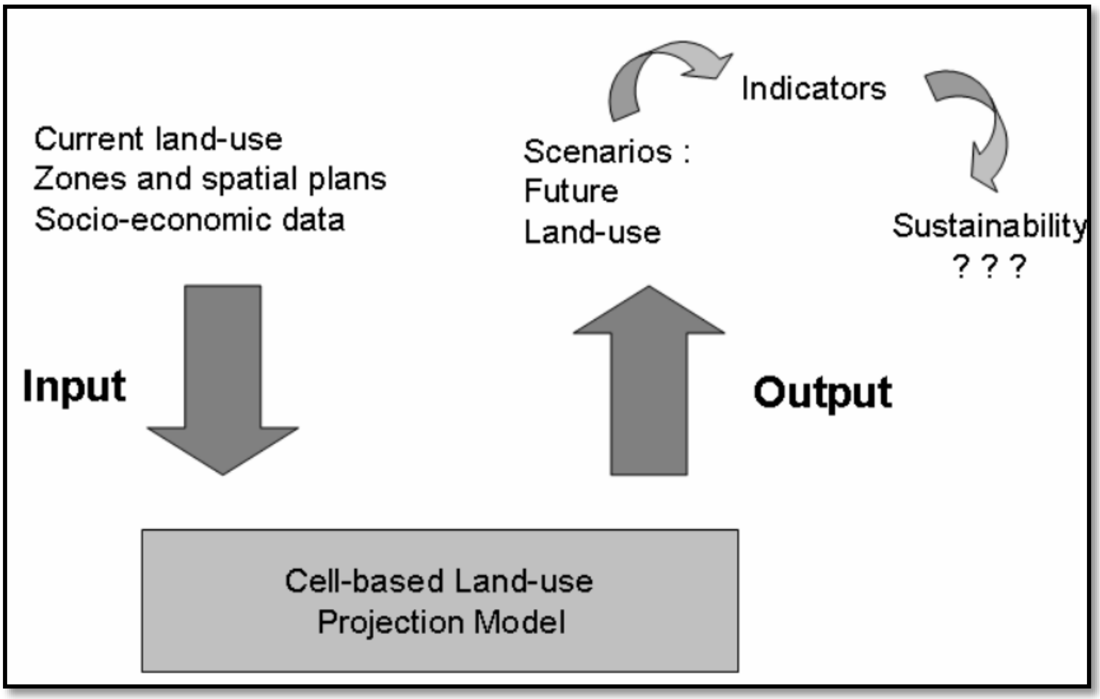



Figure 10: LUCIA land-use simulation model. Source: (Hansen 2007, p160)

### 3.4.3 The Agent Based Model (ABM).

In urban modelling, city planners and other users have leaned more towards some models than others have. However, dynamic and spatial models are more favored because of their ability to clearly capture and visualize the ideas for better planning and policy making for urban areas.

The Agent Based Modeling (ABM) as one of the models commonly used was originally developed by a mathematician by the names of John Conway as a game known as the ‘Game of life in the 1970s. The game’s framework is built upon the Cellular Automata concept (Gardner 1970). The ABM as a model is now used to represent how populations and various objects behaved through time and space thus creating a pattern that can be modeled. This model has help provide understanding for the dynamics and complexities in urban growth processes (Donghan and Batty 2011)a.

Furthermore, Macal and North elaborate on the close relation of ABM to various fields like computer science, system dynamics and social sciences to name but a few. In order to understand ABM, it is relevant to understand the components that make up this model Macal and North describe an Agent in ABM as an individual with characteristics than can be identified though discrete residing in an environment where it interacts with other agents. It is also adaptable to its environment based on experiences with a sense of self-direction and goal-motivation in behavior as shown in the figure 11 below (Macal and North 2005).

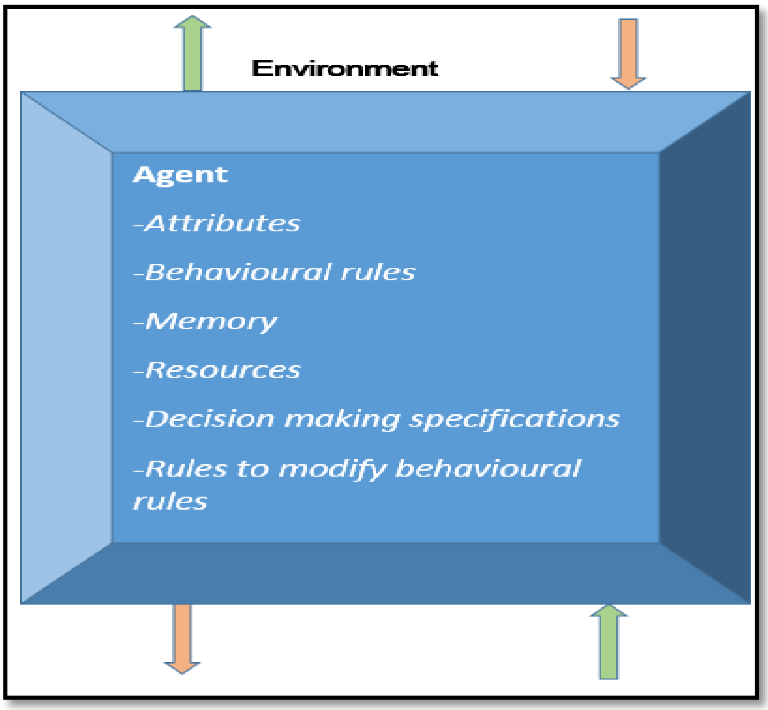



Figure 11: Attributes of an Agent. Adapted from (Macal and North 2005, p3).

The advantage that ABMs may have over the other modeling systems is its ability to include the human aspect into the model's setup thus helping to enhance the understanding of some social complex factors in the urbanization concept. The framework of ABM makes it much easier to analyze real world phenomena like land-use change thus the reason why it is one of the key modeling systems in explaining urban complexities (Batty, 2005).

## 3.5 Modelling with Cellular Automata (CA).

Invented by John Von Neumann and Stanislaw Ulam in the 1940s (Torrens 2000), several researcher like Batty, 2004, 2011; Batty & Longley, 1994; White, 1997; Torrens, 2000, 2012; Clark & Gaydos, 1998; to mention but a few have , explored and analyzed the capability of CA to model various phenomena for example urban growth and its complexities. Torrens further defines CA as made up of an element known as an Automaton which is a parallel process thus carrying out more than one process at any given time. The machine is fed data from which it produces the necessary information (Torrens 2000).

### 3.5.1 The Neighborhood

There are however two commonly applied versions of CA one by Von Neumann, which consist of four cells enclosing a cell in a square, lattice commonly known as the Von Neumann neighborhood and the other by Edward. F. Moore, which consist of eight cells on the outside of a square lattice of a central cell thus the Moore neighborhood in CA and the cell size of both types can be increased accordingly. These two types of CA as shown below have revolutionized the dynamics of modeling.

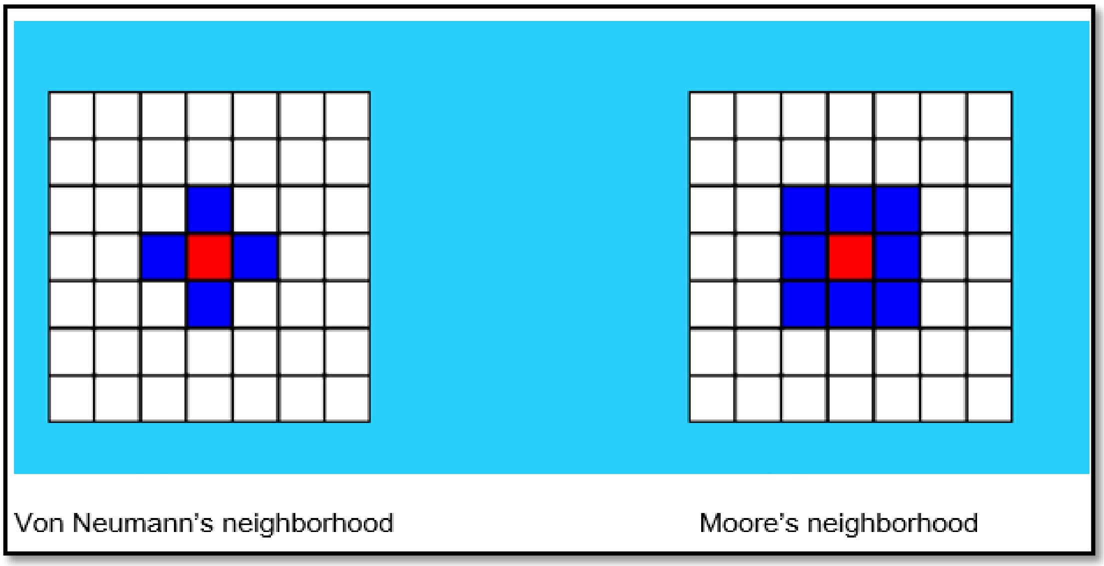



Figure 12: Cellular automata neighborhoods by Von Neumann and Moore. Source: (Hansen 2013)

Hansen, further outlines some of the characteristics of these neighborhoods adding that *'neighborhood comprises the localized region of a CA lattice, from which the finite state* *machine (cell) draws input and consists of a CA cell itself and any number of cells in a given configuration around the cell* ', (Hansen 2013).

Additionally, modelling urban growth there are some attributes like the population of an area, which are usually factored in modeling urban growth. These attributes can be indexed for example by using the cells in the CA model because of the fact that the cells in themselves are permanent and do not change. Cells can also accommodate other urban growth attributes like boundaries of land, land-use zones, and land cover types, among others (Lahti 2008).

### 3.5.2 Cell state.

Using CA in simulating urban growth gives somewhat direct result because of the transition rules involved. These rules question the state of the cells and their neighborhoods (Demirel and Cetin 2010). Cell-states are usually characterized by the attributes of finite state (Hansen 2013). This therefore means that each cell can be given a value for example from 1-5 machines in a Cellular Automata lattice.

### 3.5.3 Cell size.

Various cell sizes have been applied by several researchers such as (Clarke and Gaydos 1998) with a nine-cell Moore neighborhood or (White and Engelen 1997) with 112 cells distributed within 6 cells thus with no particular formula of how to get the correct cell size except for the trial and error method. However, the most suitable cell size should ideally be able to represent the smallest possible entity in the lattice. Within the urban context, the Lattice may be represented as physical structures, transport networks, whereas the cell space could ideally be the landscape or type of environment (Lahti 2008).

### 3.5.4 The Transition Rules and the Time factor.

Additionally Macal and North explain that CA being a lattice of cells, which at any given time can take on a finite number that is pre-determined by the previous state also, operates under some rules in order to update the state of the cells. These rules are follows:

**Rule 1:** for the cell to stay ON in the next phase, three of its digits in the eight neighboring cells have to also be ON.

**Rule 2**: The second phase states that cell in question will not be altered if exactly two of the neighboring cells stay ON.

**Rule3:** In the final rule, the cell is rendered OFF if rule one or two do not apply.

The use of CA is urban simulation has also been affected by other outside factors that cause the model to develop some inconsistencies also known as ‘noise’ or ‘randomness’. According to Yeh and Li, this ‘noise’ can also be introduced by the transition rules into the model in form of a stochastic disturbance indicating a non-uniform urban pattern in the model (Yeh and Li 2001).

Therefore, in relation to urban modelling, the concept provides better results in terms of clarity and interpretation in an urban model for local users like the municipalities and the planners due to its ability to represent various classifications of data simultaneously (Hansen 2003).

When modeling, there are certain aspects of measurement that cannot be precisely established for example adjectives like taller, smaller, long, short, slow or fast. In such cases, these non- numeric measurements have to be represented in another way such that a computer can process them. One of the ways to do this is by using the Fuzzy logic concept whereby the result is generalized and an algebraic structure is attached to it (Rojas 1996)

Therefore, based on the transition rules mentioned above, the foundation of how CA operates is established (Macal and North 2005). These rules are further illustrated by the figure below, with the assumption that all the cells have similar characteristics except for the cell of interest and its surrounding neighbors. To understand the rules of transition in a scenario of urban growth whereby the cell states change with given time, can be attributed to the factors favouring urban growth or the vice versa. The influence of such factors on the neighborhood cells therefore dictates the state of the given cell thus whether it’s going to change from undeveloped to developed which is usually the case. However, there is also a rare possibility of the cell state changing from developed to undeveloped.

The effect of the Time step (t) feature of the lattice in the figure 15 below is represented as the yellow spot for the urban area (developed space). The black spot for non-urban (undeveloped) and the‘t’ for the time step When the input is introduced into the model. In time‘t’ this time step will change to‘t**+1’** (Liu and Phinn).

The length of the Time step in CA varies for every model and since it is not a fixed concept the method allows for dynamic structural pattern simulations as the cell states change from t=0 to t=30.

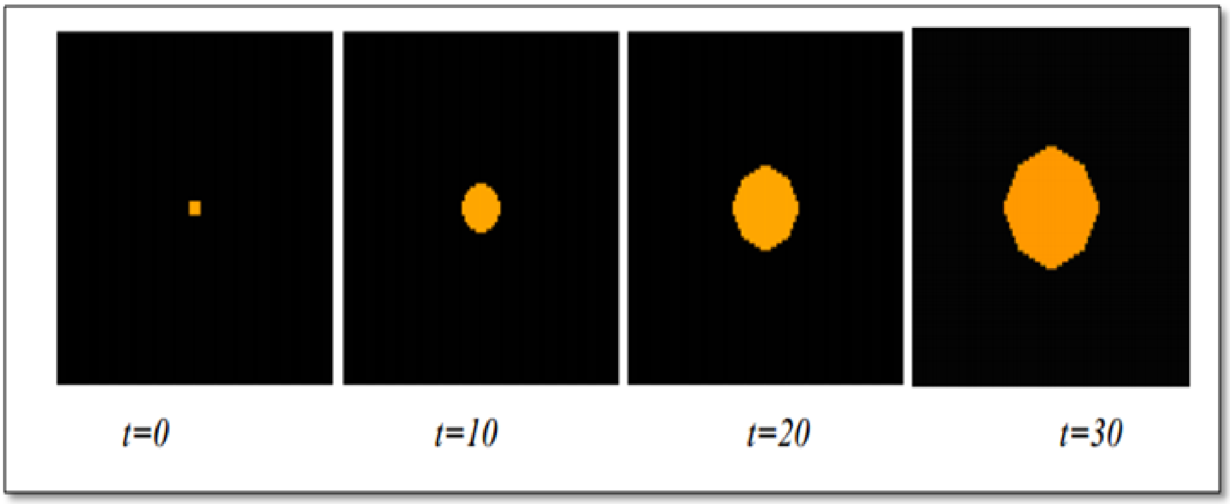



Figure 13: Urban growth simulations using CA. Source: (Donghan and Batty 2011, p6)

### 3.5.5 Strengths and weaknesses of Cellular Automata.

The use of CA as a modeling system is one of the popular methods today.

Several researchers will agree to it for example (White and Engelen 2000) have given some of the reasons as to why CA works in urban modeling namely:

1. The method is simplistic and almost straightforward in nature. This means it is easy to apply in a computer-based environment to attain efficient outcomes.
2. The spatial element in CA representations may be dynamic but reliable and effective in displaying the results.
3. Because CA is rule- orientated, it is possible to incorporate other factors in the simulation with a vast array of spatial behaviors.

However, CA is not without shortcomings. The CA system does not effectively represent the behavioral patterns of the cells in question and it does not clearly capture the relationships with distant cells because it concentrates mostly on the local interactions (Hansen, Fuglsang and Munier 2013)

Lahti (2008) also further notes that CA has weaknesses when processing the top-down hierarchy thus making it impossible to use in incorporating new policies in urban development. The changes that take place in urban settings are usually prone to change and as such, a model used to capture or incorporate these changes should be able to do so efficiently. Some researchers have combated this problem with CA by assigning zero to the affected cells thus adjusting or increasing the suitability level of the model accordingly (Lahti 2008).

In the further pursuit for understanding the patterns of land-use (Hansen 2007), points out that Concentric Zone Model was invented by Burgess over one hundred years ago and though later revised by others like Hoyt, Ullman and Harris. Their version known as the Multiple Nuclei Model helps in the understanding of diversity of land-use patterns in the actual cities is an ever-evolving kind of mystery.

Nevertheless, Ramachandra and Barath (2013), elaborate on the need to understand models like land- use models adding that if urbanization is not planned, it could potentially become harmful to the environment and the natural resources. They also emphasize that land- use needs to be understood and modelled not only on a spatial scale but also on landscape scale thus the changes brought about by the change in land-use can have environmental implications that need to be addressed.

It is proven that urban development in cities in generally follows the bottom up pattern (Batty and Longley 1994). Cellular Automata method is used for the study because of its ability to capture urban change patterns and phenomenon, prediction of land-use change, urban growth, traffic control and environmental scenarios among several other uses. Due to the fundamentals that are inbuilt within the system like the time, transition rules, networks, neighborhood and cell status the method is used in Chapter four to simulate the urban growth in the greater Copenhagen area.

### 3.5.6 Calibration and Validation.

In the modelling process, the terms calibration and validation have been referred to by several authors like (Donghan and Batty 2011), (Torrens 2011), (Engelen and White 2007), among others however their proper definition has somehow be elusive. Pontius *et al.* emphasize that it is important to have a clear definition for these terms as lack thereof could cause confusion in this field of study and could mislead people through (Pontius Jr, Huffaker and Denman 2004).

According Torrens, '*Cellular automata models are generally calibrated by tailoring the parameters that control transition rules. In addition, calibration may be performed on a state-basis or cell-basis, allowing special conditions by which the normal state transition procedure for those states or cells might be specially treated'* (Torrens 2011, p4).

Sometimes it is important to understand why there is a need to calibrate and validate models. In this study however, the emphasis was not placed on this but it was necessary to simply define the reason as to why calibrations and validations are necessary. The concept of calibration whereby the actual values are compared to the simulated is carried out to help assess the best fit. This statistical procedure uses the coefficient values, which are then used to calculate which parameters have a more realistic representation of the original dataset.

According to Deitzel and Clarke (2007), calibrating a model is vital in that it helps to check whether the model will be able to replicate a similar growth pattern as in the original file used as an input to run the cellular automata model. The calibrated values generated from this process can then be used to make future growth predictions in what they call the 'Brute – force' in their SLEUTH model. (Deitzel and Clarke 2007).

Some of the way through which a model can be calibrated include; the stop –rule. In this method, a rule is derived to regulate the simulation procedure to a certain extent or defined parameters. Some of these stop- rules could be administrative, environmental restrictions or political influences. An example given by Torrens indicates that the stop-rule method can be applied in urban modelling with the assumption that a city can only sustainably contain a given population, vehicles or infrastructure (Torrens 2011).

The other method of calibration is what is known as the Threshold method. In this procedure, threshold are introduced to whereby the lower and the upper limits of the classes in the dataset values are fixed. This method may go hand in hand with the visual method in order to check if the threshold fixed coincides with the actual pattern on the original dataset. Torrens, further mentions that when the threshold value is achieved in it always affects the simulation process with a looping effect thus giving the cells new state. These type of transitional analogies are often seen in real urban scenarios (Torrens 2011). The threshold method will likely be applied later on in this study to calibrate the cellular automata model due to its simplicity in the calibration process and straightforwardness.

Validation is usually the next step after the calibration process. Validation takes place after the model has been run whereby the performance of the model is assessed. There are mainly two ways to carry out the validation; quantitative where the goodness of fit is analyzed and the qualitative where the simulated and actual values are assessed.

Another method of validating can be by pixel matching. In this method, the human eye acts as the tool to visually analyze the differences between the simulated and the actual map. By looking and comparing the results from the simulation, the results are adjusted accordingly until a satisfactory outcome is attained. In order to ensure that the visual result is correct, the pixel method can be taken a step further by doing a side-by-side comparison of the pixels between the actual and simulated in a matrix- type table. In their model, Clarke and the others were looking out for incidents like the clustering, the area size, and the shape of pixel edges to help calibrate their model (Clarke, Hoppen and Gaydos 1997).

## 3.6 Patterns and trends of urban growth in Copenhagen.

According to Batty, the multiple processes of how cities function through a time series are dictated upon by choices and the lifestyle of the existing group of people or population at that given time. Their choices form a spatially visible pattern of their activities based on how the land is used this in turn creates trade-offs between economies of agglomeration and the diseconomies thereof. This also means that different activities and population densities in different locations are represented with a unique spatial pattern accordingly. (Batty 2011)

The core city thus the municipalities of Copenhagen and Frederiksberg, and its suburban municipalities make up the greater Copenhagen area or also known as the metropolitan area of Copenhagen.

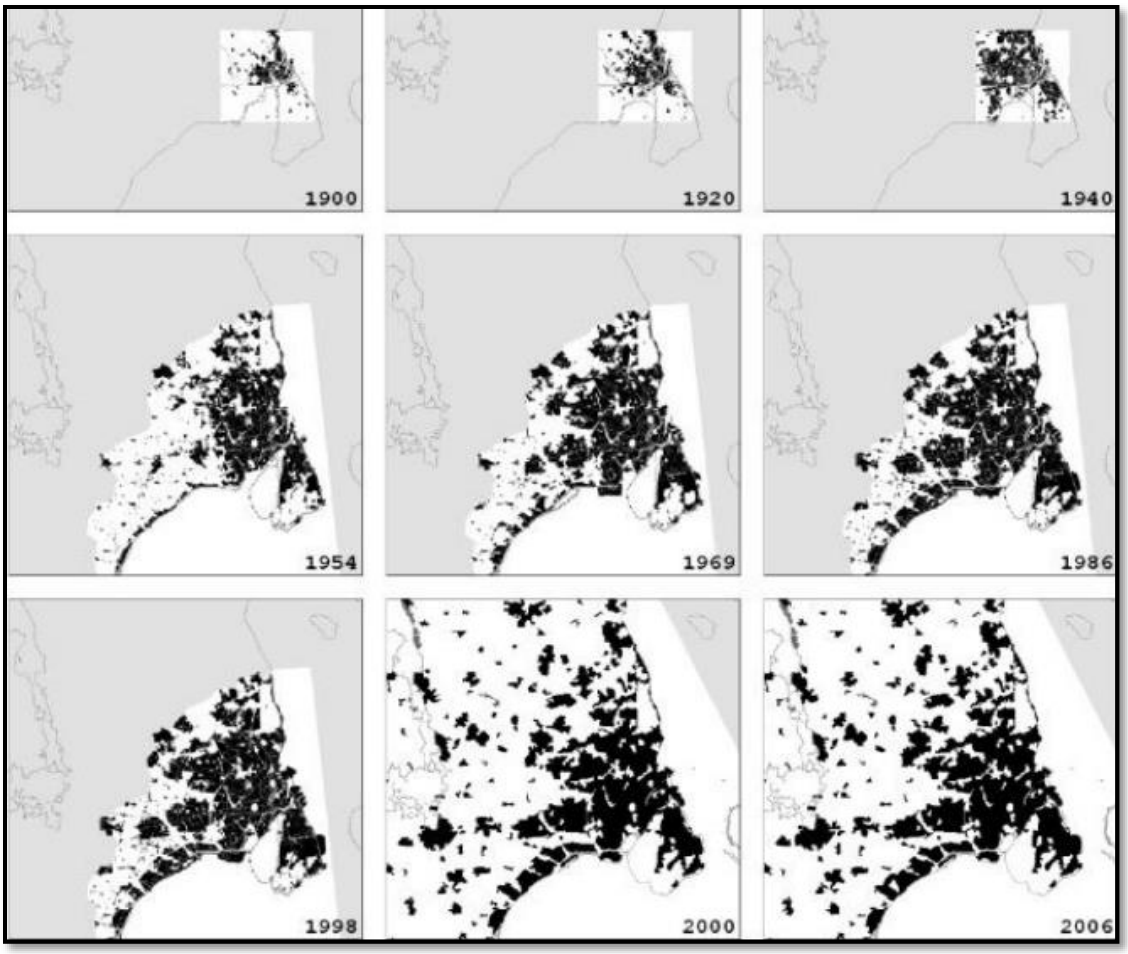



Figure 14: Urban morphological pattern for the greater Copenhagen area from 1900 to 2006. (Fertner 2012, p18).

This area is covered under the five-finger plan, which is the backbone of urban planning in Copenhagen (Østergård 2007). However, just like many European countries, the Copenhagen metropolitan area started as a small core and expanded with time. The city underwent several structural changes as the new planning models were introduced and investments injected into modern urban projects (Fertner 2012)

Copenhagen just like so many other cities around the world has experienced changes in the rates and trends of the urbanization process. According to (Andersen and Engelstoft 2004), Hansen states that in the start of the 19th century, approximately 80% of the population in

Denmark lived on the country side with only 10% in the Copenhagen greater area and the other 10% scattered among the other towns in the country. In the second half of the same century, vast economic growth boosted mainly by improvement in the transportation system led to the growth of several new towns and the expansion of the old ones as illustrated in figure 17 below:

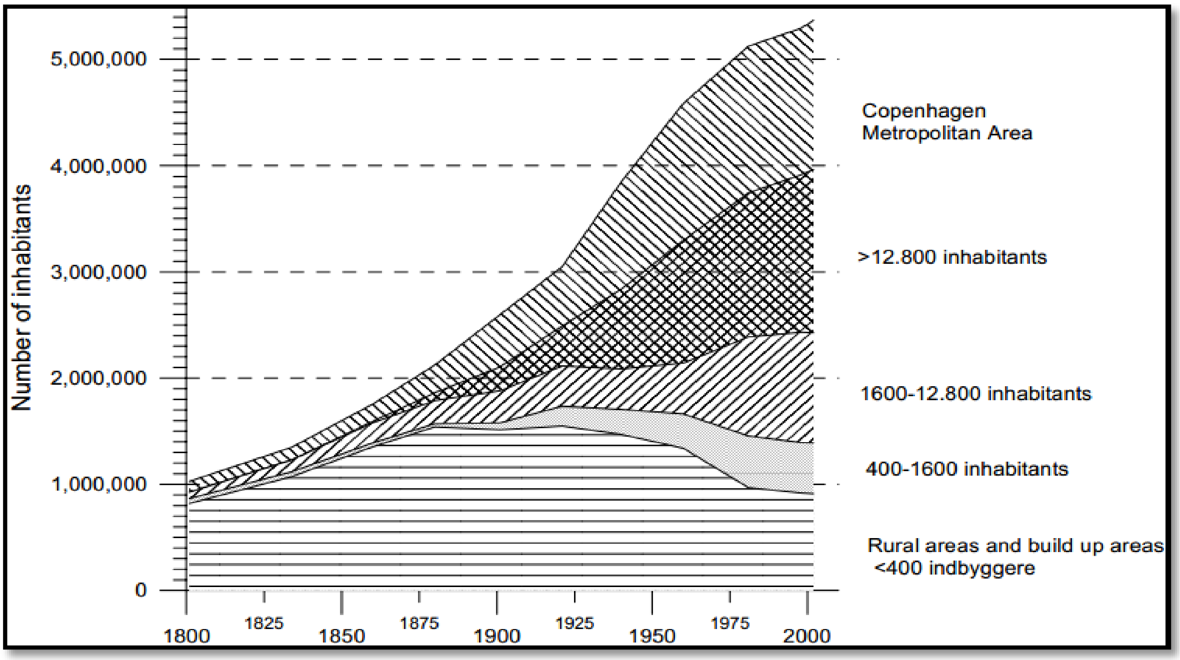



Figure 15: Urban growth trends for Denmark from 1800 -2000. Source: (Andersen and Engelstoft 2004) p. 56

In the case of urban growth in the U.S, the urban economists have identified some of the forces that fuel the spatial growth of these cities some of which include the increase of city population numbers, increase in household incomes thus raising the demand for living space, reduced costs on transport. However, these very factors are influenced by other distortions like market failures thus disrupting the upward growth process causing cities to sprawl (Jan 2003). Sprawling occurs when the growth of cities is uncoordinated but the physical growth fueled by centrifugal forces of population needs and the need for more space for the increasing workforce in the city sustains the urban growth concept using the forces usually in towns and cities (Batty, Bessusi and Chin 2003).

Urbanization trends have changed with the times and these world trends have been noted as far back as the 1950s and in 2006 where the population in the urban areas in OECD countries at approximately 2.5 billion people is already higher than in the rural areas. However, the challenges attached to the population explosion more than half a century ago in these countries are now experienced in the rest of the developing mostly in Africa and Asia where high rates of urbanization are still taking place (OECD 2009)  These trends are clearly illustrated in the figure 16 below:

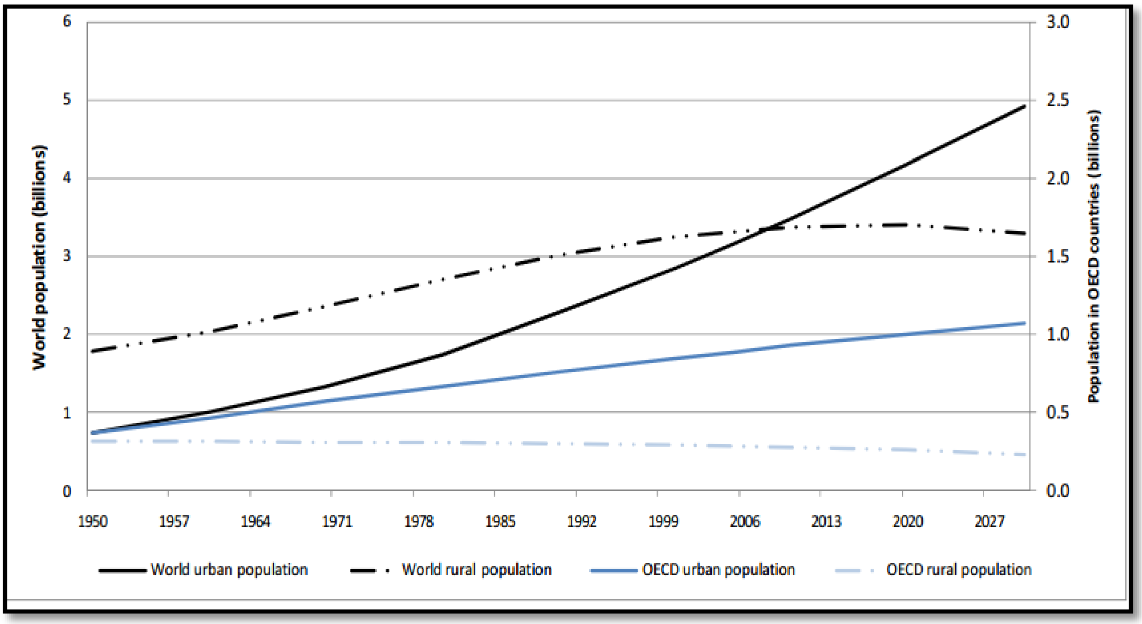
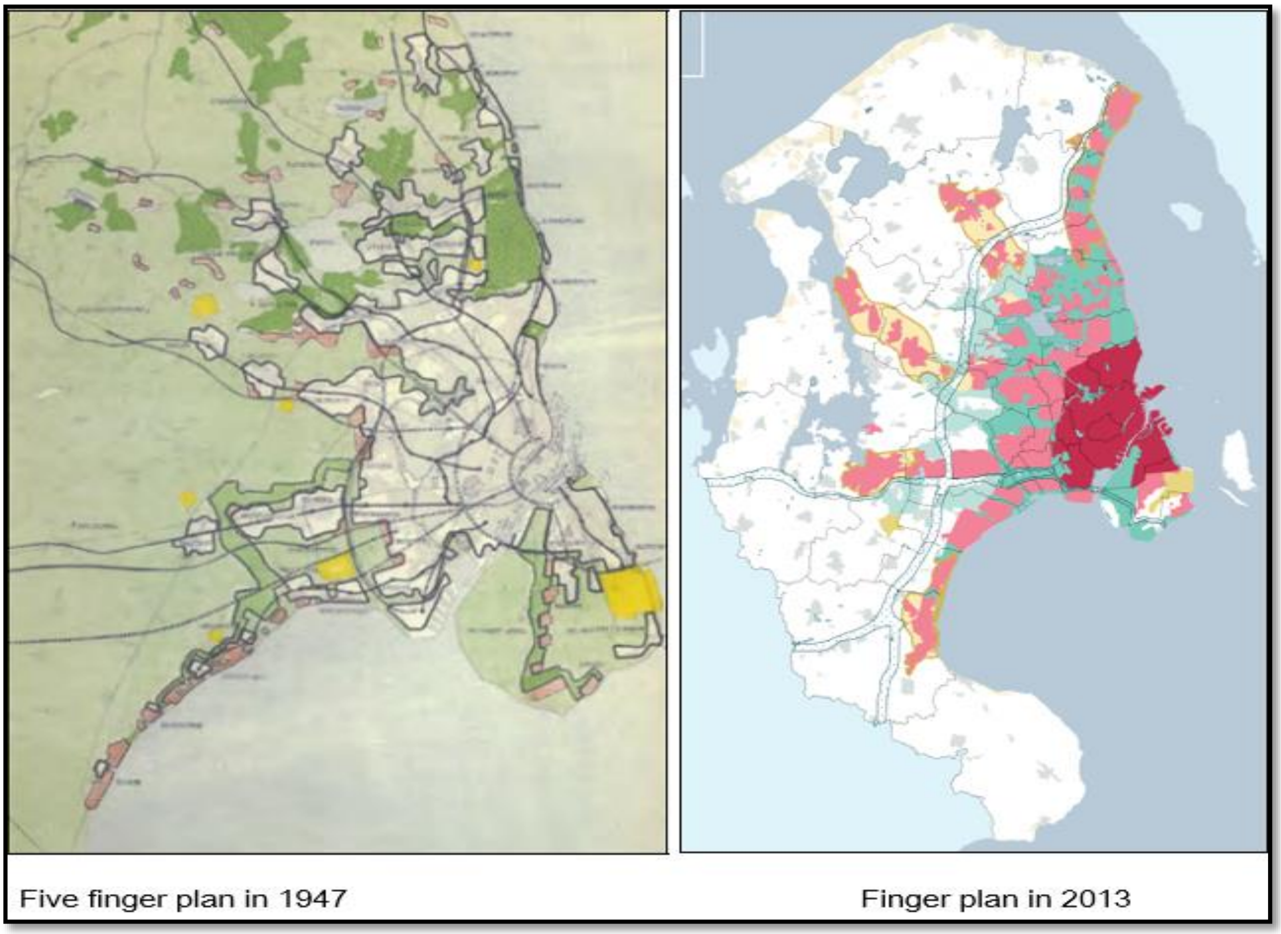



Figure 16: Illustration of OECD urban population trends. Source: OECD 2009, pg.1

According to statistics Denmark report, more space per economic output or per capita is increasingly being used up further reporting 1.4% annual increase in urban area between 2000 and 2012 with an annual population rise of 0.4%. This however has been a trend reported in other European cities too, whereby the cities are expanding twice as fast as the population thus creating a wider gap due to low population growth (Shlomo et al. 2011). With Denmark, during the 2008 financial crisis in the GDP dropped substantially however this did not affect the increase and growth of urban areas.

## 3.7 The evolution of the Finger plan model.

A famous Danish architect called Steen Eiler Rasmussen based urban planning for Copenhagen on a strong framework of an idea that started in 1947. The framework famously known as the ‘five finger plan’ was ideally designed to mold the urban growth of Copenhagen and the suburbs along a finger-like structure. The plan was structured along the railway and transport lines thus directing rather than limiting urban growth along these designated areas. This model carried on and indeed molded the structural make-up of the greater Copenhagen area whereby its influence is still effective even today. For example, the spaces in between the fingers also known as the green wedges are preserved for agriculture and recreation (Maternoski 2013). The finger model has however transformed since then as seen figures




17 below.

Figure 17: Transition of the Five-finger plan from 1947 to 2013. Source: Danish society of Nature Conservation (Danmarks naturfredningsforening) and Finger plan 2013.

The finger plan represents a strong spatial planning background for the greater Copenhagen area going back to the late 1940s. Borrowing its name from the fact that the plan looks like fingers of stretching out from the palm, the plan gained its popularity with urban planners not only in Denmark but also in also other parts of the world.  The model was designed with the major transport systems in mind thus, the S-train lines which run parallel to the major road networks. The finger plan now stretches out to include 34 municipalities, 18 of which make up the greater Copenhagen area today (Bernd et al. 2012).

According to (Cahasan and Clark) the finger model is driven by some principles that define its functionality. Known as the backbone of the urban design and model of Copenhagen the plan has for more than sixty years, steered the urban growth based on the following principles:

- Easy accessibility of public facilities like train stations, leisure parks, road network
- Easy and manageable traffic flow and movement of goods and people.
- Connecting the people easily to green spaces like forests, streams, and the surrounding beautiful landscapes yet living within the metropolitan area.

Today, the fingers as shown in the finger plan 2013 map above run from the core part of Copenhagen city to the outer cities of Helsingor, Hillerød, Frederiksund, Roskilde and Køge. However, there has been a recent addition to the fingers. Another finger joining the region of Oresund to the city core was developed connected by the Oresund Bridge. The finger plan is characterized by railway lines and road networks connecting the outer cities mentioned above to the core city and other parts of Denmark. Part of the network includes the Ring 2, 3, and 4, which encircle the core of Copenhagen spreading outwards respectively (OECD 2010). The Copenhagen greater area is further linked to the rest of the country and its neighbors by one of the major road infrastructures. The big H, which is a set of road and railway networks connecting the various, parts of Denmark forming an H-like format thus the name. The networks are connected with two corridors, one in Jutland to Zealand and the other Esbjerg to Zealand via the Oresund Bridge towards Sweden. The OECD report further predicts the importance of Denmark as a whole to better the infrastructural network connection to the big H. This will boost and support the local industries and businesses in these regions (OECD 2010).

## 3.8 The finger plan zones

The spatial planning for Denmark is managed under the Ministry of Environment with the backing of the 1975 planning Act and with a population of approx. 5.4 million people in Denmark covering an area of 43,098ksq.km. The greater Copenhagen area has since experienced considerable urban growth in the last decades and its functional urban area is reaching up to 100 km from the city center. In the whole country, Forests, Agricultural land, wetlands and water bodies, cover 80 per cent of the land. However, the planning reform has undergone several changes among which include the joining of the counties to form five major regions in the country and the reduction of 275 municipalities to only 98 (Bernd et al. 2012).

The Copenhagen greater area is divided up into four zones within the finger plan model. The division process carried out under the Danish planning Act, allows these geographical divisions to be planned and managed accordingly. These zones are according to Østergård divided up as follows:

### 3.8.1 The Core city

This is the palm of the hand, which is the core of Copenhagen city. This is the center of urbanization and as such, any developments are restricted to this area with great emphasis on improving the public means of transport to the rest of the greater Copenhagen (Østergård 2007) as shown in the figure 18 below

Figure 18: Core city of Copenhagen. Source: (Miljøministeriet 2013, p3)

The greater metropolitan area of Copenhagen comprises of fingers, which stretch out from the core, part of the city to the finger-like surrounding urban area. Along the fingers, the transport network of railways and roads are structured. The easy transport boosts the business growth and furthers the urbanization process along the fingers and the neighboring municipalities (Østergård 2007).

### 3.8.2 The Fingers

This area is both urbanized and non-urbanized with possibilities for further development. For any kind of development especially for industries and companies in this area, the development should adhere to the city plans and the already existent framework of the finger plan and the general layout of the local area or municipality among so many other conditions (Miljøministeriet 2013).

Figure 19: The Fingers in the greater Copenhagen area. Source: (Miljøministeriet 2013, p5)

### 3.8.3 The green wedges/ areas.

This area is divided into two thus the green area comprising of both the internal wedges within Copenhagen city and the coastal green areas also sometimes known as the outer wedges because of their location in the outskirts of the core city towards the Danish coastline (Miljøministeriet 2013)

The green wedges, which are the spaces between the fingers, were ideally designated for recreational areas like parks and leisure areas amidst the urbanized surrounding thus breaking down the pattern of monotony of high raised concrete buildings.

No other kind of development is allowed in this area. The greater Copenhagen area, which consists all the neighboring municipalities of Helsingor, Hillerød, Frederiksund, Roskilde and Køge. The ministry of Environment ideally oversees and regulates the developmental activities in this area (Østergård 2007). According to the Danish ministry of Environment report, different regulations do apply to the leisure industry based on the location of the green area in question (Miljøministeriet 2013).

Figure 20: The Green wedges. (Miljøministeriet 2013, p8)

Infrastructure is a major contributor to urban growth in various cities around the world including Copenhagen. At the end of the 17th century and the start of the 18th, the sea mode of transport in Denmark then was being gradually phased out as new highways were built connecting various towns to support trade. This road construction phase peeked in the 19th century with a vast network of roads and highways crisscrossing the country (Danish Ministry of Foreign Affairs 2008).

The urban development in Copenhagen even today is mostly due to the finger plan, which was coined back in 1947, and thus providing the framework for the urban plans and placing more emphasis on the urban growth along public transport lines within the metropolitan area (OECD 2010).However, the finger plan did not come with some criticism.

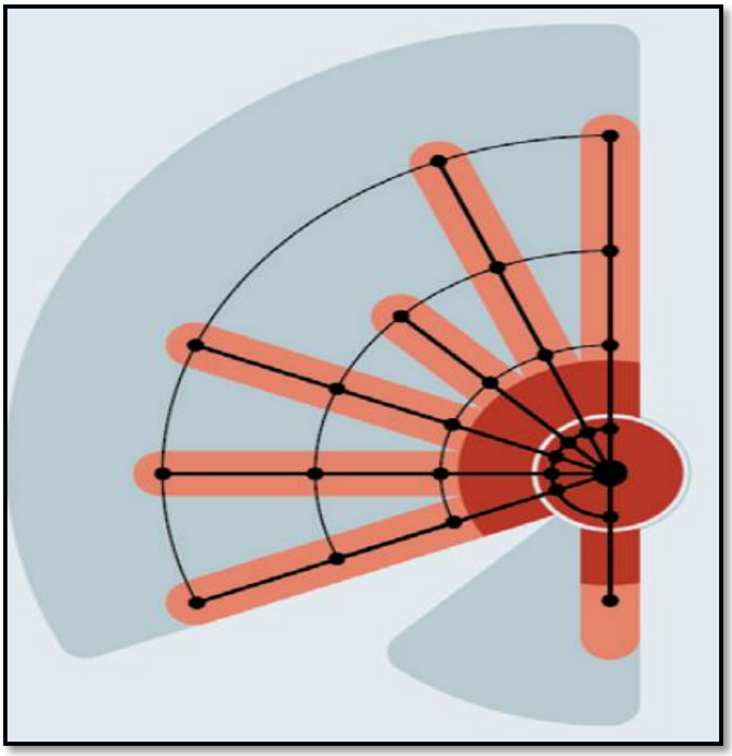


Figure 21: The main network structure in the finger plan. Source: (Miljøministeriet 2013, p2)

Maternoski highlighted that the finger plan's sustainability and ability to control growth outside the core city was threatened. The threat of urban growth in the suburban areas of Copenhagen rendered the finger plan ineffective after 60+ years of steering and controlling urban growth in the Copenhagen area (Maternoski 2013).

This hence has left room for the city to come up with another urban plan, which is being highly considered today by several urban planners. The Loop City plan is one of those key plans today which points out several urban planning challenges like waste, energy, global warming, water that were not effectively sustained within the finger plan due to the urban growth of the Copenhagen Metropolitan area (Realdania 2014).

## 3.8 Suitability in urban growth Modelling.

When the suitability analysis is introduced into urban growth modelling, there are several factors that can be applied to such an analysis: The common factors include:

- Accessibility
- Zoning  (control factor)
- Terrain
- Demographics

However, the suitability of these factors may be evaluated using various criterion depending on the purpose of the suitability analysis and nature of the data used. One of the commonly applied evaluation methods is the Multi- Criteria Evaluation (MCE). Factors or constraints like the Zoning data used for this study in the next chapters can act like the criterion. Additionally, White, Engelen and Uljee note, "*although constraint s have been examined in some cellular automat a models, they are used to make more reliable and reproducible prediction s of actual urban land-use patterns*" (White, Engelen and Uljee 1997).

The use of constraints or control factors as referred to as a means of defining suitability. The constraints can also be applied when considering accessibility thus evaluating whether the area in question is accessible or not by a given means of transportation, where in the case of this study it was railways and motorways.

According to Eastman, the various layers can then be combined using various methods and a formula like this one: S $= \sum W^{i} X^{i}$ (2)

Where S = suitability

$W^{i}$ = weight of factor i

$X^{i}$= criterion score of factor i

(Eastman 2001, p7)

The methods used include the Weighted Linear Combination, Boolean Intersection and the Ordered Weighted Average all of which are used depending on the analysis being conducted (Eastman 2001). Methods like this can now be carried out within the ArcGIS platform too.

### 3.8.2 The Accessibility factor.

The Accessibility factor is important when creating the suitability map for this study and as such little, more about it is mentioned in this section of the chapter. The access points for the study include the train stations and the motorway junctions.

According to Hansen, measuring Accessibility in the real world can be somewhat challenging and using Distance as one of the factors is one of the simplified method of carrying out such an analysis. The Distance can be weighted on proximity to important locations like urban centers, schools, hospitals and road or rail networks (Hansen 2009). In this section of the study, the emphasis is to analyze the relationship between Accessibility to urban growth in the Copenhagen greater area. For this study, the Accessibility factors considered are two thus: Motorways and Train stations. The role-played but the Accessibility factor in urban growth is significant. According to Hansen, the roles played by Accessibility include the modelling of urban land-use, development of spatial policy and regional planning among others (Hansen 2009).

The Accessibility factor is derived when the size of the urban attracting factor is multiplied by a probability based on the distance required to arrive to this point. Due to the fuzziness of the result, an equation like this is formulized to bring normalization to this result (Semboloni 2005, pg.4)

$$A_i = \frac{\sum_j W_{j} e^{-\beta dij}}{\sum_j W_j} \qquad (3)$$

Whereby:

- $A_i$ is Accessibility of the cell **į**,
- $W_j$ is size of that attracting factor which is located in cell **j**
- β is that element representing the inverse average of the transportation cost that will be incurred.
- $\boldsymbol{dij}$ Is the distance between cell **į** and cell **j**.

Semboloni further breaks down the equation explaining that *'the transportation cost is supposed to be influenced by the available technology and by the spatial scope of the urban cluster. For this reason the average distance traveled d is calculated at each iteration and β is re-calculated by imposing that e−βd = vmin, where vmin is some established value'.* (Semboloni 2005, pg.4)

## 3.9 The ABC model for Denmark.

The model is borrowed from Holland where it was first put into action. The model shows various scenarios of business based on its accessibility needs for the transportation networks like motorways. The model explains why some businesses are more suited locations based on the classification method for types of businesses and various types of locations (Martens and Griethuysen 1999).

| **Accessibility profiles** | | | |
|---|---|---|---|
| **Mobility characteristics** | A – Locations | B - Locations | C- Locations |
| **Work intensity** | Intensive | Average | Extensive |
| **Car dependency for business trips** | Low | Average | High |
| **Visitors' intensity** | Intensive | Average | Incidentally |
| **Dependency on freight transport** | Low | Average | High |

Table 2: Corresponding Accessibility to Mobility (Martens and Griethuysen 1999, p3)

In the figure below, the entities situated around point A, which is a junction on a motorway or a train station, do have good accessibility. Point B is accessible two ways by car and by public transportation, which could be railway line. Point C is easily accessible by car and this is due to proximity to the road network or motorway.  The ultimate aim of tis model is to

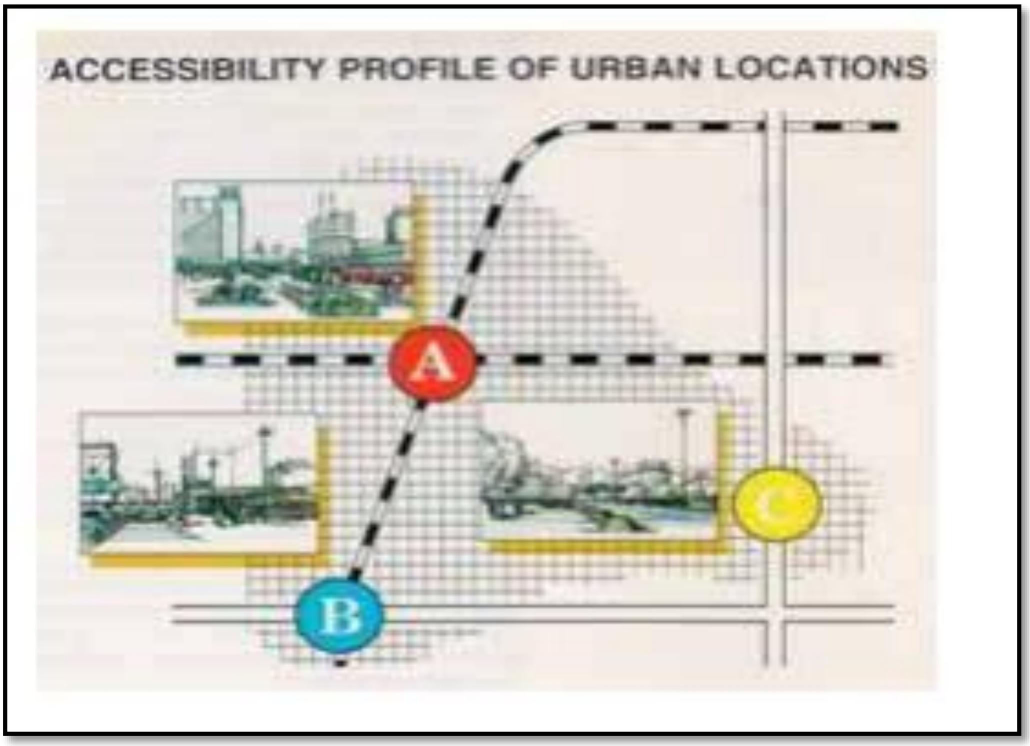



Figure 22: The ABC model for Holland (Kuben Management, Guldborgsund, Lolland og Sønderborg Kommune 2009, p13)

ensure that a business entity is in the right location by considering the characteristics of its mobility (Martens and Griethuysen 1999)

The Danish ABC model therefore has been largely influenced by the Holland model in regards to business locations. In the past, business like warehouse, production and distribution companies in Denmark have been located near transportation networks due to their demand for Accessibility. The similar trend is seen even today with other business like IT companies, pharmaceuticals, service providers among others (Miljøministeriet 2010).

In order for the model to suit the Danish system, the ABC model was coined so the municipalities could use it in the planning and development. Five key steps were coined to guide this planning method and these include:

1. **Classification of businesses**: Thus, which business categories are within the municipality and what are the traffic needs for such businesses.
2. **Areal classification**: To identify the available and suitable areas for the various categories listed in step 1.
3. **Localising the model**: How the two steps 1 & 2 mention above be applied accordingly.
4. **Environmental awareness**: Considering the local environmental impacts caused by the traffic and other factors brought about by urbanisation of the area.
5. **Guidelines and requirements**: The guidelines and application requirements to be fulfilled by the businesses before they are deemed eligible to locate to an area.

(Miljøministeriet 2010, p57)

The municipal planning process for Denmark has evolved over time and today a more solid and iterative model is used. This model has been shaped by repeating the similar planning processes over time and learning from the previous mistakes and avoiding them. The planning and development goals attained by the municipalities are because of strategic planning with consideration to available spaces and layout of the area (Kuben Management, Guldborgsund, Lolland og Sønderborg Kommune 2009). The iterative planning model is summarised as shown in figure 23 below.

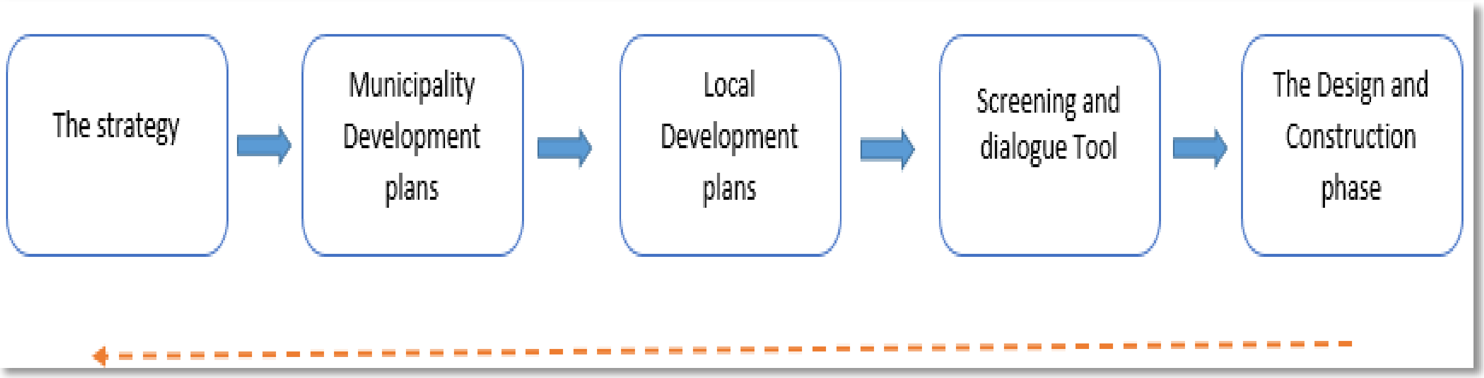



Figure 23: The planning schema. (Kuben Management, Guldborgsund, Lolland og Sønderborg Kommune 2009, p60)

### 3.9.1 The Motorways

There are two main transport networks in Denmark namely the main motorways and the railways, which are interlinked to other smaller roads and other forms of transport like the bus terminals and the cycle paths. The Danish transport system is well connected with motorways connecting all the three major islands of Jylland, Fyn and Zealand. The motorways also connect Denmark to other European countries like Germany, Norway and Sweden among others. According to Statistics Denmark, the motorway network within the greater Copenhagen area comprises of 101 km (Statistics Denmark 2014)

| **Road type** | **km** |
|---|---|
| Motorways | 101 |
| Dual carriageways | 4 |
| Other roads | 1,640 |
| Total road network | 1,745 |

Table 3: Road type and length in the Zealand region of Denmark. Source: (Statistics Denmark 2014)

According to the Danish ministry of Transport, a well- connected and operating transport network helps to thrive the Danish economy by enabling easy and faster transportation of goods back and forth the country. The report further points out that a big percentage of the population in the country depend on public transport to access their businesses and places of work (Ministry of Transport 2012). In addition, the Infrastructure commission for Denmark

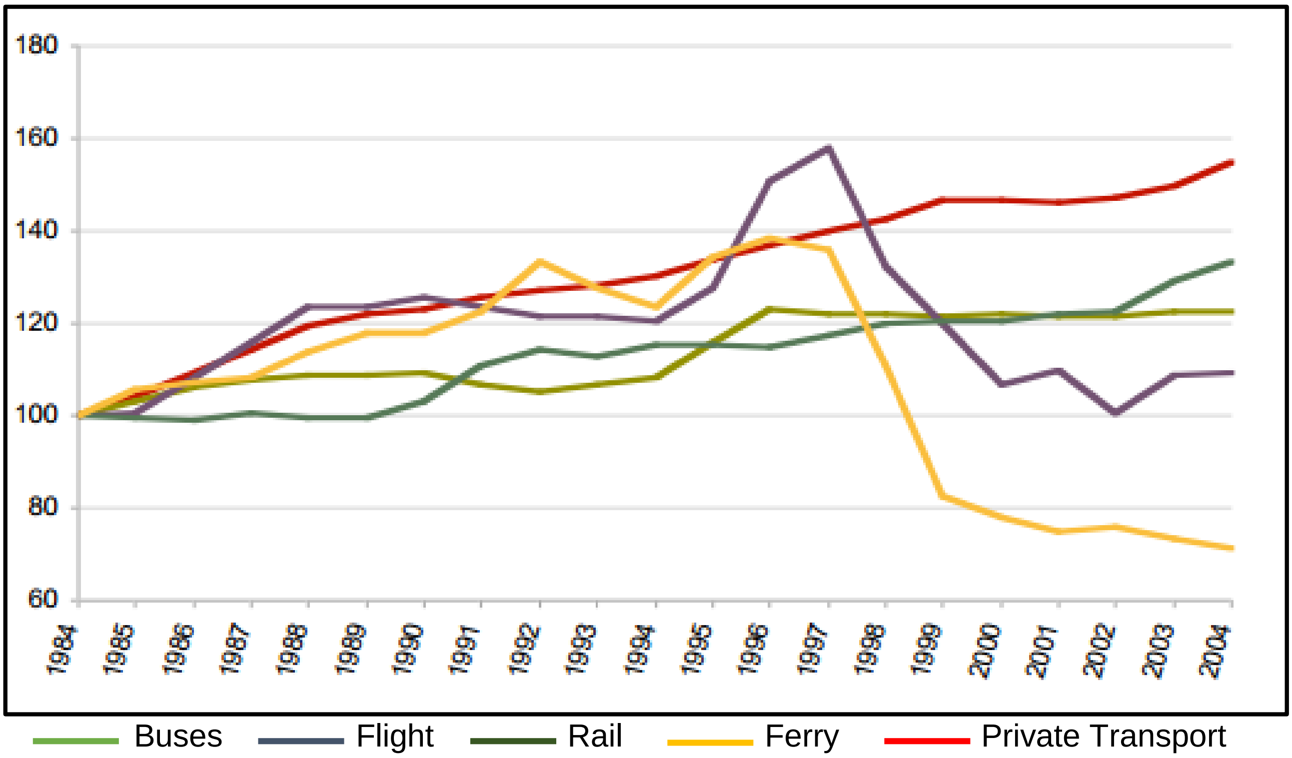



Figure 24: Development of the Danish Traffic system. (Infrastrukturkommissionen 2008, p31)

further reported of a more than 50 percent rise in the traffic on the Danish roads from 1984 to 2004 as shown in the figure 26 below (Infrastrukturkommissionen 2008).

The figures shown above have definitely risen since 2004. Today the Danish infrastructure has developed and improved with a total road network of 74, 109 km of road network in the whole country. Therefore efficient transport network has been considered as one of the major drivers for economic growth due to the accessibility factor for businesses not only in Denmark but also in Europe and other parts of the world (Ministry of Transport 2012).

In the greater Copenhagen area, two main motorways are considered thus the E20, 47and 55 whereby the 'E' represents the European route, thus this motorways connect not only Copenhagen but also the whole country to the other European countries. The European route is part of the United Nations E- road network to create easy accessibility throughout the European Union. Starting from Ireland, the E20 route runs via the United Kingdom, Denmark, Sweden, Estonian and ending up in Russia. In Demark, the route runs from

Esbjerg in Jylland to Malmo in Sweden via the Oresund bridge located in the main island of the Danish peninsula. The E47 on the other hand runs from Lubeck in Germany through Copenhagen in Zealand and joins the E55 on the Helsingør motorway in Denmark to Helsingborg in Sweden. This motorway locally known as the Sydmotorvej in Denmark together with the E20 route create a link between the greater Copenhagen area with other cities in Europe. The E20 and E47 network through the greater Copenhagen area are shown in the figure 25 below.

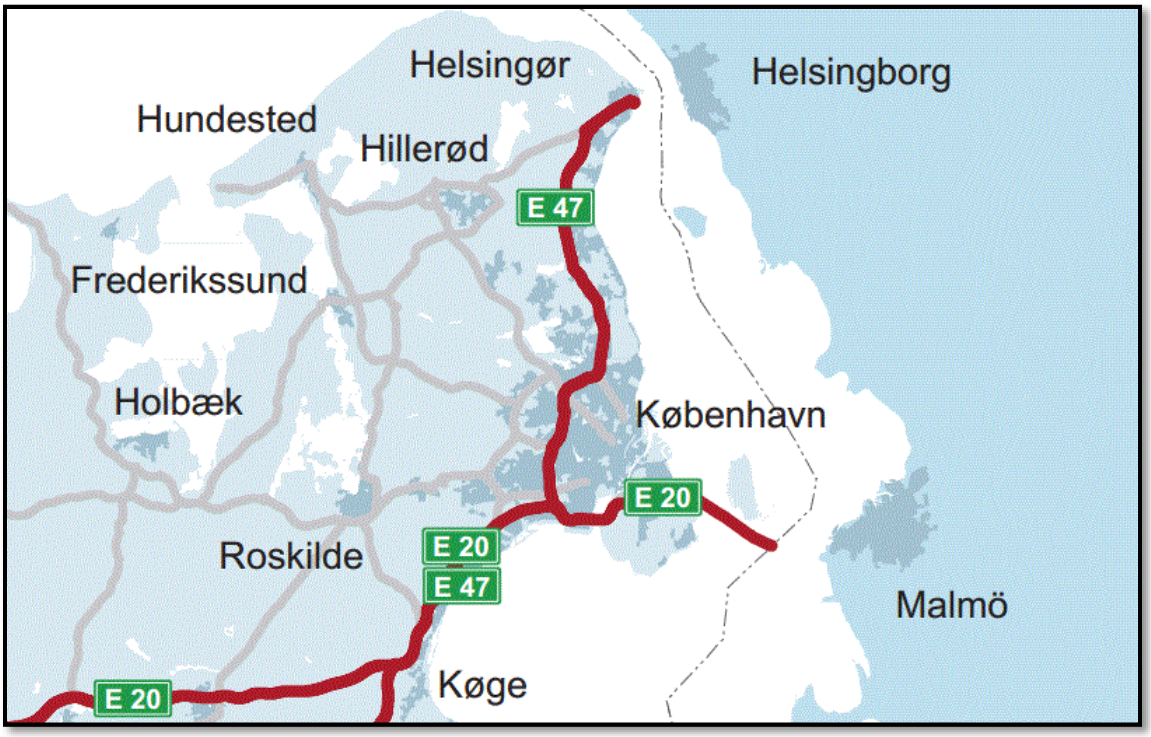



Figure 25: The E20 and E47 routes in from Esbjerg in Oresund in Zealand. Source: (Danish Road Directorate 2013, p46)

### 3.9.2 The railways

The railway network in the greater Copenhagen area is the other form of transportation that is highly used. The Danish railway network is supported by a vast array of rail links therefore making accessibility to the rest of the country and its neighbouring countries easier. Within the greater Copenhagen area, the Danish state railway commonly known as S-train is well established and serves to meet the area transport needs for majority of the population within the Copenhagen area (Ministry of Transport 2012).

The road and rail transport network together make up a solid transport infrastructure for Denmark in general. This infrastructure known as the Big H derives its name from the way it is laid out as seen in figure 26 below.

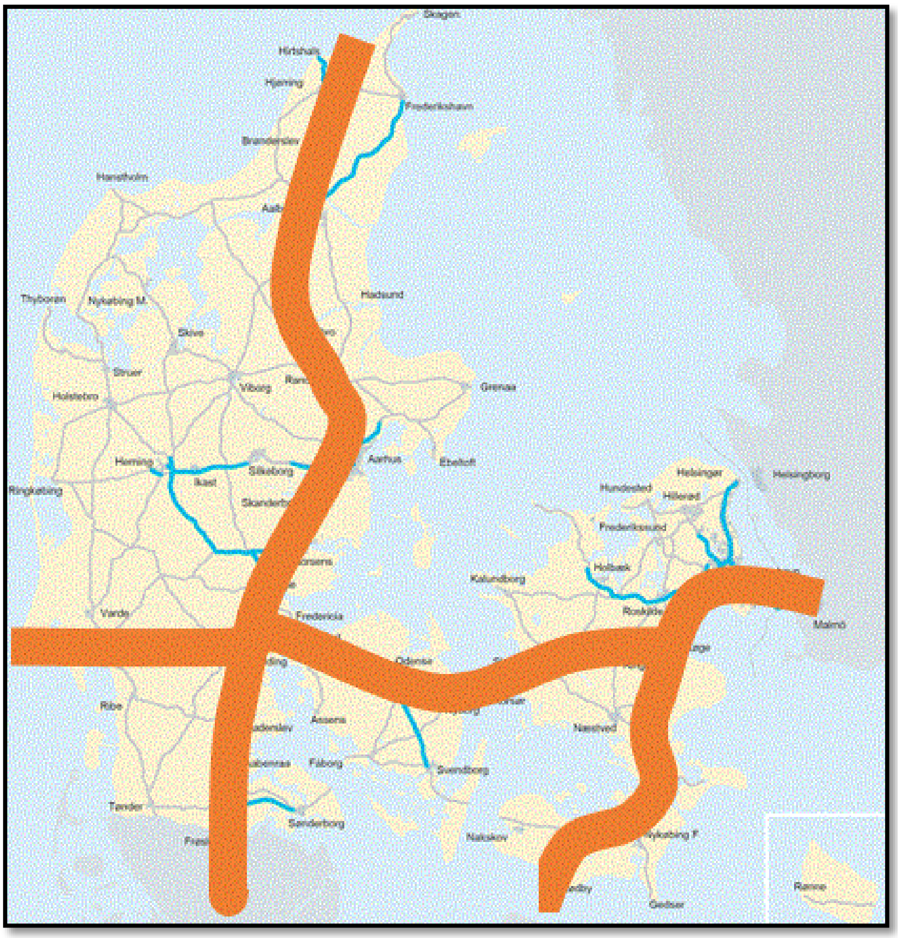


Figure 26: The big H infrastructure of Denmark. Source: (Ministry of Transport 2012)

The Big H connects Copenhagen in the main island Zealand to the rest of the country and to Sweden via the E20 motorway through the Oresund bridge. Together with other road networks that feed the motorways, the time spent travelling from one end of the country to another is greatly reduced.

The location factor of businesses and developers closer to the train stations and road junctions promotes easy accessibility and according to the Danish ministry of Environment, to promote environmental soundness, the large companies with more 1500 m2 requirement for office floor space should to be closely located to train stations in order to encourage people to use public transportation. (Danish Ministry of Environment 2007).

In conclusion, it is important to note that there are several measures of urban growth drivers or indicators. Some of which have been previously explored by other researchers like Cervero et al. (1995), Spillar and Rutherford (1990), Bhat, and Singh among others. Some of the popular urban growth indicators include Accessibility and Density wherein factors like population trends and the existing land-use are incorporated.

When considering what indicators to apply in urban growth analysis it is vital to firstly, define what the analysis is intended for. Secondly, the availability and quality of the data necessary to carry out the analysis (Hansen 2001). The indicators chosen for the study consists of a spatial reference element. This is important in order to enable the mapping process using GIS. According to Cheng, individual indicators in urban growth usually apply to a particular aspect thus dividing the indicators into two types temporal and spatial (Cheng 2003). The indicators considered for this study thus are:

1. Land-use
2. Accessibility to facilities in and out of the city (motorways and railway lines)
3. Population factor
4. Zoning data (protected areas)

# 4. Methodology

In this section of the study, the spatial tools used to do the data analysis are elaborated on. The methodology used is also described providing a better understanding of how the tools operate to attain the results, which are discussed in the next chapter.

However, in order to help refocus the purpose of this study, a recap of the research questions is necessary and they are as follows:

1. What are the key drivers of urban growth in the greater Copenhagen area?
2. Which under developed areas are likely to attract further urban growth and why?
3. How has the five-finger plan model influenced spatial planning in the greater Copenhagen?
4. How can Cellular Automata (CA) help in modelling urban growth in the area?
5. How can the challenges of urban growth in Copenhagen be addressed?

The Methodology flow chart is a pictorial summary of the procedures that will be carried out in this chapter have been summarized in the methodology flow chart below. In this chapter, the data is prepared and extracted in preparation as input for the cellular automata modelling for the urban growth in the greater Copenhagen area. The procedures are summarized as follows:

- Sources of Data
- Processing of Data
- Mapping process
- Cellular Automata
- Quantitative analysis
- Temporal comparison of results

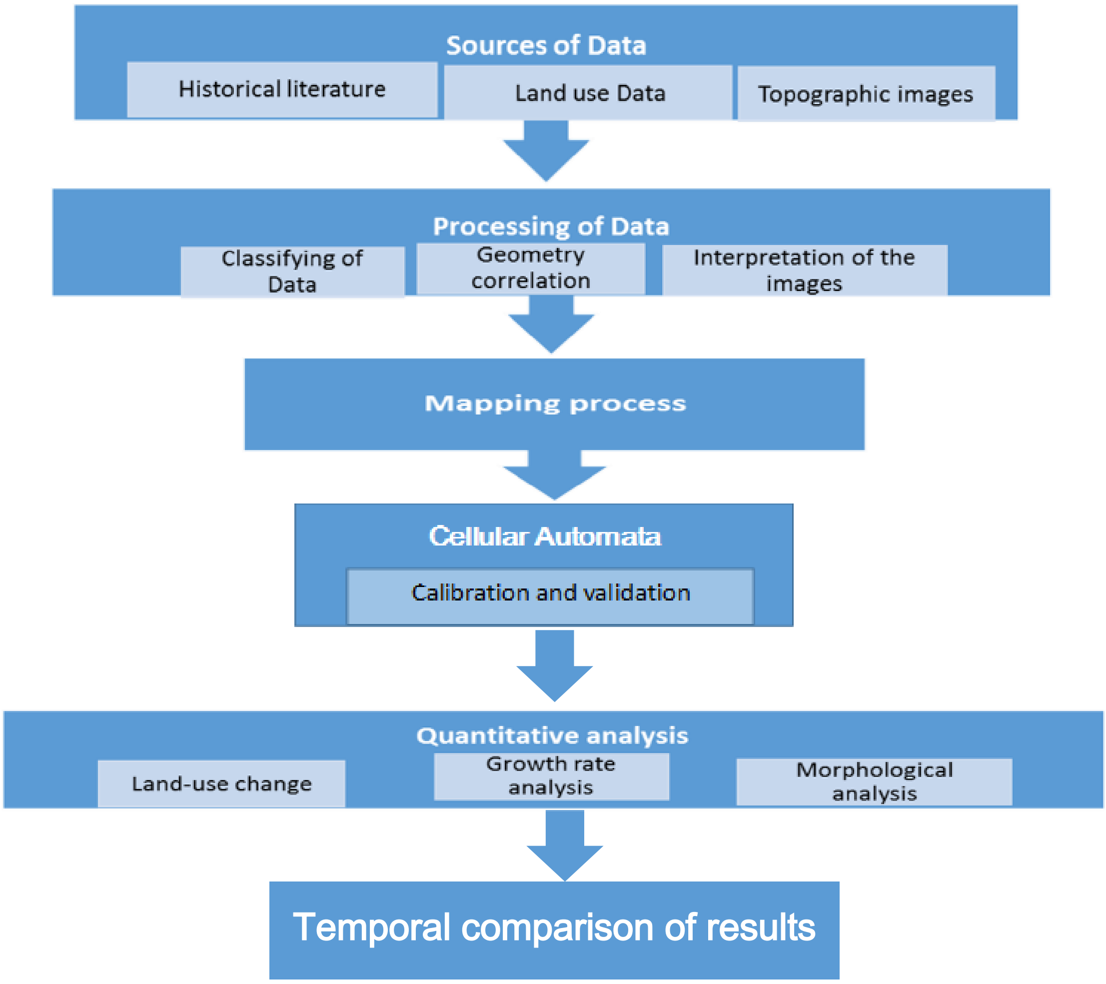


Figure 27: Workflow representation of the methodology chapter.

## 4.1 Sources of Data.

Data required for this study includes topographic maps, satellite images and photos. These mainly provide the visualization of the urban growth factors. These data can be attained for individual use or by companies from the Danish Geodata Agency (GST) thus making it publicly accessible. Other sources of data are available online from various data suppliers. However, it is important to cross- check and ensure that these sources are legitimate and the data supplied is accurate. The data necessary for this study include:

### 4.1.1 Municipalities

The municipalities are represented as a polygon feature class with attributes such as Object ID, shape, municipality number which serves as the unique identifier for each municipality. The greater Copenhagen area consists of 18 main municipalities and then the suburbs. These municipality dataset together makes up the regions of Denmark. The study area is located in the region of Zealand, which is the biggest of the three main islands of the country.

The regional data shows the different islands that makeup the country Denmark. The highlighted area in the map below shows the some of the municipalities of Zealand and the greater Copenhagen area.

The study area was re- projected to the European Terrestrial Reference System (ETRS) 1989 Lambert azimuthal equal-area projection (LAEA). The Administrative boundaries for the municipalities are used to demarcate the extent of the study area however, it should be noted that these boundaries do not ideally restrict or necessarily control the extent of urban growth in the greater Copenhagen area but can only be used as reference for comparison purposes.

### 4.1.2 Roads

It has been shown previously that urban growth in tends to happen along communication lines and networks like roads and railway lines (Hovegesen and Nielsen 2005). The dataset is in vector format and its attributes are namely: Object ID, shape, road class, and type of road, width and the municipality number. The data is supplied and managed by the Danish Geodata Agency (DST). For the purpose of this study, the road dataset is relevant because it helps to accurately locate the road junctions for the analysis later on thus the Danish transport corridor in the Zealand region, which also consists of the E20, E47 and E55 Motorways. The two motorways are busy transport corridors connecting Copenhagen to the rest of Denmark and other European countries like Sweden and as such consists of approximately 800 junctions in Zealand alone. The transport corridor as shown on the map below is also a main business transit route.

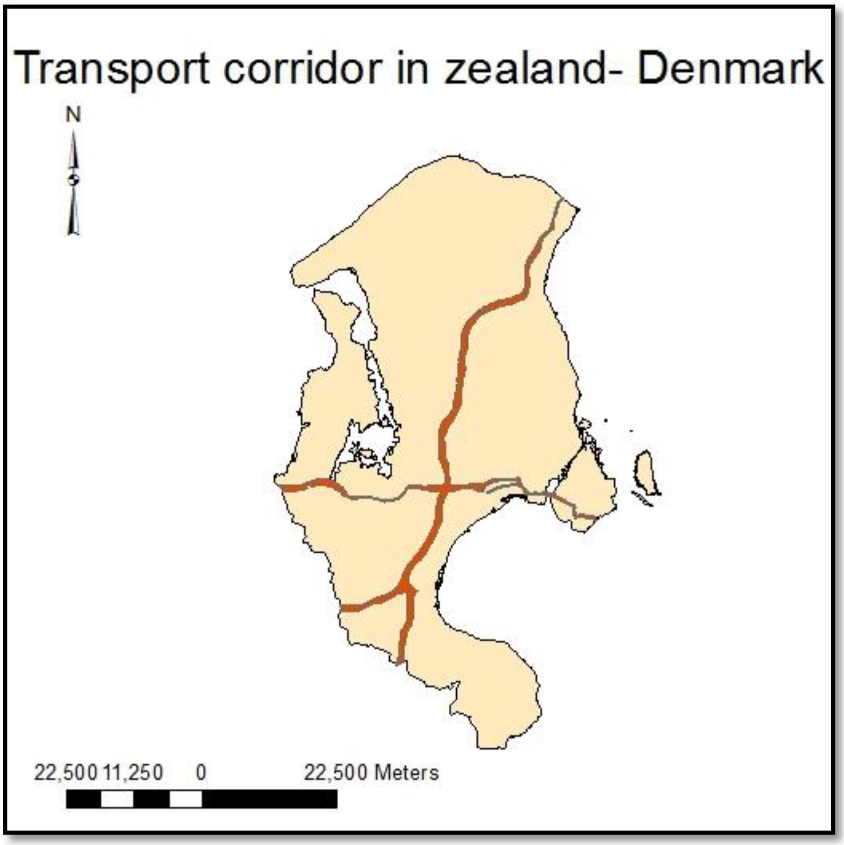



Figure 28: The E20, 47 and 55 motorway within the study area

### 4.1.3 Train Stations

The Train stations data was taken from FOT Denmark, which is a public portal supplying digital data in Denmark. Within the FOT traffic, dataset consists of the train stations for the S-trains, which only operate within the greater Copenhagen area in the Zealand region and the regional trains, which connect the different regions of the whole country. It is important to note that the Metro stations are not included in the dataset and the train stations considered are only those that lie within the greater Copenhagen area.

The dataset consists of the Object ID, which is the identifying factor of the given station, the Name of the train station, which is a text field and represented on map as a point feature class.

### 4.1.4 Population Data.

The population required to carry out the analysis in this study was taken from a Statistikbanken, the Danish statics bank. The data is extracted as a data based format file showing the populations of the municipalities within the study area. However, for this study only the data for the years 1990, 1995, 2000, 2005 and 2009 are considered in order to create uniformity and consistency with the land use datasets.

### 4.1.5 Land use Data

In order to model the different land use types in the greater Copenhagen area, land use data is needed. The data that is originally in ASCII format is prepared in the next chapter where it has converted and classified as necessary for the study. Since the period examined by this study is between 1990 and 2009, the land use data will also be limited to only that.

### 4.1.6 Zoning Data

The Zoning data in this study will represent those areas under strict restriction from any other types of land use other than what they have been designated for These data will provide the control factor that will be used in the next chapters to carry out the urban growth modelling. In this case, three restricted zones were considered namely:

- The nature conserved areas(green areas),
- The summer cottage area and
- Urban Zone

These areas are strictly designated for their corresponding functions whereby the green spaces are conserved nature areas, the summer cottage areas are areas demarcated for only summerhouses and no other type of settlement is permitted. Some of these summer cottage areas also lie within the coastal area. Finally yet importantly, the urban zone which is an area where all kinds of urban development can take place including commercial, residential, industrial and administrative settings. These zones are shown in the figure 29 below:

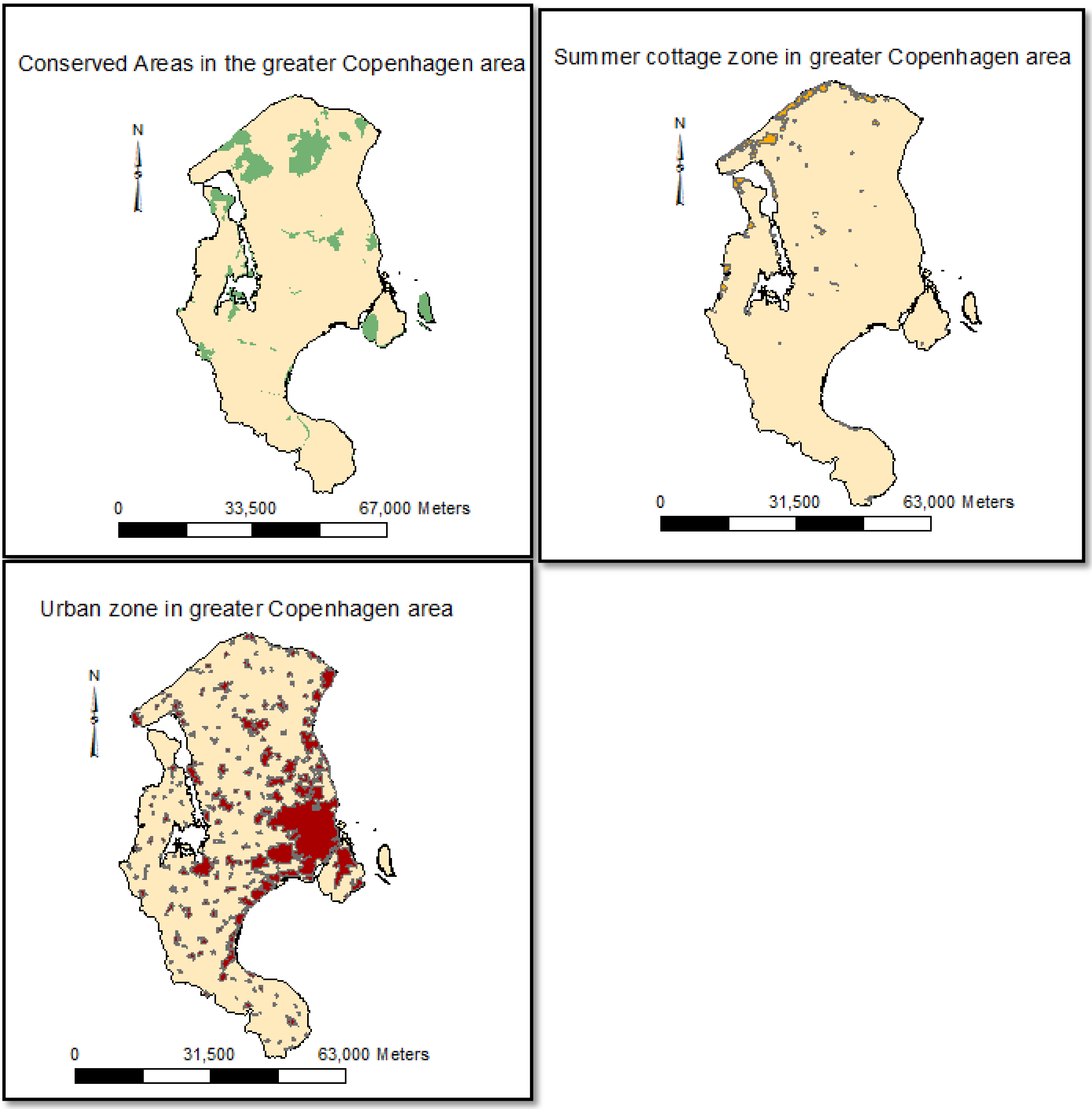



Figure 29: The three main zones in the study area.

These data was all taken from the plansystem.dk which is website managed under the Danish Nature Agency (naturestyrelsen). The data are retrieved as polygon features and is ArcGIS user friendly since most of the data will be prepared and visualized on this platform.

The areas were chosen because they are categorized under restricted area by the Danish ministry of Environment. Therefore, no form of urban development is allowed with certain distances of these areas. According to the Danish ministry of Environment, a designated Coastal zone can only be converted to urban use if there is a specific and planned justification as to why that particular project has to be located within the coastal zone.

With this in mind, several summerhouses are located near coastal areas and new summer cottages cannot be erected as a replacement. The existing ones should only be used for leisure not as permanent residence. A new mandatory distance of at least 300 meters from the shoreline was established in 1994 to protect the coastal areas in Denmark. However, in order to promote economic growth in the smaller urban regions, 8000 new summer cottage spaces were later permitted and these spaces had to be carefully selected by the ministry (Danish Ministry of Environment 2007)

## 4.2 Processing of Data

Because the data acquired for this study is in its raw state. In this section, these data are manipulated by sorting, classification and re-projected among other methods. These will prepare it and make it useable for the urban growth modelling procedures and analysis that follow. It is also in this phase of the study when most data anomalies may be encountered and corrected whenever possible.

In order to prepare all the above data for use. The first step taken was to re-project all the datasets to the same projections using the ArcGIS *Define projection tool*. The projection chosen is the UTM zone 32 ETRS 89. After the datasets projection has been defined, the next step is to classify the land use data as seen in the next section of this chapter.

### 4.2.1 Processing Land-use data.

Land use data in urban growth modelling provides a backdrop from which other analyses can be carried out. Cheng further explains, *"Land use/land cover information is fundamental for understanding the spatial and temporal dynamics of urban development, which is the basis for urban development planning and sustainable land management"* (Cheng 2003, p61).

In order to produce a more detailed land use dataset suitable for this study, a specific land use dataset was used. This study however does not cover the making of this specific dataset but outlines the procedures, which were used. The landuse dataset used in this study was because of a combination of the Corine land cover and the data from the Danish building and housing registry (BBR). The corine land cover was for years 1990 and 2000 and the BBR dataset, which is updated on an annual basis, has been in existence for more than 30 years now. This dataset is also geo-referenced using the Address database of all the Danish buildings (Hansen 2010).

| Active land-use classes | Passive land-use classes | Static land-use classes |
|---|---|---|
| **Residential areas** | Grass and arable land | Harbour |
| **Industry areas** | Forest | Airport |
| **Private and public** | Semi-nature | Waste and |
| **service areas** | | extraction site |
| **Summer cottage areas** | Wetlands<br>Recreational areas | Lakes<br>Sea |

Table 4: The distribution of land-use classes into active, passive and static classes. Source: (Hansen 2010).

The land-use data, which originally is obtained in ASCII format, is then converted to raster grid format within the conversion toolsets, from the Arc Toolbox that is in the ***To Raster tool – ASCII to Raster tool***, with a grid size of 100x100 meters.

Next, the data are categorized into 44 unique color-coded classes as shown in the figure below. These classed can be reclassified accordingly to visualize only the necessary ones.

| Map description | Data | Format | Year | Source |
|---|---|---|---|---|
| **Zoning map** | Restricted areas | vector | 2012 | Kort.plansystem.dk |
| **Land-use maps** | Land-use for Copenhagen<br><br>CORINE land-use maps | Vector<br><br>Vector | 1990-2009<br><br>1990,2000, 2006 | Henning Sten Hansen (Aalborg university)<br><br>EEA |
| **Suitability maps** | - Transport infrastructure with the<br>E20,E47 and E55 Motorways and junctions<br>- Train stations for S-tog | Vector<br><br>Point | 1990-2010 | Banestyrelsen.dk<br><br>Danish ministry of transport<br><br>FOT.dk |
| **Other** | - Finger plan<br>- Population data | Vector<br><br>Table | 2013<br><br>1990-2009 | Kort.plansystem.dk<br><br>Statistibanken.dk |

Table 5: The table of the Data requirements for this study.

In order to better analyze the urban growth patterns for the Copenhagen metropolitan area from 1990-2010, the period is divided into four intervals of 5-year periods each. The intervals form 1990-1995, 1995-2000, 2000-2005 and 2005-2009. Due to shortage of consistent data, the data for year 2010 was lacking thus 2009 was considered instead.

The method of categorization of land use within the greater Copenhagen area was borrowed from CORINE. Here the data is broken down into three levels defining the individual land use types. In Level 2, several land use types categorized in Level 1 are mentioned and finally allocated an urban or non-urban status. The aims of this project mainly is to be able to identify the extent of urban growth in the greater Copenhagen area by establishing any changes in the land use types whether urban and non-urban from 1990 to 2009.

The Land use data were reclassified as shown on the table 6 below. The reclassification process involved merging of the classes into seven main classes and then further into two main classes thus urban and non-urban as shown on the map above. The merging of these classes helps to narrow down the study to mainly analyze the urban factor of the study area.

The land use datasets for 1990. 1995, 2000, 2005 and 2009 used were originally ASCII files; these are converted into Raster format accordingly in ArcMap as shown below. The Raster datasets are then projected to the same projection like the original ASCII files, and all the other datasets using ArcMap *Define Projection tool* in Data management to ensure that the image pixels are not distorted thus avoiding data misrepresentation and errors.

CORINE land use classes

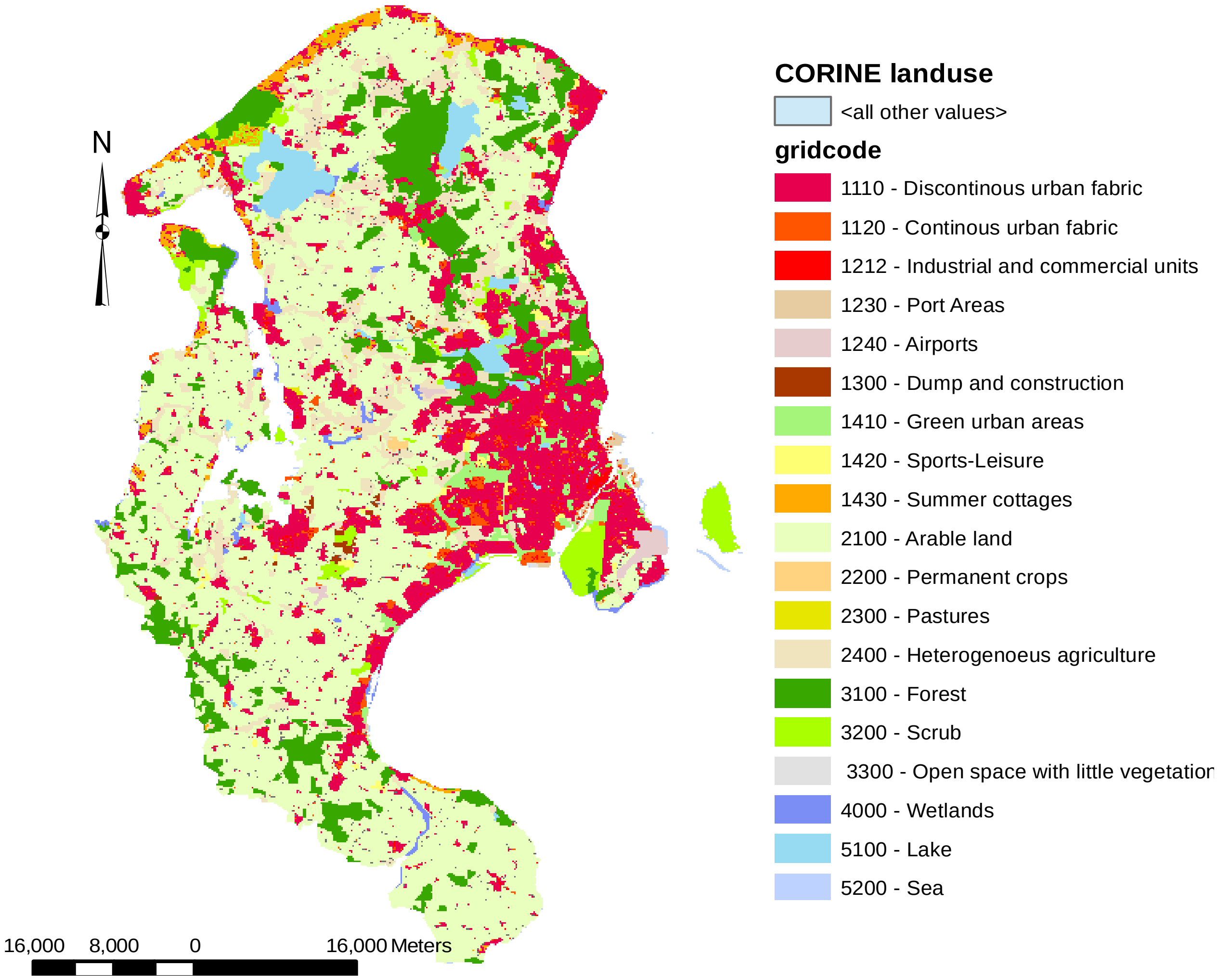



Figure 30: The different classes of land use types.

| Classes | Level 1 | Level 2 | Level 3 (Land-use status) |
|---|---|---|---|
| 1110 | Residential | -Accommodation facilities | Urban |
| 1211 | Industry | -Factories ,Workshops, Warehouses<br>-Transport Networks | |
| 1212 | Shops and Administrative units | - Commercial centers<br>- Business centers | |
| 1213 | Agricultural buildings | -Permanent and Semi-permanent structures | Non-Urbanized |
| 1430 | Summer cottages | -Cabins and<br>Semi permanent structures | |
| 1430 - 5100 | others | Other land use types not mentioned here | |
| 5100 - 5200 | Water bodies | Sea, ocean, inland waters | |

Table 6: Land use categorization

In order to retrieve the land use for the study area only, the Raster files of 1990, 1995, 2000, 2005 and 2009 are clipped to the greater Copenhagen area only using the *Clip tool* found within Data Management tools to retrieve the data for the area of interest. The classes are then reclassified using the spatial analysis Reclassify tool to seven categories that represent some of the main land-use patterns within the study area.

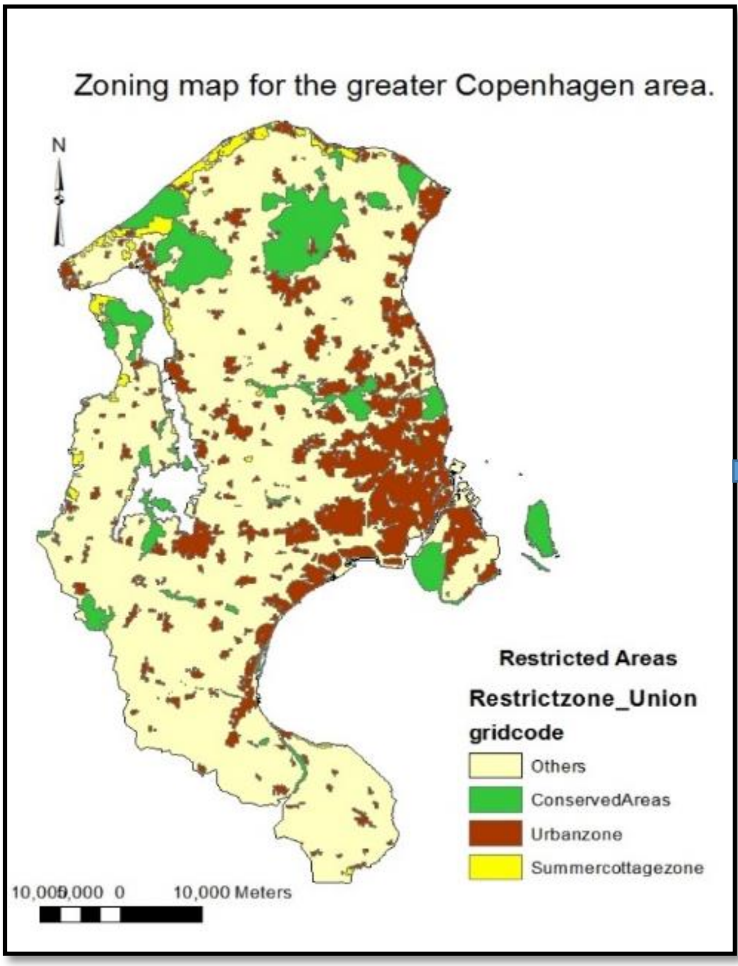
These categories are Residential, Industrial, Shops and Administrative units, Agricultural facilities, summer cottages, others and Water bodies.

Then another reclassification is done to only two categories thus the focus of this study namely Urban and Non- urban. All the datasets were processed in the similar manner.

### 4.3.2 Processing of the Zoning map

The result from these data is a map with restricted development. This will be the ‘control’ factor in the modelling process ahead. How and what the land is used for in the greater Copenhagen area is strictly monitored by the Danish ministry of Environment with the help of the 18 municipalities that make up the core of the greater Copenhagen area. The finger plan concept is one of the main zoning models for the Copenhagen area. The land is demarcated or preserved for particularly purposes. Some of these land use types according to several theories on urban growth are easily converted to artificial urban spaces. Within the finger plan model, three of these zones were considered in this chapter namely:

a) Summer cottage area
b) Conservation areas
c) Urban Zones



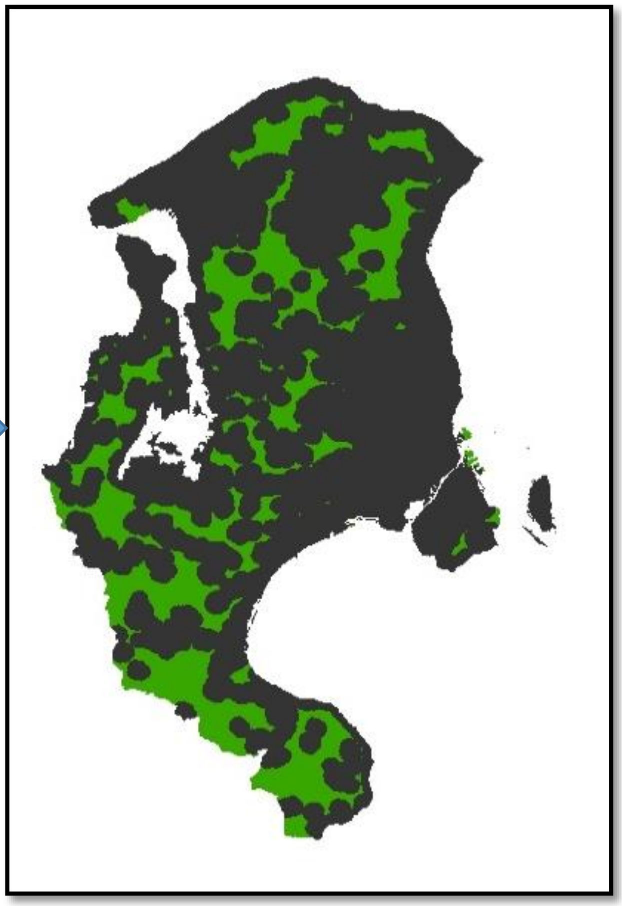



Figure 31: The three main landuse zones

Figure 32: The Zoning (restriction) Map

### 4.3.3 Processing the Suitability map.

In this study, the brief definition of suitability is referred to as the potential of an area to grow new urban cells because of not only favorable but also growth control factors. The purpose of the suitability factor in modelling is to help filter out any cells, which do not meet the required conditions for growth. It also identifies the areas that could potentially fit the defined criteria thus new suitable cells.

The application of the suitability factor in urban modelling is sometimes referred to as suitability CA modelling because the suitability is included as an input in the modelling process. This is quite different from the classic cell- state based CA modelling. White and colleagues refer to these kind of CA simulations as development suitability and probability models (White et al. 1997). The method used to calculate the suitability states:

$$S^{t+1} + \{x, y\} = \mathrm{f}(P^{t}\{x, y\} \quad (4)$$

- Whereby S{x,y} is the state at location {x,y};
- f is the transition function
- P{x, y} is the probability of transition to the state S at the location.

The influencing factors considered in the study include the distance to accessibility points like junctions and train stations, distance from the CBD, distance from the suburban areas to the accessibility points. The control or stopping growth factor used here is the zoning layer. The zoning layer defines the boundaries of how far the stated land uses can go. No other kind of development is allowed outside the designated zones. To process through these datasets, the factors considered as suitability inputs were:

- Accessibility (S- train stations and E20, E47 and E55 motorway junctions)
- Distance from Suburbs to CBD
- Distances from the CBD

- **The Accessibility factor.**

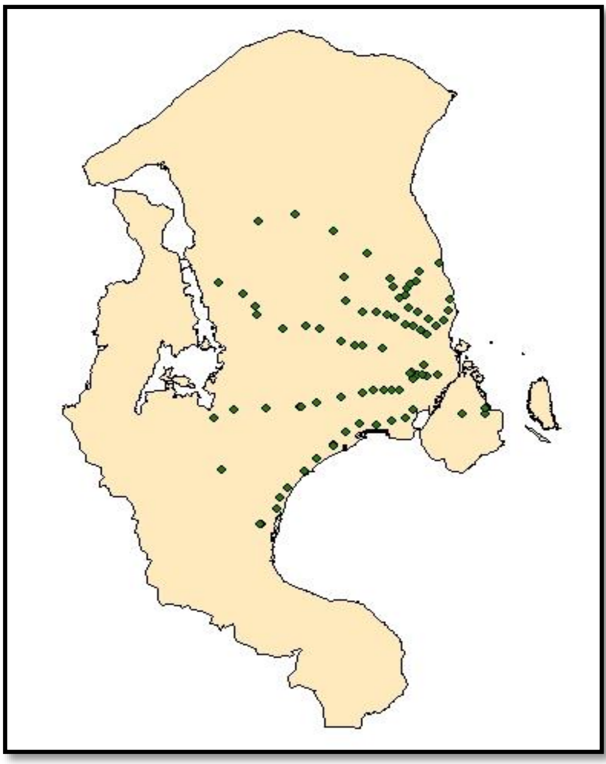


Figure 33: Map of selected train stops

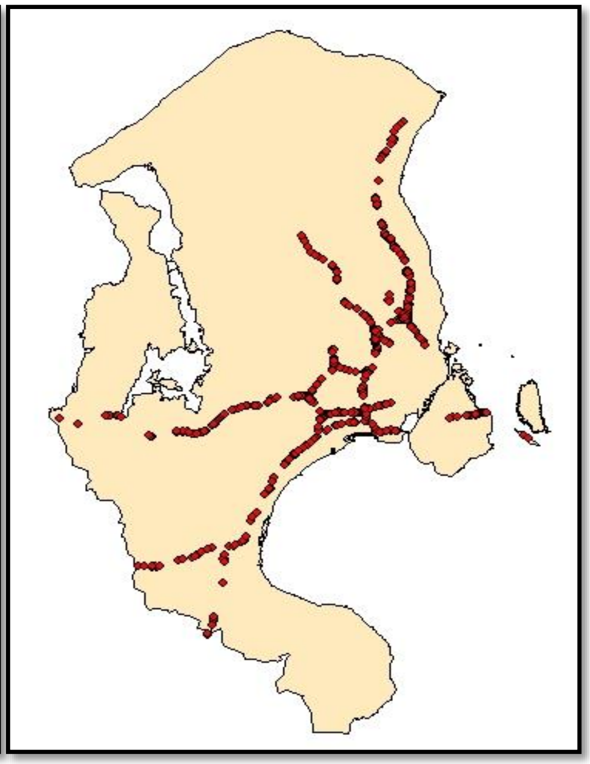


Figure 34: Map of the Motorway Junctions

Two key points of access used are the S-train stations and the all the Motorway junctions along the transport corridor and the E20, E47 and E55 within Zealand. The data is represented as point features. However, for the purpose of this study, the original junctions dataset was manipulated in order to extract the necessary junctions that lie within the transport corridor, which is a polygon feature class. The junctions and the transport corridor are intersected using the ArcGIS ‘intersect’ tool in the geo processing toolbox. The ‘Dissolve’ tool is then used to extract only the junctions that are within the transport corridor. The total number of junction retained are 352 as shown below:

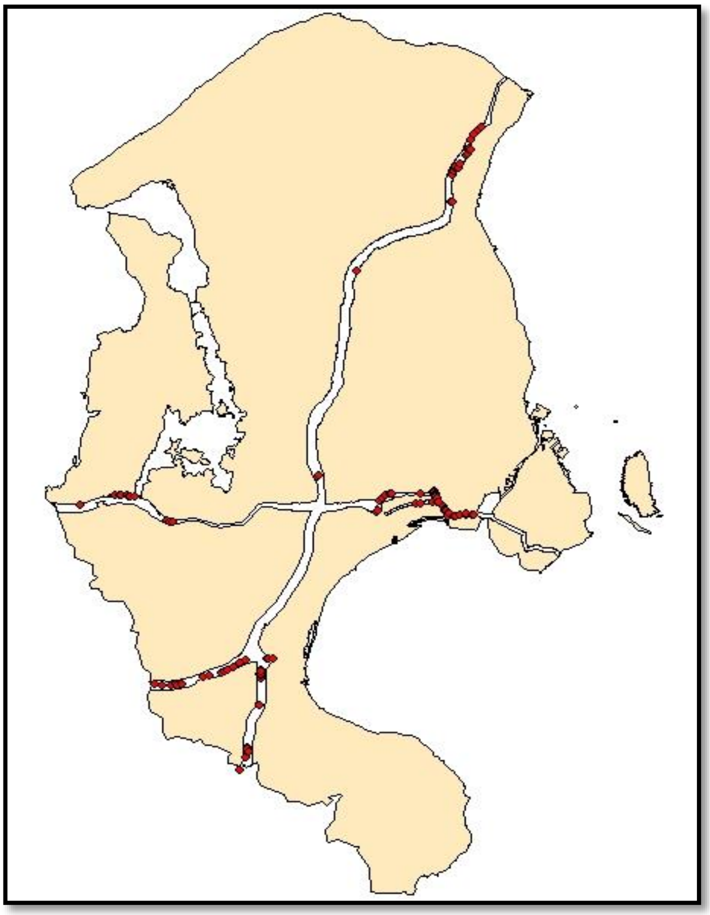


Figure 35: Map of the selected motorway junctions

It is a known fact that urban growth tends to cluster around accessibility points. In the case of this study the Junctions and Train stations, the points were buffered. Using the multiple buffer tool within the proximity analysis toolset in ArcGIS, the multi buffer rings were created for the Junctions and Train stations.

The distances were chosen by running a buffer test to determine what distance is necessary to cover the study area after which the 3000meter buffer was considered the farthest suitable distance any other distances were simply not favorable. Then the output from the buffer distances is converted to raster and reclassified, the similar procedure was carried out for both the Train stations and the motorway junctions as shown on the map.

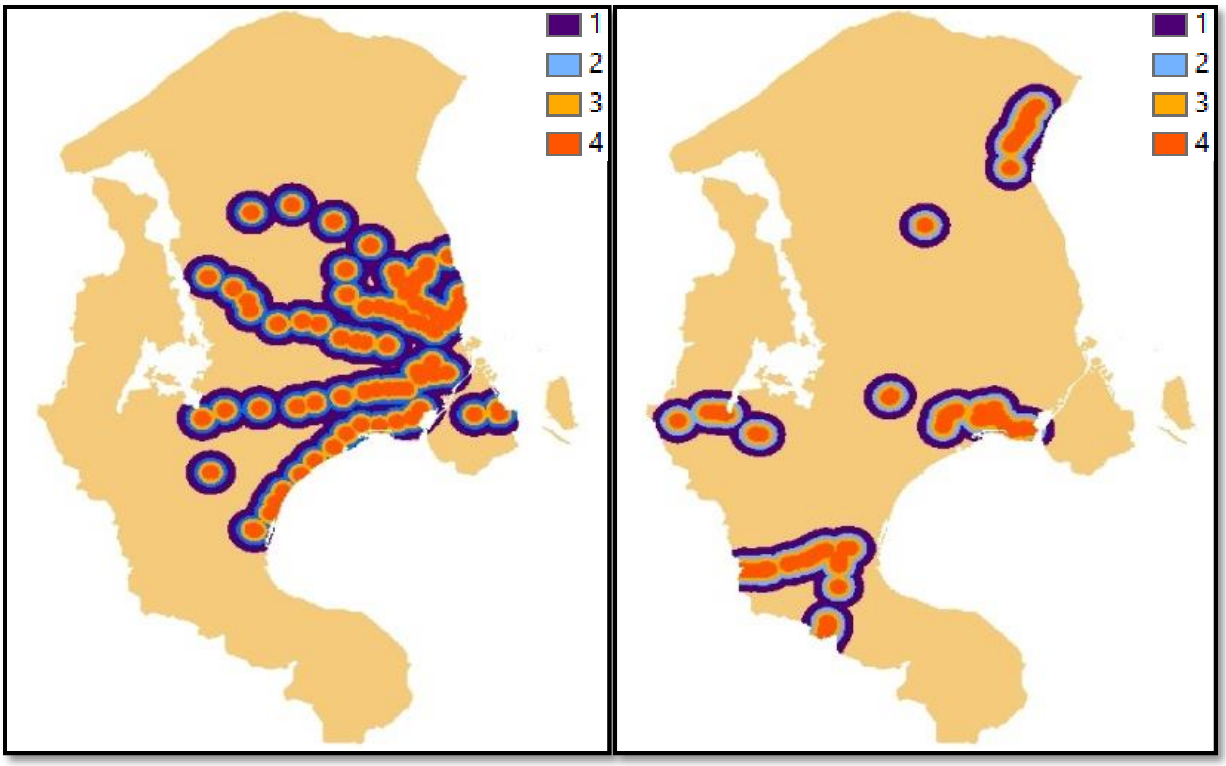



Figure 36: Buffer distances from train stations and junctions respectively.

The table below shows the distances which were applied as buffers for the tain stations and the motorway junctions and how they were reclassified and rated.

| **Buffer Distances in meters** | **Reclassification** | **Final output** | **Rate** |
|---|---|---|---|
| **3000** | 3000 - 2000 | 1 | Least favorable |
| **2500** | | | |
| **2000** | 2000 - 1500 | 2 | Good |
| **1500** | 1500 - 1000 | 3 | Favorable |
| **1000** | 1000 - 0 | 4 | Most favorable |
| **500** | | | |

Table 7: Buffer distance reclassification

- **The influence of the distance from the suburbs**

The suburbs in the case of this study are the urban areas outside of the core metropolitan Copenhagen as shown in the figure 37 below. To determine if there is any sort of growth pattern in relation to accessibility.

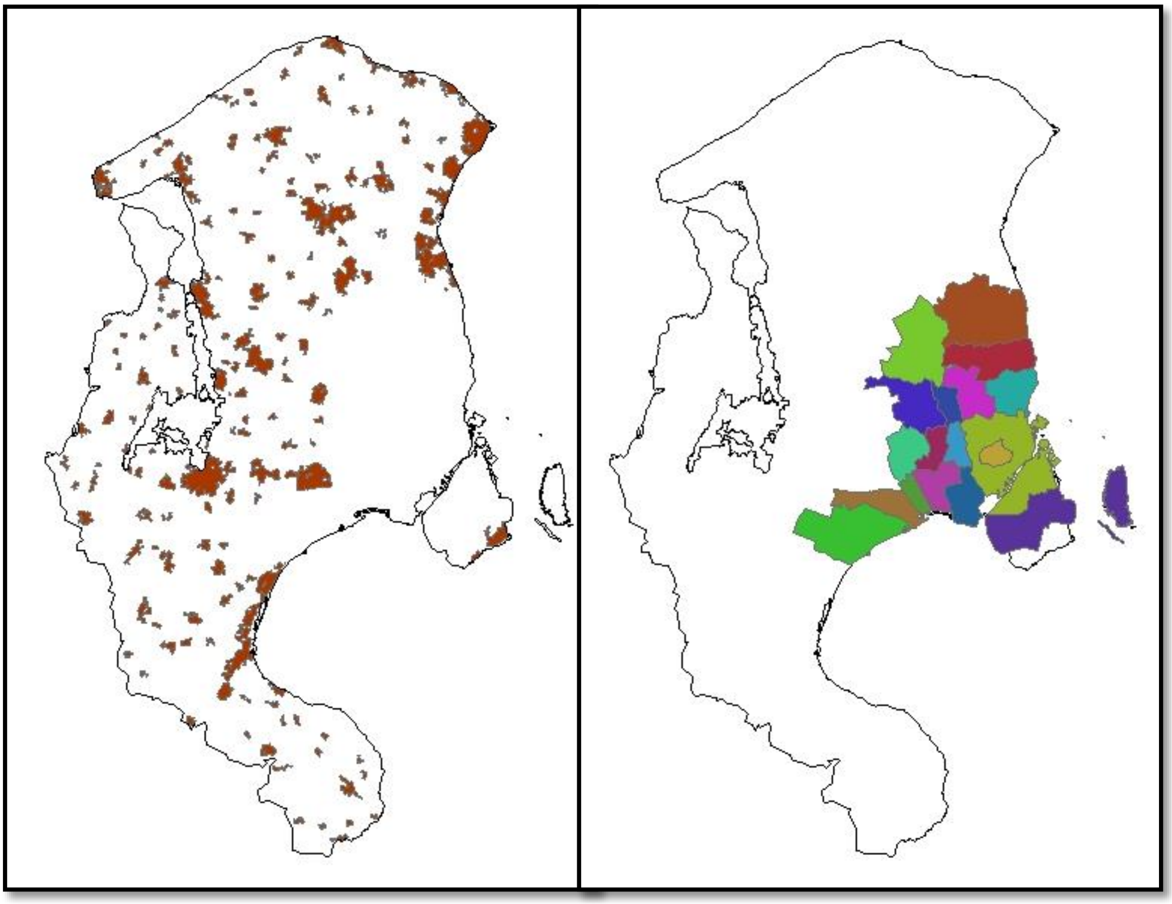


Figure 37: Suburbs and the core urban area (18 municipalities) respectively.

After the suburban area is defined, the 'Near' tool in ArcGIS analysis toolset is used to generate the distances between the suburban areas and the train stops and junctions respectively. Next, the outputs from the distances are merged using the 'Object ID' field and the output is converted to a raster with the 'Near_Dist' field, which is the field with the near distances calculated from the train stations and the junctions. The output is then reclassified as illustrated below.

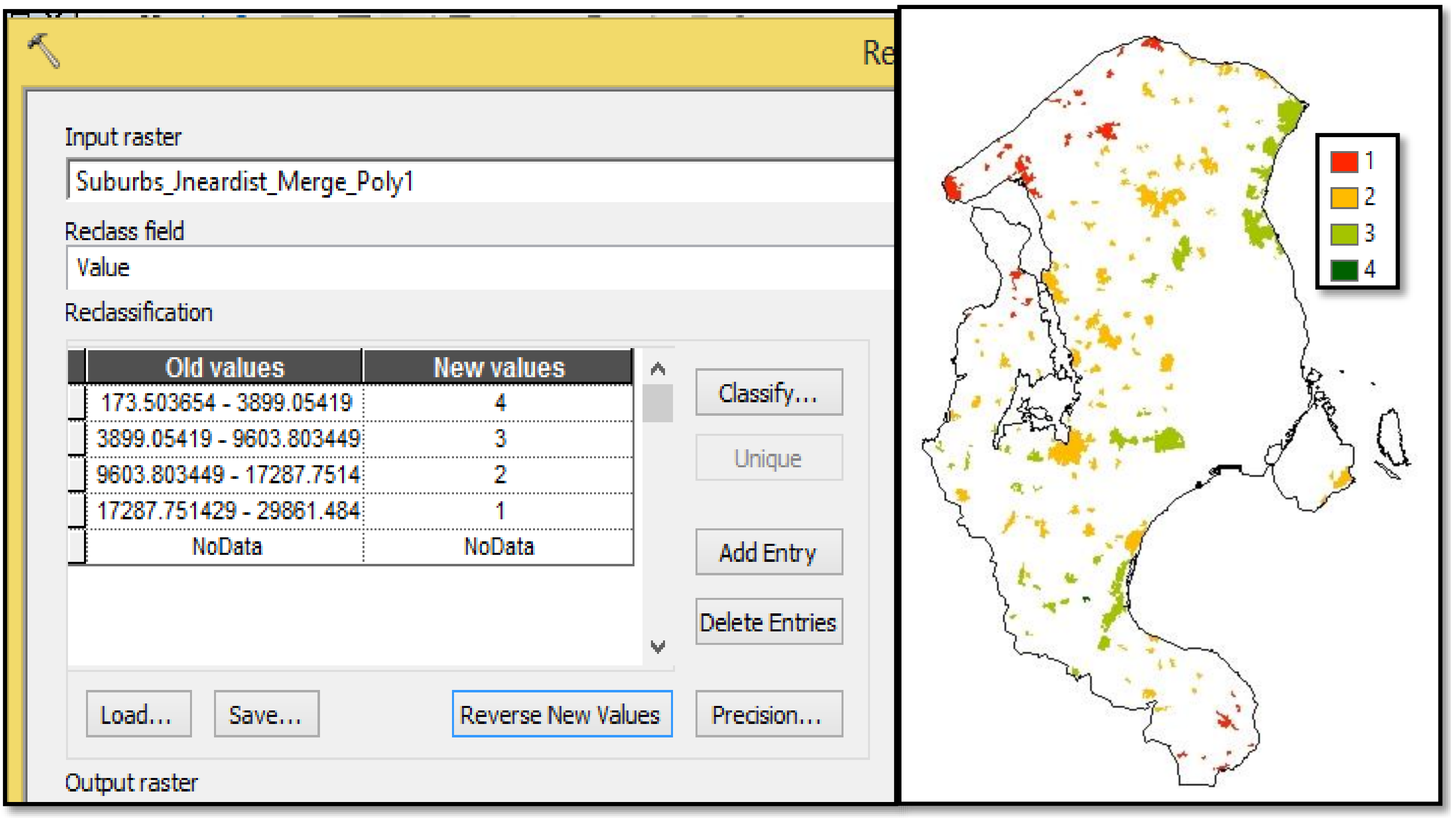



Figure 38: Reclassified distances from the suburbs to accessibility points.

The reclassification process as shown on the table above, allocated the distances of the suburbs nearer to the train stations or junctions a higher rate of 4 as the most favorite and vice versa. This means that the suburbs nearer to accessibility points stand a higher chance of becoming urbanized because businesses tend to cluster and locate near these access points as earlier discussed in the theory chapter (3.9).

- **The CBD Influence**

It is a common occurrence in urban growth that the Central Business District (CBD), is where growth of most urban centres starts. The CBD is usually characterised with many network links, business entities, dense population and competition for limited space. In Copenhagen, the need for more space in the CBD has led to alternative sources like underground metros lines, parking spaces, shopping malls and sports facilities among others.

The central Business District (CBD) for the Copenhagen greater area is situated within two municipalities thus the Copenhagen and the Frederiksberg municipalities. The Frederiks -

berg municipality is engulf within the Copenhagen area making it seem like a municipality within another as shown in the figure 39 below.

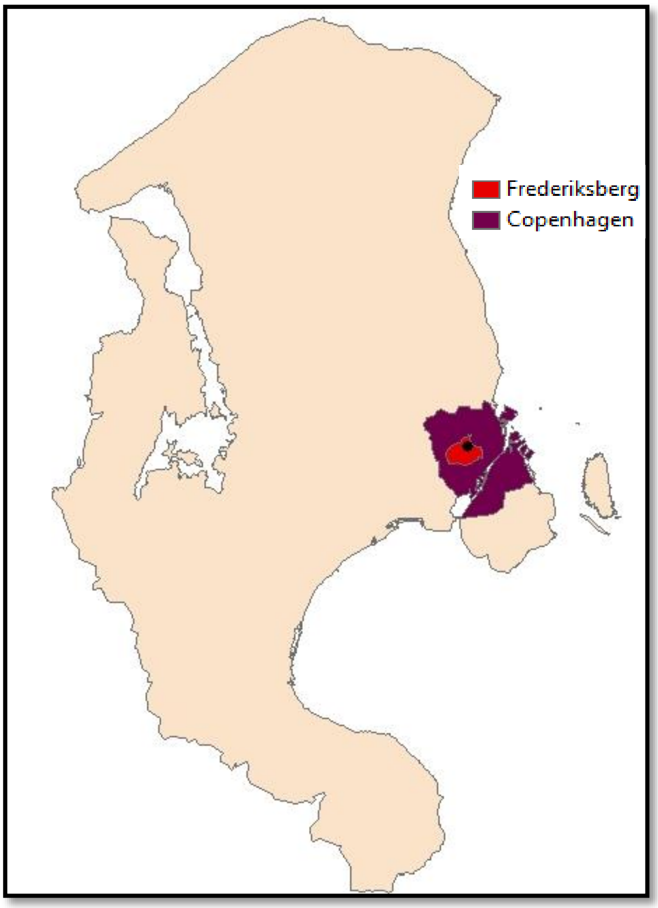



Figure 39: The two municipalities within the CBD

The impact of the CBD was determined by analyzing the distance from the center point of the CBD to the all the area demarcated as urban zone. First, the center point (centroid) of the CBD, which is a polygon feature class, is determined using the ‘calculate Geometry’ function in ArcGIS table of attributes from the CBD polygon. The result is used to make the XY Event layer, which is then exported as a shape file.

Next step, the ‘Near tool’ in the proximity toolset of ArcGIS is used to calculate the nearest distances from the center point to all the other surrounding urban areas within the urban zone.

In the illustration on this map, the distribution of this urban zone can be seen thus it displays the pattern of which municipality the various zones lie. However, in this study the focus here was to also determine the relationship between the distances from the CBD and the population density of the area.

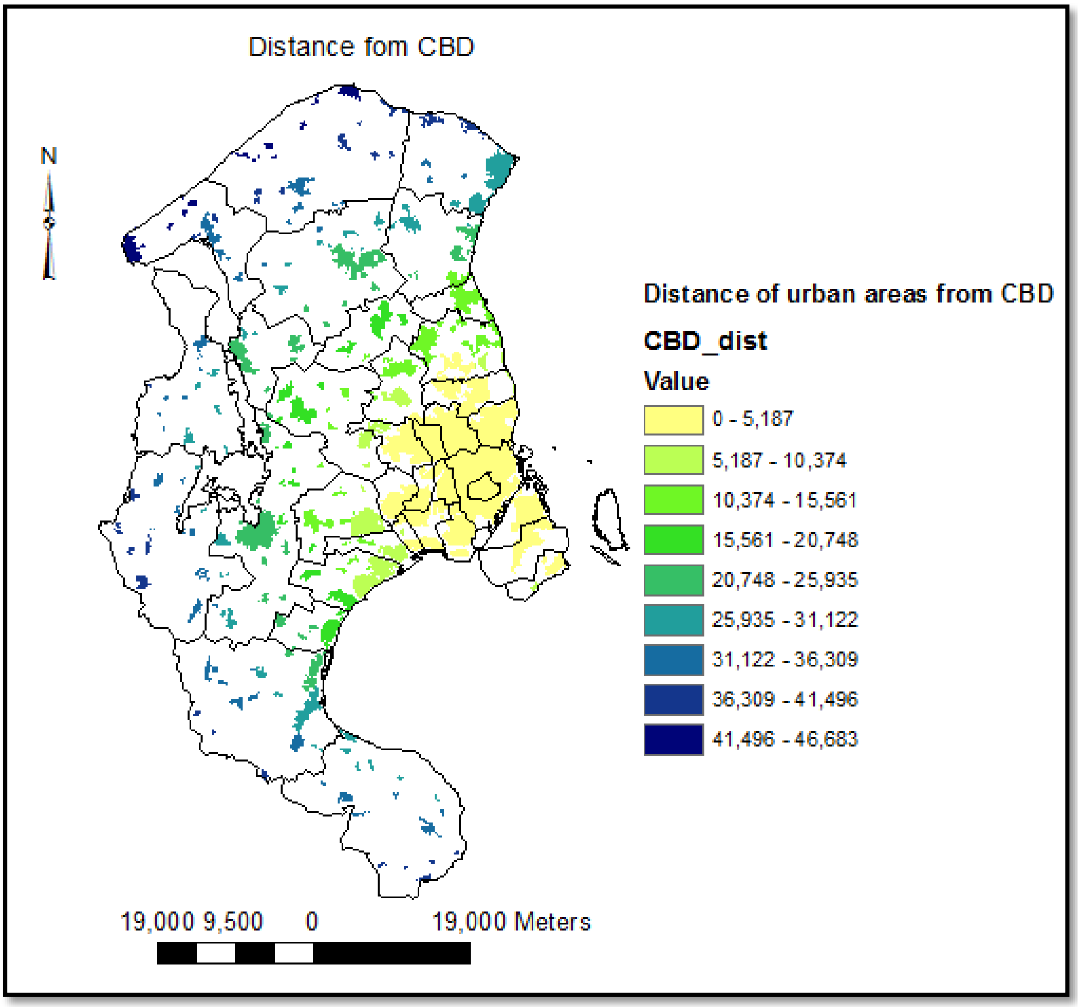



Figure 40: Buffer distances from the CBD.

### 3.3.4 Combining the layers for suitability map.

There is different ways of combining these datasets based mainly on what the intended outcome is for. The Multi- Criterion Evaluation considered for combining these datasets was the Weighted Linear Combination method (MLC). The choice of this method was due to the nature of pre-processes applied to the dataset and the expected result.

The datasets were weighted, and summed. The best method for this is the Weighted Linear Combination method whereby different rasters are overlaid on a basic measuring scale and weights assigned to the datasets based on their importance or influence to urban growth in the Copenhagen greater area.

As shown in the table 8 below, these weights were assigned to the datasets. According to the MLC method, the total sum of the weights should not be more than one.

| **Input layer** | **Assigned Weights (%)** | **Scale range** |
|---|---|---|
| CBD | 0.25 | 1 - 10 |
| Suburbs | 0.2 | 1 - 10 |
| Distance from Train stations | 0.3 | 0 - 10 |
| Distance from motorway junctions | 0.25 | 0 - 10 |

Table 8: The Distance weighting of the input factors.

The weights assigned to these factors are close because the assumption made is that all the factors play a vital role in activating urban growth.

The combined contribution of all these factors is much higher than if only one of them is considered. The Distance from the other surrounding areas to the CBD and the motorway junctions were each assigned a weight of 0.25%, this means that the level of importance is the same. The distance from the suburbs and the train stations weighted at 0.2 and 0.3 respectively. The train stations weighed more than all the other factors due to the good distribution of train stations in Copenhagen whereby most of the stations are on average 10 minutes away from each other making commuting by trains very reliable.

### 4.3.4 Processing the population data

The population density is considered as a single input, which will be directly introduced into the cellular automata after the data, has been prepared. First the population data which is in a database table is cleaned up, sorted and imported into ArcMap where it is joined with the municipalities shape file, which is polygons' attribute table. The join is made using a common field in this case the ‘KOMNAVN’ field, which is the names for the municipalities to get a result**.** Only the population for the municipalities within the study area were selected for the period between 1990 to 2009.

Next, the population density for the municipalities is calculated by dividing the population by the Area for all the years from 1990 to 2009.  The population status is mapped as shown in figure 41 below

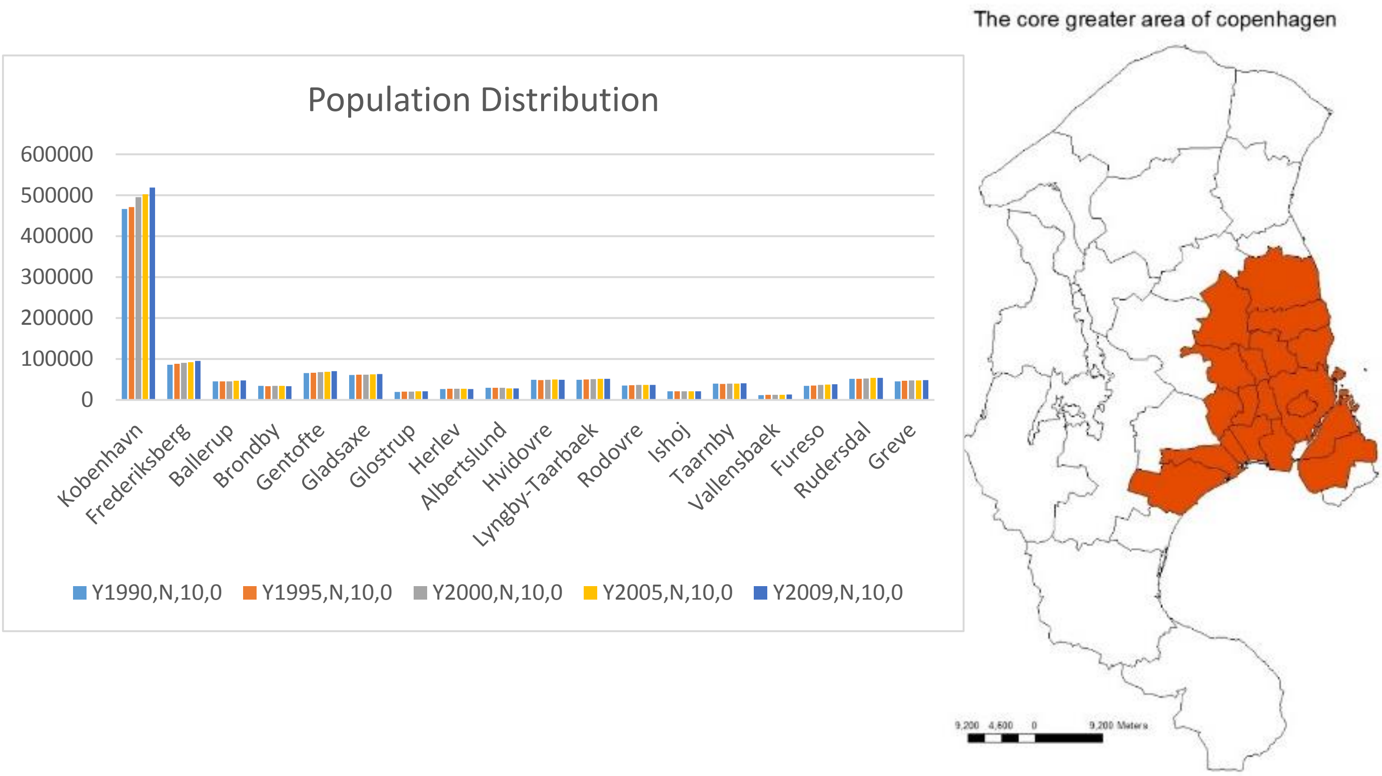


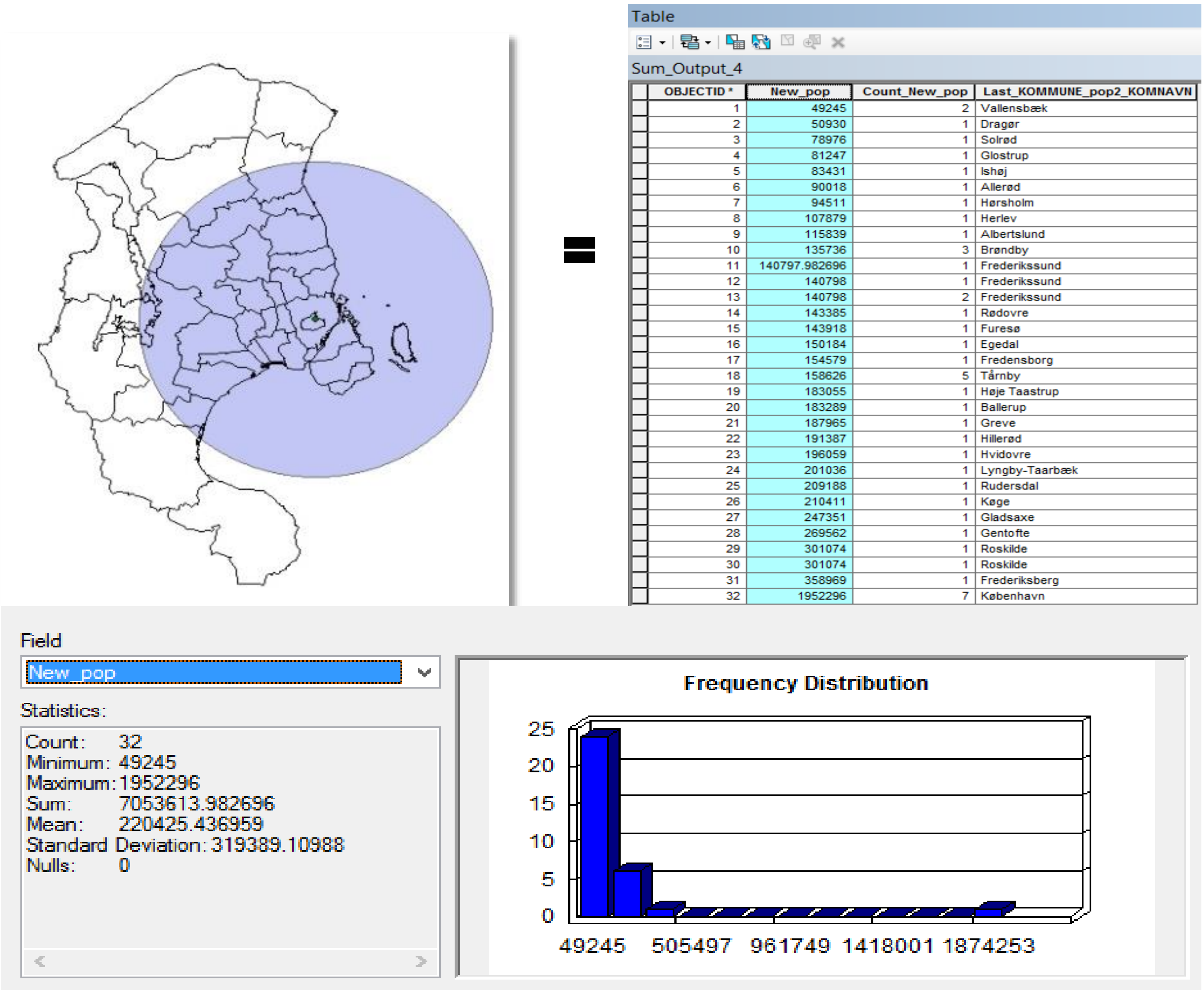

Figure 41: Population Distribution in the 18 core municipalities within the study area.

In the figure above, the population growth of the core municipalities shown on the map in figure 43 of the Copenhagen greater area are used selected to determine any patterns in the population figures of these 18 municipalities in a period of 19 years from 1990 to 2009. The graph does show that strikingly high populations in Copenhagen, which is also, the central business district compared to the other urban areas, which is an expected trend when analyzing patterns between populations in urban areas. The graph also shows that the further away the municipalities are from the CBD, the population is averagely spread out with municipalities like Gentofte, Gladsaxe, Hvidovre, Lygnby-Taarbæk, Rudersdal and Greve showing more population.

| | **YEAR** | **TOTAL POPULATION** | **POPULATION AVERAGE** |
|---|---|---|---|
| 1 | 1990 | 2017491 | 48035.5 |
| 2 | 1995 | 2050727 | 48826.8 |
| 3 | 2000 | 2115225 | 50362.5 |
| 4 | 2005 | 2156487 | 51344.9 |
| 5 | 2009 | 2202405 | 52438.2 |

Table 9: Population status for the greater Copenhagen area.

However, to give an estimation of the number of people living near the CBD, a 3000-meter buffer was made around the CBD. Next, the CBD buffer was intersected with the population data as shown below:




| OBJECTID * | New_pop | Count_New_pop | Last_KOMMUNE_pop2_KOMNAVN |
|---|---|---|---|
| 1 | 49245 | 2 | Vallensbæk |
| 2 | 50930 | 1 | Dragør |
| 3 | 78976 | 1 | Solrød |
| 4 | 81247 | 1 | Glostrup |
| 5 | 83431 | 1 | Ishøj |
| 6 | 90018 | 1 | Allerød |
| 7 | 94511 | 1 | Hørsholm |
| 8 | 107879 | 1 | Herlev |
| 9 | 115839 | 1 | Albertslund |
| 10 | 135736 | 3 | Brøndby |
| 11 | 140797.982696 | 1 | Frederikssund |
| 12 | 140798 | 1 | Frederikssund |
| 13 | 140798 | 2 | Frederikssund |
| 14 | 143385 | 1 | Rødovre |
| 15 | 143918 | 1 | Furesø |
| 16 | 150184 | 1 | Egedal |
| 17 | 154579 | 1 | Fredensborg |
| 18 | 158626 | 5 | Tårnby |
| 19 | 183055 | 1 | Høje Taastrup |
| 20 | 183289 | 1 | Ballerup |
| 21 | 187965 | 1 | Greve |
| 22 | 191387 | 1 | Hillerød |
| 23 | 196059 | 1 | Hvidovre |
| 24 | 201036 | 1 | Lyngby-Taarbæk |
| 25 | 209188 | 1 | Rudersdal |
| 26 | 210411 | 1 | Køge |
| 27 | 247351 | 1 | Gladsaxe |
| 28 | 269562 | 1 | Gentofte |
| 29 | 301074 | 1 | Roskilde |
| 30 | 301074 | 1 | Roskilde |
| 31 | 358969 | 1 | Frederiksberg |
| 32 | 1952296 | 7 | København |



Figure 42: The population representation of municipalities within 3km radius of the CBD.

This figure illustrate a population estimation of people who have resided within 3000 meter buffer of the CBD between 1990 and 2009 to approximately 7053613 people as shown in the statistics table above. For a CBD like Copenhagen, this figure is close to the actual population meaning that Copenhagen municipality alone has had an average population of 130,000 people per year between 1990 and 2009.

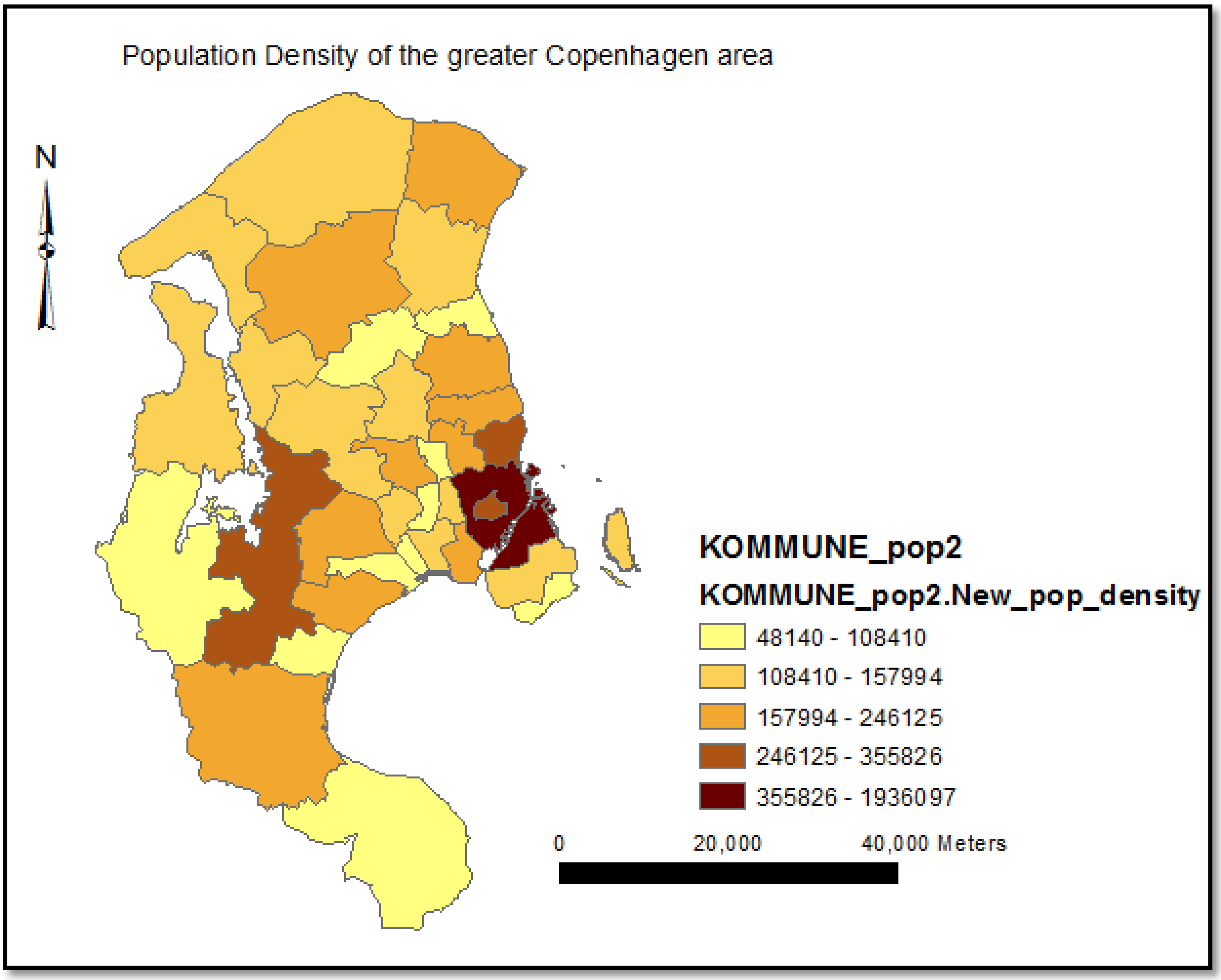



Figure43: Population Density of the greater Copenhagen area.

In this population density map, it clearly illustrates that the areas around the population density in Copenhagen and Frederiksberg municipalities as the highest. The other municipalities with high densities included Gentofte and Roskilde, which is also reasonable considering Gentofte is, is right next to the CBD and Roskilde, which is approximately 25 km outside the CBD. This could be due to some good social amenities like easy accessibility by both train and motorway, Roskilde University, Roskilde hospital, Roskilde Dorm kirke, an Old Danish cathedral with lots of Danish history. The Dorm kirke is a famous tourist site. The other attraction could be the famous annual Roskilde music festival, which draws thousands of international music fans to the area. These factors and more can be a good attraction factor for population growth in an area.

# 5. Cellular Automata Modelling.

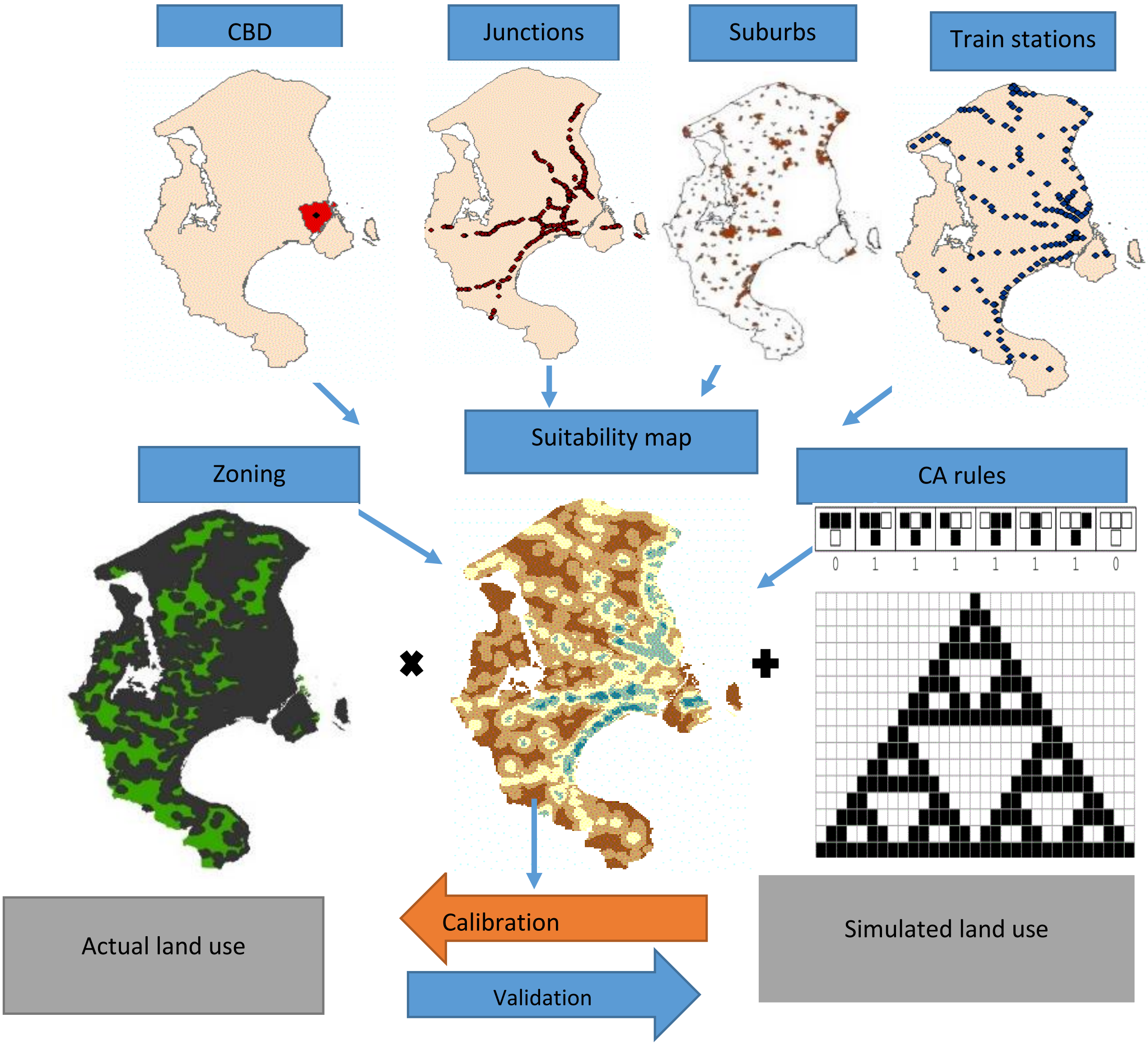



Figure 44: The conceptual diagram of the CA modelling process.

In the CA method, the state of the cell is influenced by the state of its neighbors, in this modelling the membership of the cells is categorized under two states, urban (1) and non-urban (0) meaning that the cells with a membership higher than 0 will be categorized as urban. The higher the membership level of the cell, the faster the cells are developed and vice versa for the cells with a membership lower than zero.

The type of CA model considered for the study has constraining factors. These factors are namely:

- The Zoning map: This consists of the defined boundaries for growth and is made up of the urban zone, the summer cottage zone and the conserved areas. This map is classified into two classes and given the values of 0 and 1, whereby 0 is for restricted area and 1 for areas for possible development.
- The Suitability map: This showing the most suitable areas for development is made up of the accessibility points thus the junctions and the s-train stations, the distance from the CBD to the suburbs, and the influence of the suburbs to the rest of the study area.

## 5.1 The set-up of the model.

This is how one cell spatially relates another in a given neighborhood. To define a proper neighborhood for the model is an important step in the initial process of CA. Because of literature on modeling urban growth for example by Li and Yeh which mention, *"In urban simulation, the most general state for a cell is developed or not developed (alive and dead). The essence of cellular automata is that the states of the neighboring cells influence the stat e of the central cell",* (Li and Yeh 2010).

### 5.1.1 The Neighborhood.

The method used to choose the above parameters was mostly based upon the background literature of the study, experience and the trial and error method whereby a 3x3 and 5x5 and 7x7 Moore's neighborhood sizes where tested in the model. The CA model in this study is already predetermined, meaning that each cell in the neighborhood has two states urban or non-urban. By testing, the neighborhood sizes stated above there is a so many combinations of value that can be derived from 3x3, 5x5, and 7x7 thus $9^2, 25^2, 49^2$possibilities of transitional rules. The transitional rule used here was stated as follows:

- IF the cell in question is non-urban and is surrounded by 1 or more urban pixels, THEN transform the cell to urban.

- IF the cell in question is urban, THEN keep it urban.

The 1995 land use data was used as the input for testing the neighbourhoods. Using the error matrix table below, the results from the 3x3, 5x5 and 7x7 Moore neighbourhoods are calculated. The error matrix overlays the simulated land use with the actual land use and thus can be used to calculate various statistics. This method has been used mainly also in the modelling of urban growth to calculate the differences between the actual and the simulated growth (Pontius and Schnieder 2001).

| | | | Actual Map | | |
|---|---|---|---|---|---|
| | | **Urban** | **Non-urban** | **Total** | **Overall accuracy (%)** |
| **Simulated Map** | **Urban** | TU | FNU | TU + FNU | TU + TNU/TU + FNU + FU + TNU |
| | **Non-urban** | FU | TNU | FU + TNU | |
| | **Total** | TU + FU | FNU + TNU | TU +FNU +FU + TNU | |

Table 10: Error matrix table

The Error matrix table abbreviations are represented as follows:

- TU- True Urban
- FU- False Urban
- FNU- False Non-Urban
- TNU- True Non- Urban

In the matrix, the urban and non-urban are indexed with letters whereby ‘True Urban’ and these are the urban areas of the actual land use map and ‘False Urban’ are the urban areas of the simulated map. The ‘True Non-Urban’ are the areas that are non-urbanized in the actual land use while the ‘False Non-Urban’ are the non- urban areas from the simulated map.

Next, after the letters in the error matrix are replaced with the actual number of the simulated and actual urban and non-urban areas to compare the results. However, a method known as the percent correct match (PCM) can be used to determine how accurate the model is based on the pixel-by-pixel basis (Pontius and Schnieder 2001). The PCM formula used in the study is shown below. This is derived

$$PCM = \frac{Simulatated\ pixel\ values}{Actual\ pixel\ values} * 100 \qquad (5)$$

### 5.1.2 Transition Rules

Based on the transition rules from Conway's Game of Life method, the CA for this study is written. In order to see the simulation, various parameters are considered including the neighborhood and the cell size. In this CA model, the future state of the pixel in the beginning is at time (t+1) and this is determined by three factors namely:

- The current state of the pixel.
- The state of the neighboring pixels.
- The transition rules that are applied to direct the simulation.

The transition rules for this simulation are stated to simulate the urban growth. To drive the simulation, the transition rules are as follow:

**IF-THEN** rule is applied to the modeled as follows:

- If the state of a cell is urban, then the state of the cell will not be changed in time't'.
- If the state of a cell is restricted, then the state of the cell will not be changed in Time't' of the simulation.
- If a cell is closer to the influencing factors, then it has a high chance of transforming to urban.
- If the neighborhood of the cell is mostly urban, then the chances for it to change to urban are high.

This rule was written in the Raster calculator in ArcGIS using the ‘Con’ tool as: Con (“input_raster”1, 1, 0)

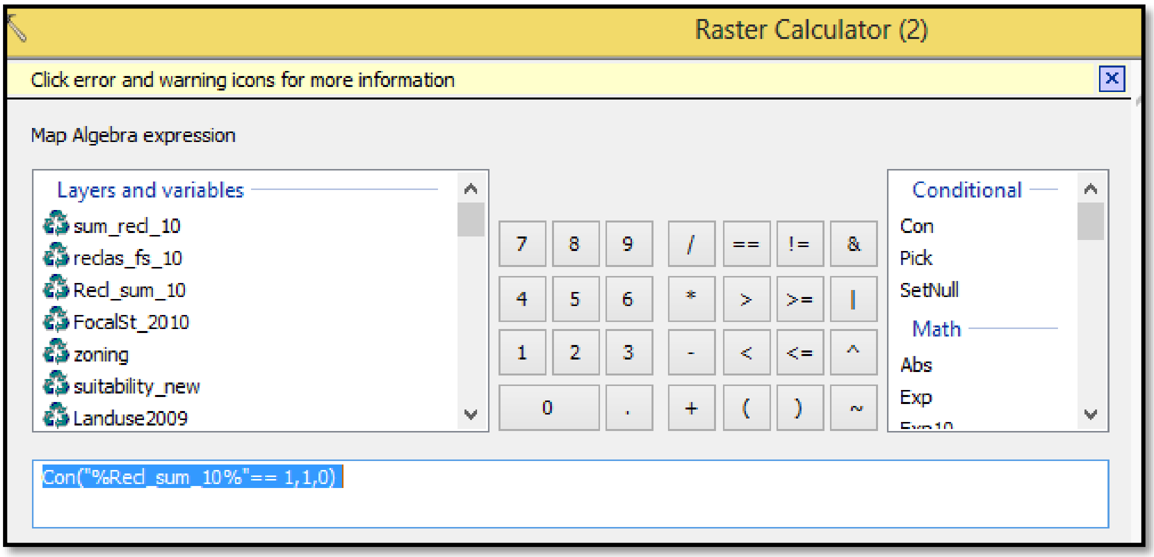



Figure 45: IF… THEN conditional statement using Raster calculator.

## 5.2 Calibration and Validation

After eliciting the transition rules using the ‘Con’ tool in Raster calculator, the iterator function is introduced into the model to loop the process for all the other years 1995, 2000, 2005 and 2009. The starting input used which was Land use map for 1990 and this was used to calibrate the simulation in the model. This phase was also used as a testing phase for the most suitable and realistic thresholds to be applied. The threshold calibration method is chosen due to its simplicity and straightforwardness. With this method, the results of the calibration can immediately be seen and adjusted accordingly.

### 5.2.1 Choosing the threshold.

In order to choose the best threshold of the simulated pixel values, three different thresholds were tested. The values range from 0 to 10, these are reclassified, and the various thresholds applied using model builder in ArcGIS. The table below displays the various results from the various thresholds tested and the one closest to the actual datasets was picked. The actual datasets used for testing were urban land use datasets of 1995, 2000 and 2005.

The results are then analyzed using the kappa index, which is a diagonal contingency table of the two map results being compared. The results are drawn up on rows and columns as shown in the table below.

| | Map B categories | | | | | | |
|---|---|---|---|---|---|---|---|
| **Map A categories** | | 1 | 2 | 3 | … | n | **Total of map A** |
| | 1 | P11 | P12 | P13 | … | P1n | P1T |
| | 2 | P21 | P22 | P23 | … | P2n | P2T |
| | **Total map B** | PT1 | PT2 | PT3 | … | PTn | 1 |

Table 11: The contingency table

The analysis carried out by applying the kappa statistics is to assess the agreement between what was simulated and the predicted. In this study, the 1990 land use map was the input of the cellular automata and the land use map from 1995 and 2005 were used to calibrate and validate the results accordingly.

Because the kappa statistic is used when assessing the reliability of the results observed for example when modelling urban growth whereby the actual or observed is compared to the simulated. The Kappa is an improvement from the %agreement method for assessing the correctness of the statistical data. The observed, which defines the amount of agreement that is present and the expected % agreement which states how much agreement is expected based on only, chance (Viera and Garrett 2005). These are calculated using the kappa as shown in formula 6.

In order to understand the meaning of the kappa values, Kappa has a range from 0-1.00. The larger values indicate better reliability however whereby a value of 1 is perfect and 0 is chance, the other values in between are graded as shown on the table below:

| Kappa | Interpretation |
|---|---|
| < 0 | Less than chance agreement |
| 0.01 – 0.2 | Slight agreement |
| 0.21 – 0.4 | Fair agreement |
| 0.41 – 0.6 | Moderate agreement |
| 0.61 – 0.8 | Considerable agreement |
| 0.81 – 0.9 | Good agreement |

Table 12: Interpretation of kappa values. Adapted from: (Viera and Garrett 2005)

The kappa statistics in this study are defines using the formula:

$$kappa, k = \frac{P_o - P_e}{1 - P_e} \quad (6)$$

Whereby:

$P_o$ Is the percentage of the observed and

$P_e$ Is the percentage of the expected

The human eye is one of the reliable tools in image comparison whereby the actual and the simulated are looked at side by side for any inconsistencies or unusual patterns. A simplified formula is used to calculate the extent of the error and the accuracy between the images whereby:

- Error = (simulated Urban) – (Actual Urban) and
- Level of accuracy is measured using the PCM method stated in formula 5.

Next, the results are further statistically investigated using the Error analysis method. This method works by analyzing the differences between the simulated urban cells and the actual urban cells by drawing up a matrix where the cells are cross-referenced with other to determine the accuracy of the model using the Error analysis matrix in table 10**.**

# 6. Results

In this chapter the results of the study are shown and discussed in attempt to answer the problem statement for this study which is ***'How can the use of GIS be beneficial in the assessment of urban growth and planning for the greater Copenhagen area?***

The results obtained from the cellular automata model in this study is a combination of various datasets, which were run in a model to depict the simulation of urban growth in the Copenhagen greater area. The simulation of the CA is carried out with the start input of Land use 1990 through to 2009. The results are classified into two categories: Urban represented on the maps in purple and non-urban in green. The results are then evaluated and checked for errors using the visual comparison method. The results in this chapter include:

## 6.1 The thresholds and neighbourhood window-sizes.

In the table below, the neighborhood, size is calculated by taking the results from the Error matrix table 11 by first, calculating the observed and the expected percentage agreement using the formula below:

$$\%Observed\ Agreement = \frac{\mathrm{TU + TNU}}{\mathrm{TU + TNU + FU + FNU}} * 100$$

$$\%Expected\ Agreement =$$

$$((\frac{\mathrm{TU{+}FU}}{\mathrm{TU{+}TNU{+}FU{+}FNU}})*(\frac{\mathrm{TU{+}FNU}}{\mathrm{TU{+}TNU{+}FU{+}FNU}}) + (\frac{\mathrm{FNU{+}TNU}}{\mathrm{TU{+}TNU{+}FU{+}FNU}})*\frac{\mathrm{FU{+}TNU}}{\mathrm{TU{+}TNU{+}FU{+}FNU}})*100$$

In substitution of the letters used in the formula, the 3x3, 5x5 and 7x7-window size observed and expected agreements are calculated. As shown below the results from the 1995 land use simulation are used:

$$\%Observed\ Agreement = \frac{57866 + 245774}{57866 + 245774 + 58214 + 244251} * 100$$

$$\%Expected\ Agreement = ((\frac{116080}{606105})*(\frac{302117}{606105}) + (\frac{490025}{606105})*\frac{303988}{606105})*100$$

The rest of the results are shown in table 13 below.

| Calibration year (1995) | Moore Window size on 100x100 grid size | No. of simulated pixels | Observed Agreement % | Expected Agreement% |
|---|---|---|---|---|
| Urban 57866<br>Non-urban 245774 | 3 x 3 | Urban 58214<br>Non-urban 244251 | 50% | 50.08% |
| | 5 x 5 | Urban 57998<br>Non-urban 244467 | 50% | 50.05% |
| | 7 x 7 | Urban 57976<br>Non-urban 244489 | 50% | 50.05% |

Table 13: The observed and expected percentage agreement results.

The above methods were used to calculate the Observed and Expected agreements of the and based on the observation made, the percentage agreement of the neighborhoods is the same when using the 5x5 and 7x7window size which depicted at 50.05% agreement. The 3x3-window size however had a slightly higher expected agreement compared to the others with 50.08%. These results will further be used to calculate the kappa statistics, which defines more accuracy in the results.

Figure 46 below shows the difference in the shapes of the three neighborhood sizes on a zoomed scale of 1:200,000.The green colour is for the non-urban and purple for the urban areas.  The three different maps do indicate some extent of difference in the cell structure.

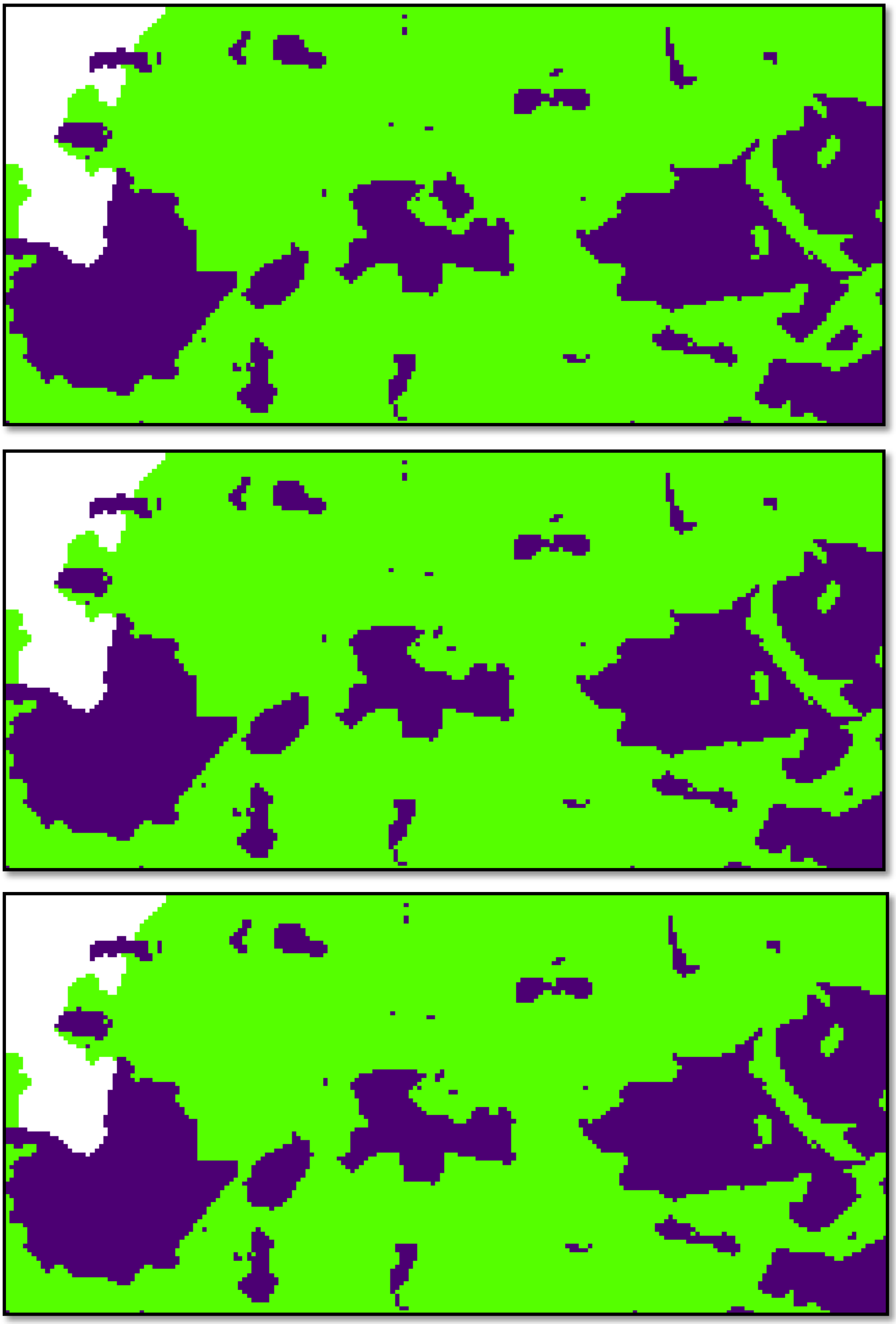


Figure 46: spatial pattern by the 3x3, 5x5 and 7x7 window sizes respectively.

The 3x3 map however seem to display a structure that is seen in both the 5x5 and 7x7 maps. For example, a closer inspection of the maps reveals that the middle section of the three maps are different with less cells again in the 5x5 and 7x7 maps. Based on this, it was considered that the 3x3 was a better neigbourhood size because of its ability to clearly and correctly display the cell structure.

The results from the selection of the correct threshold were derived by using the contingency table 12. This contingency table plus the use of the PCM and kappa statistics are used to calibrate and validate the results of the different thresholds. The kappa statistic will provide a more detailed analysis of the results from the Observed and Expected agreements shown in table 14.

Kappa, K = Potential (Observed) - Potential (Expected) / 1- Potential (Expected)

In the table below the results of how the neighborhood size of 3x3 was chosen from the kappa analysis and the PCM are shown

| Window sizes | PCM (%) | Kappa values |
|---|---|---|
| 3x3 | 100.6 | 0.01 |
| 5x5 | 100.2 | 0 |
| 7x7 | 100.1 | 0.01 |

Table14: PCM and Kappa values results

Because of the close similarity in the statistics, the choosing the neighborhood size to use was narrowed down to the decimal places and the most suitable neighborhood size with the highest percentage was selected, which according to the table above was the 3x3-window size. In as much as the PCM is very high, the result depicted by the kappa values seem to indicate a very poor agreement. However, it should be noted that the very low kappa values might not necessarily mean that the overall agreement is low. The low kappa statistics method predict very low values of 0 and 0.01 that the selected urban pixels are a chance occurrence but rather planned.

All the methods used above have been used to test the accuracy of the model to simulate urban growth however, urban growth is not only about new cells, and the morphology of the growth is another important factor. In this study, the assumption is that the five-finger plan which has greatly influenced the pattern pf urban growth in the greater Copenhagen area. This assumption was tested by calculating the morphological accuracy of the CA model. This is done using the Moran I spatial autocorrelation tool in ArcGIS which will produce a report of the Moran I index values. These values determine if the pattern is random or not by considering that objects that are close to each other and yet consist of similar spatial characteristics are more likely to be spatially correlated and vice versa. The Moran I's index values equal to zero is considered random or not correlated while values higher than zero characterize a clustering in the pattern.

The actual 2009 landuse and the 2009 simulated data was used for determining the autocorrelation. The Moran I index value for the actual landuse of 2009 was a clustered pattern with 0.394 and the simulated landuse was 0.386. This result shows that the morphology between the actual and the simulated are very close.

Next, after the window size and threshold calibration and validation were carried out, the model was run and the CA model simulation results are shown on table 16 below for the period 1990, 1995, 2000, 2005 and 2009, and 2010.

| Years | Elapsed years | No. of urban pixels on actual map | No. of urban pixels on simulated maps |
|---|---|---|---|
| 1990 | 0 | 57275 | Start year |
| 1995 | 5 | 57866 | 58214 |
| 2000 | 5 | 58431 | 59063 |
| 2005 | 5 | 59522 | 59683 |
| 2009 | 4 | 60614 | 60026 |
| 2010 | 1 | Not available | 60086 |

Table 15: Results from simulation model

As shown on table 16 above, the actual data for year 2010 was not available for this study however; the simulation was run until then. This simulation result for 2010 will be used together with the other data to further explain the urban growth process in the study area.

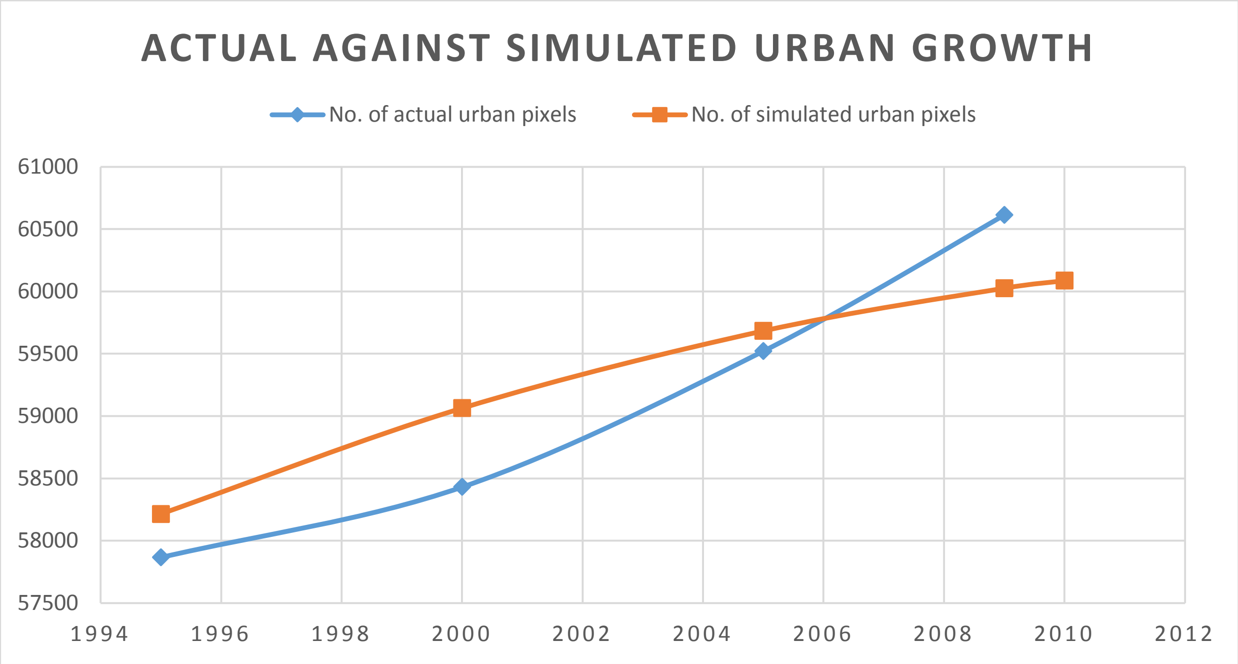



Figure 47: Actual and simulated CA from 1990-2010.

In the table and graph above, the results of the simulation are plotted side by side using the start year, which was 1990, the calibrating and validation year, which was 1995 and 2005 respectively, and the final year of the actual 2009. The simulation result for 2010 was included in the graph just to visualize the simulation trend. Moreover, as seen, the there is an increase in urban cells by about 30% in the one year period from 2009 to 2010. In the graph, the gap between the simulated and the actual maps grows wider with time. The sharp contrast is noticeable especially after the year 2000. The simulated urban growth rate seem to slow down. In the year 2005, the simulated urban growth flat lines thus showing minimal growth.

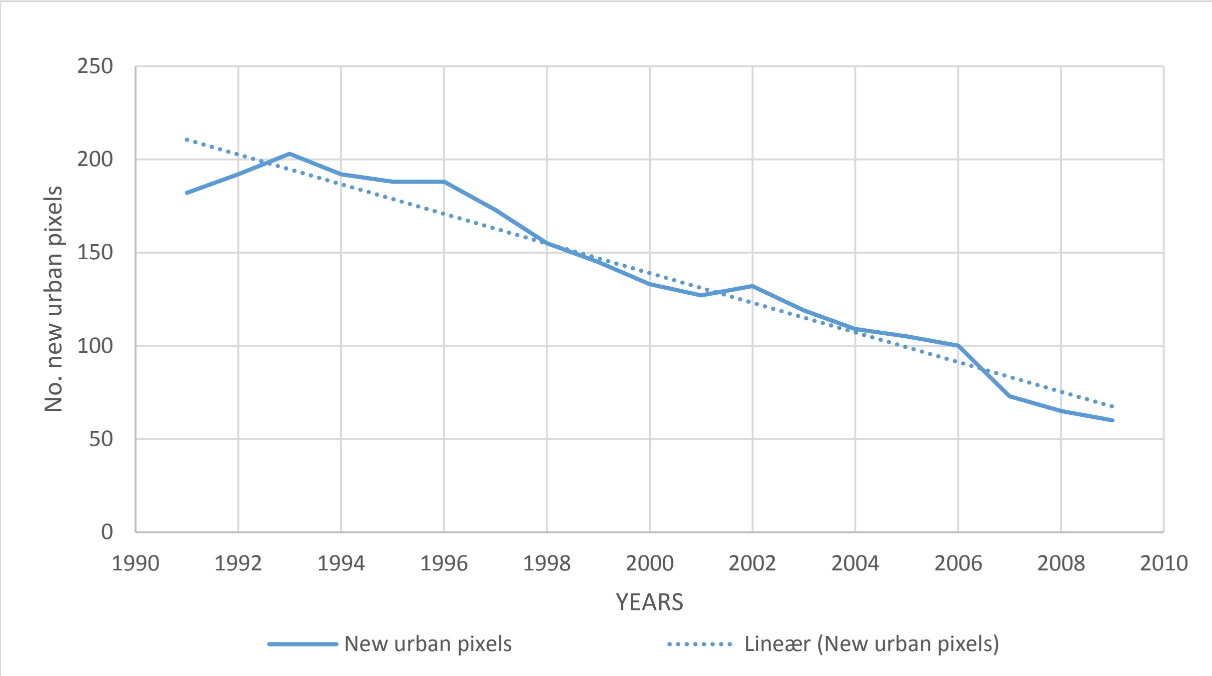



Figure 48: Growth trend of new urban pixels in 19 years.

When the number of new urban pixels over the period of 19 years is displayed on a graph like this one, it is easy to see the growth trend and to detect which years had more new growth compared to the rest. The results on the graph describe somewhat interesting phenomena whereby the number of new urban cells is actually declining over the years. Some of the years for example 1993, 1996, 2002 and 2006 the growth has slightly peaked but dropped again.

## 6.1 Temporal Comparison of Results

In this model, some cells were wrongly simulated and this error accumulated over time, in the figure below the difference can been noticed even after only 10 years especially between 2000 and 2010.

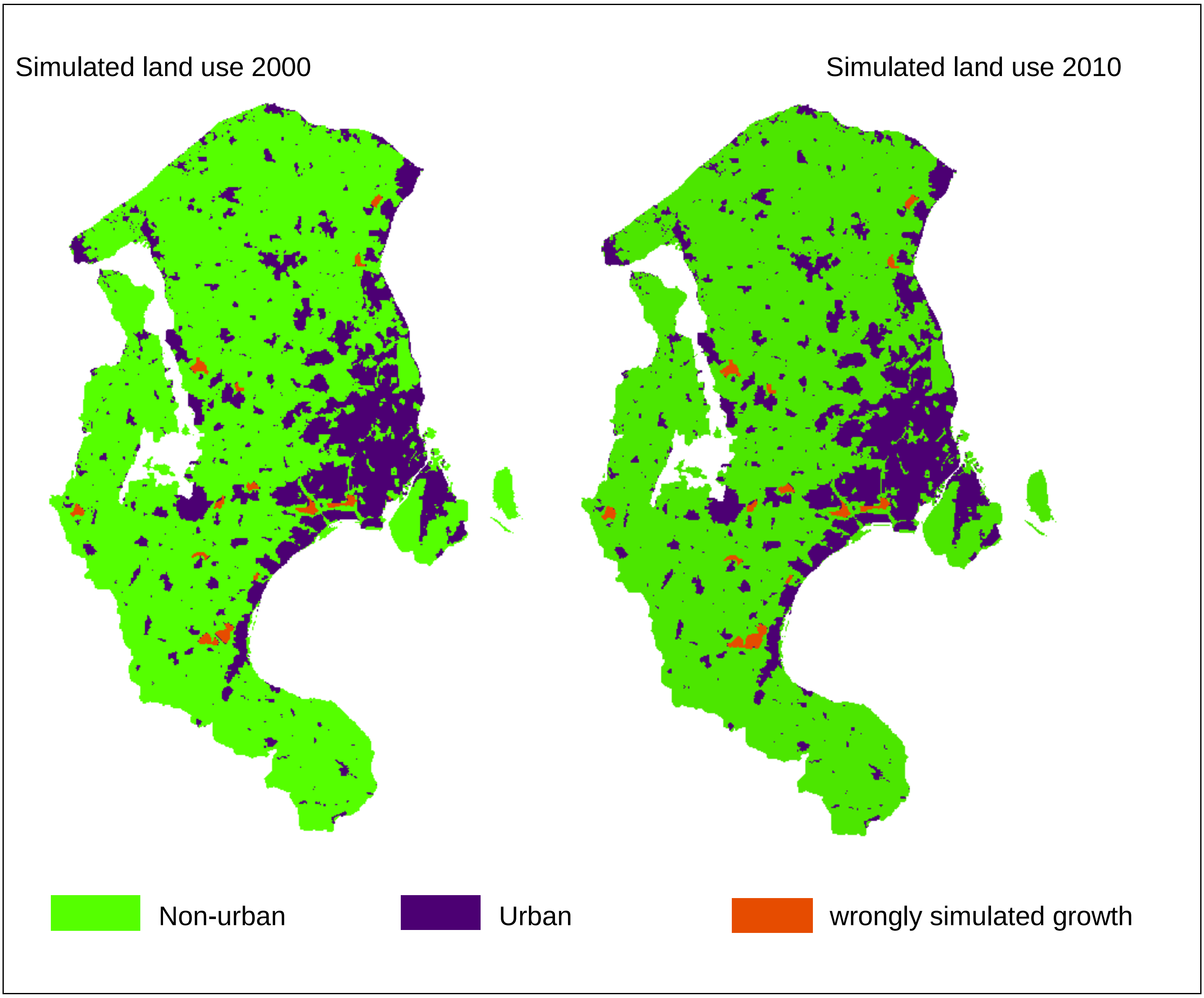



Figure 49: Error Map comparison of urban growth in 10-year period (2000-2010)

However, to clearly see the difference of the growth of the urban cells, a section of the map is zoomed into at 1:200,000 scale and here growth pattern of the wrongly simulated cells can be seen.

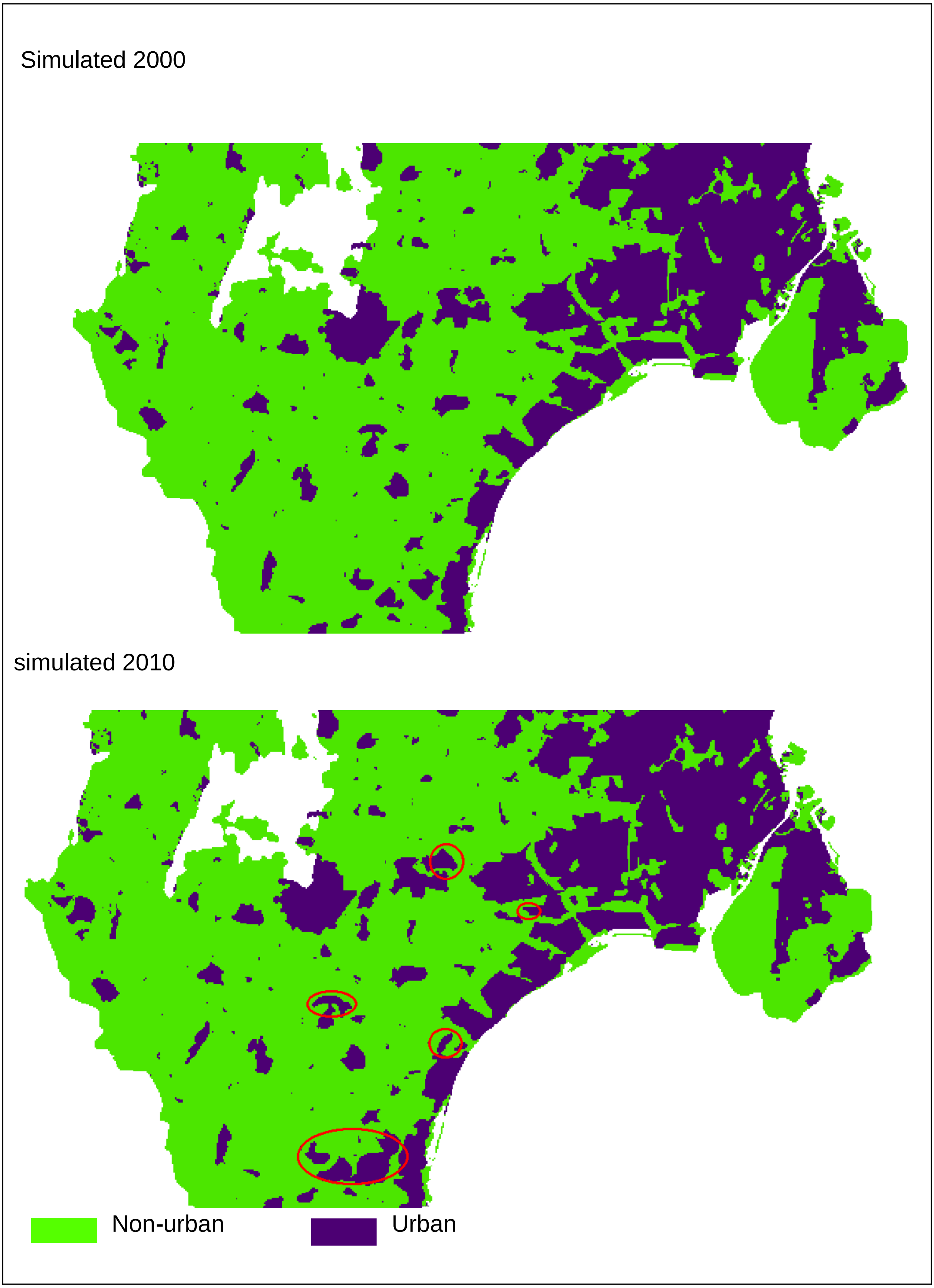


Figure 50: The growth of simulated urban cells in 10-year period.

In contrast to the figure 49 and 50, the correctly simulated urban growth is shown using the actual land use maps for 2009 against the simulated growth of 2010. On further analysis of the pixels, there is a great difference over the years. When shown side by side, these maps exhibit similar urban growth structure in the layout of the patterns and direction over the 20-year period. However, the results between the actual 2009 and the simulated 2010 maps is quite significant and the differences can be noted not only in the number of urban cells but also in the in the spatial pattern. The central area outlined in red is clearly shown in figure 51.

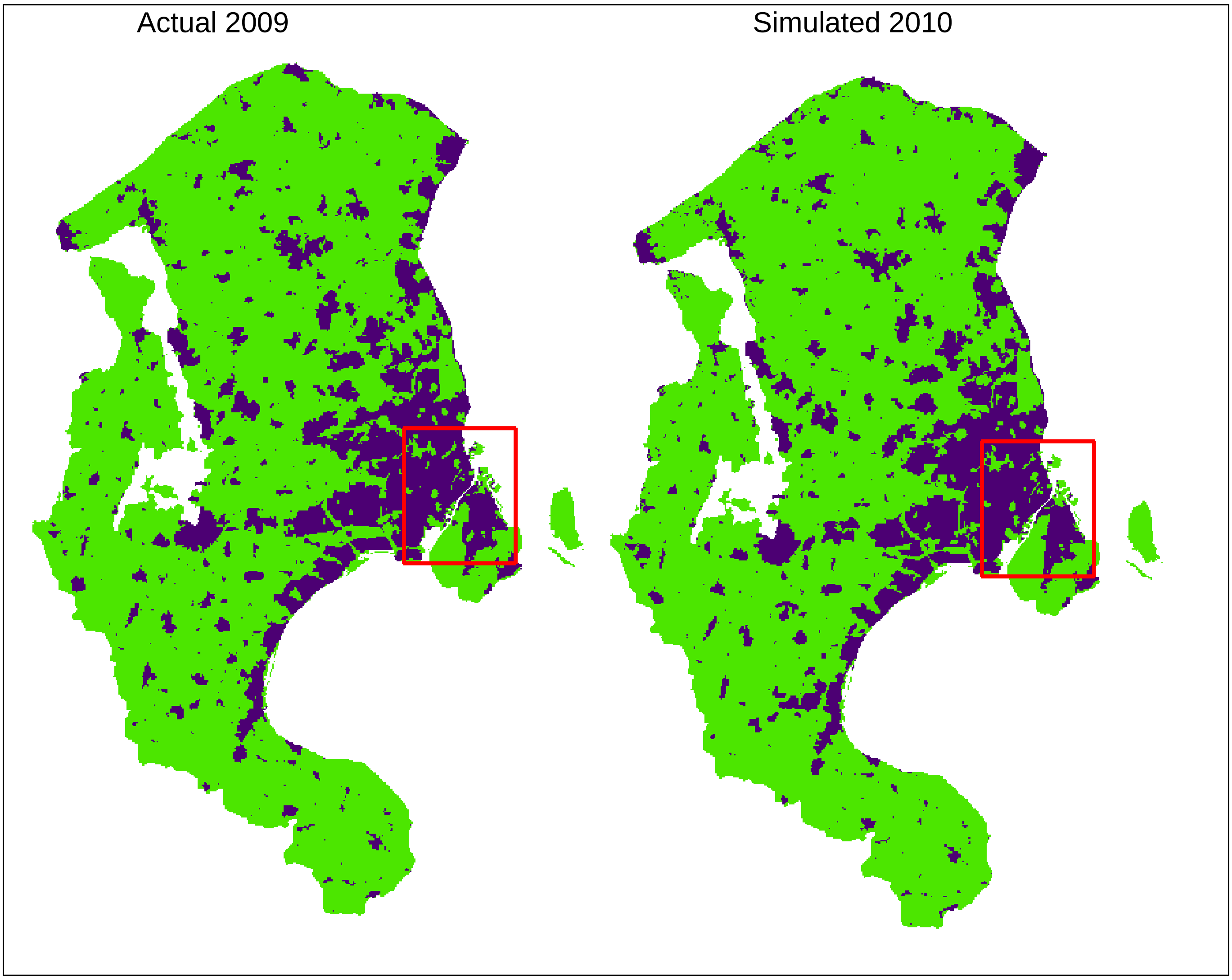



Figure 51: The 10-year actual and simulated urban growth

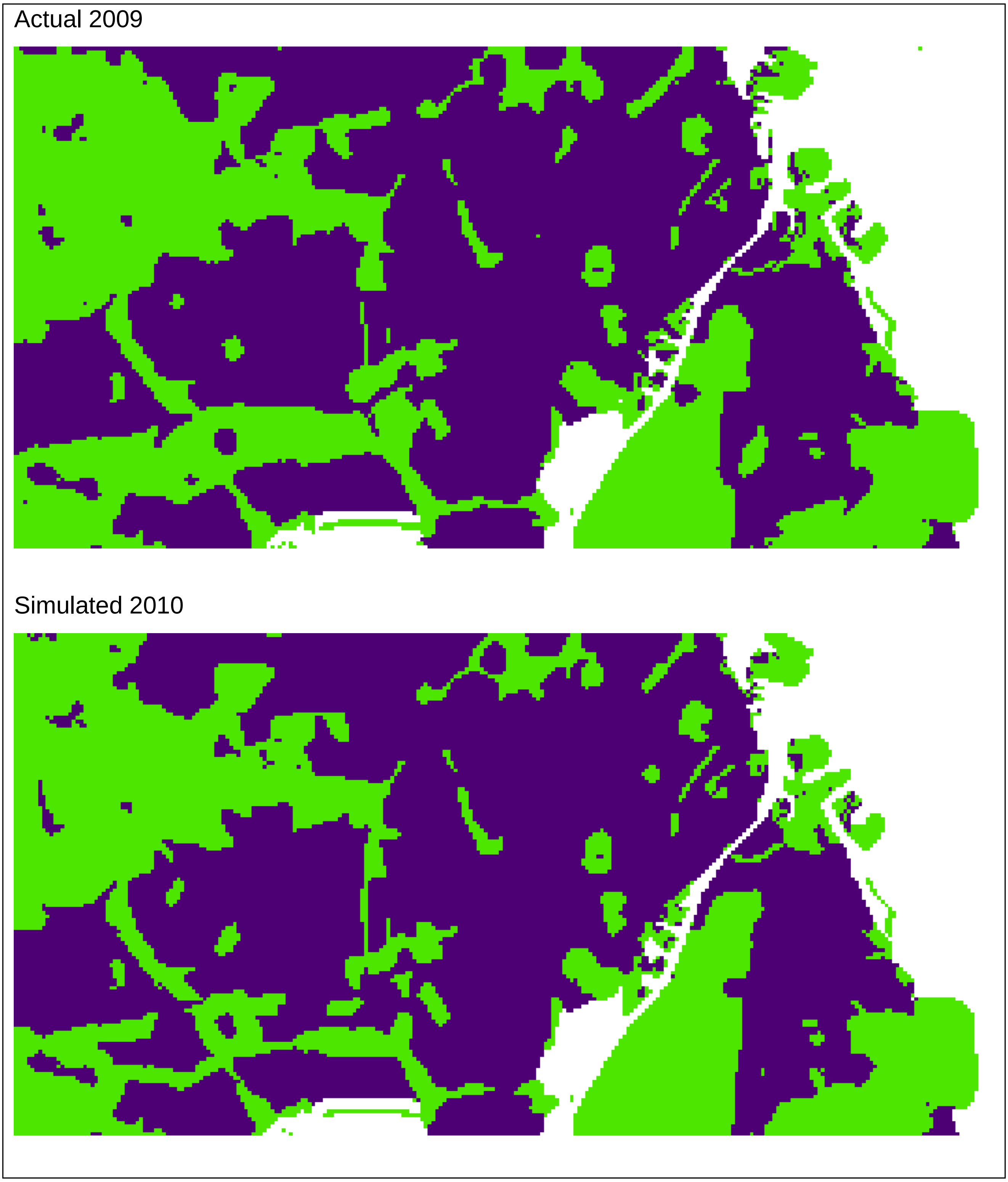



Figure 52: The urban structure of the actual 2009 and simulated 2010 urban growth.

In figure 52, the maps are zoomed to a scale of 1:80,000 and here the inconsistency in the pattern can quickly be identified. Some of the areas that show an urban tendency are showing a non-urban land use in another map.

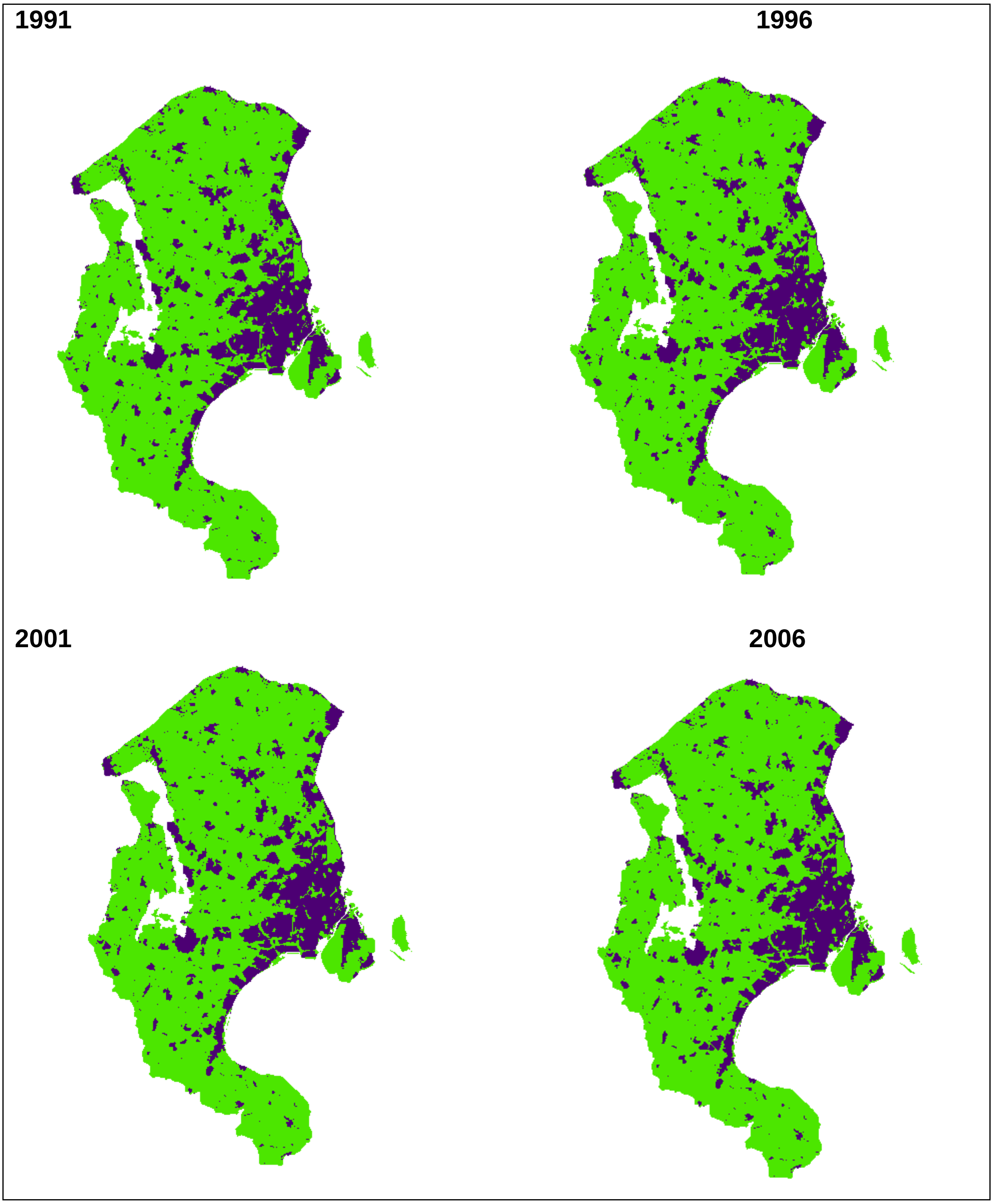



Figure 53: 5-year interval urban growth pattern

## 6.2 Qualitative analysis

To determine the percentage extent of the errors in the results, a formula was derived whereby the difference between the simulated pixels and the actual pixels is calculated, divided by the actual number of pixels and multiplied by 100 as follows:

$$\%\boldsymbol{Error} = (\frac{(\mathbf{no.\,of\ simulated\ urban\ pixels}) - (\mathbf{no.\,of\ actual\ urban\ pixels})}{\mathbf{no.\,of\ actual\ urban\ pixels}} * \mathbf{100}\%)$$

| Year | No. of simulated urban pixels | No. of actual urban pixels | Error % | Std.Dev |
|---|---|---|---|---|
| 1995 | 58214 | 57866 | 0.6 | 0.875 |
| 2000 | 59063 | 58431 | 1.08 | |
| 2005 | 59683 | 59522 | 0.27 | |
| 2009 | 60026 | 60614 | -0.97 | |

Table16: percentage Error and standard deviation results of the simulated model

As seen on table, 16 above, the percentage error and according to the result from the simulation in 2009 there are fewer urban pixels than the actual data. This means that there is a difference of 588 urban pixel cells and this is occurring for the first time since the simulation was run starting with 1990. The year 2000 depicts the highest error percentage of 1.08. The standard deviation of the percentage error from 1995 to 2009 is 0.875. There is not so much variation between the error between what was simulated and the actual urban pixels.

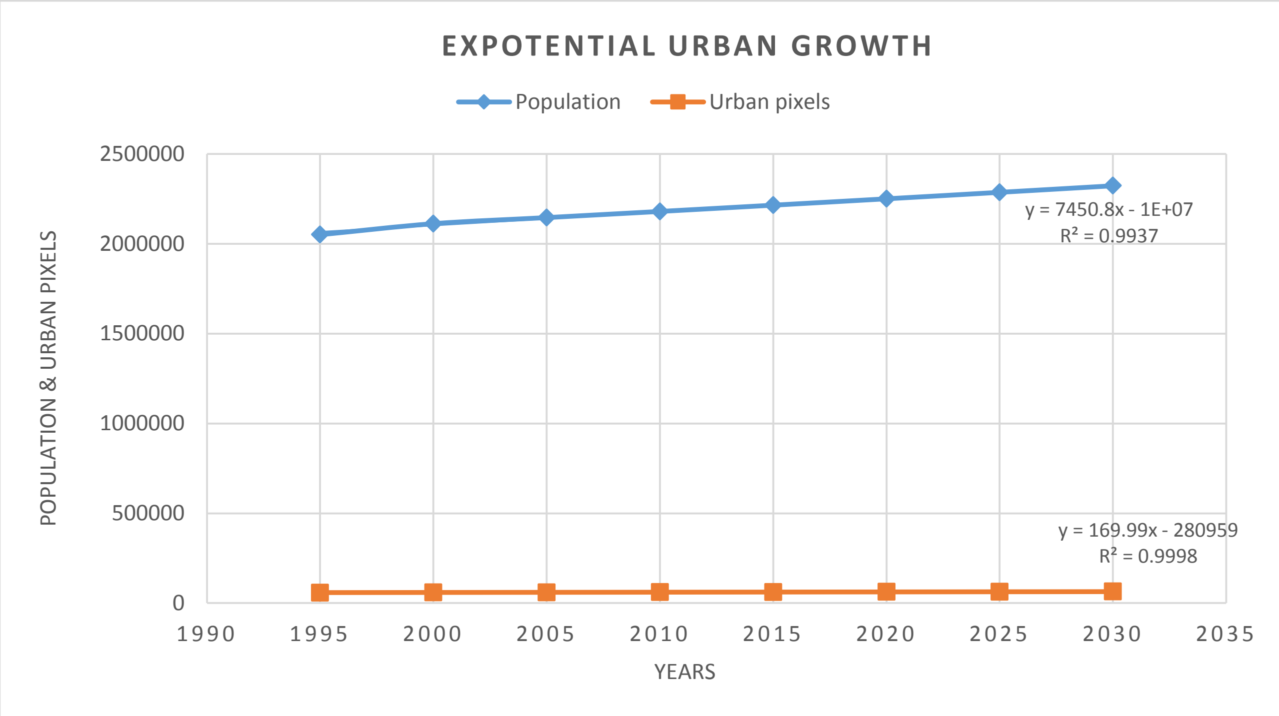



Figure 54: Exponential population and urban growth

The other factor that was considered in the overall study was the relationship of population to urban growth. In the graph 56, the annual average population co-efficient of the greater Copenhagen, area is calculated and plotted against that of the urban growth. The exponential growth from 1990 to 2030 depicts a linear growth pattern with a possibility of a small rise towards the year 2030. The look at the table below shows growth rate in the population by approximately142929 people and 3471 new urban cells for the next 20 years from 2010 to 2030. The population is showing a steady rise over the years as shown by the linear trend on the graph.

# 7. Discussion.

The use of cellular automata to measure urban growth has been considered one of the most effective ways because of its ability to perform a simulation process. In this study, the parameters, which were included in the data processing for the CA data used here do determine, the result and this could be different for every CA model.

From the results, it is obvious that there has been some growth in the urban cells from 1990 to 2010, as was shown in figure 47, which can confirms some simulation has taken place over the time. However, one of the main concerns for this study was to what extent this had happened. This will be discussed later in the subsection 7.4

## 7.1 classification of land use data

The classification process, which was used to categorize the different land use classes, is highly considered because of the nature of the original dataset, which was a combination of the Corine land cover and the BBR. The data, which was, originally 20 classes and later reclassified to two major categories urban and non-urban as was shown in table 6. Assigning the various land use classes to the right category is crucial. Classifying the land uses differently will mean that some of the classes considered urban or non-urban will give a different result than what was attained in this model. For example, the summer cottages were classified as non- urban land use, classifying it otherwise would change the outcome of the CA model.

## 7.2 The suitability map

The suitability, which was a combination of the accessibility factor, land use and the zoning map, is an important input in a constrained CA model like the one used in this study. The accessibility influence was a result of buffer distances around the train stations and motorway junctions. The result from these buffer distances showed a tendency of sorts. The influence of the accessibility factor to the result could have greatly altered the final simulation result because of the changes that were made to the accessibility factors.

These changes could range from the number of train stations and junctions considered to the buffer distances used, and the data preparation methods invoked. In this study, only 126 stations which were considered thus reducing the number by more than half and the junctions were limited to only those on the E20, E45 and E 50 motorway. Of course, there is more than these numbers of motorways with junctions in the study area. These choices provided this study with a unique and different angel of modelling the urban growth; however, this is one of the advantages of suing CA in modelling urban growth. The dynamics of it can be altered or manipulated to suit different scenarios.

The influence of the suburbs and the CBD in the suitability map as seen in figure 38 and 40 respectively, the value of urban areas nearer to the CBD was higher and this value reduced as the further one moved away. The distance measurement used here is Euclidean and as such, it is important to note that this may not accurately be equivalent to the driving distance on the motorway or train. Other factors like speed limits, and traffic interruptions were not considered in these calculations. However, the Service Area can be calculated to determine the actual distance.

## 7.4 The CA model

The model is used to test its ability to simulate, predict and expose any errors if any. This was over a period of 20 years and a prediction of the future until 2030. The calibration and validation of the mode using the original data of 1995 and 2000 respectively together with the comparison of the result with the actual data can be an effective procedure of checking the validity of the model. The method used in this model, can predict the future landuse pattern only because the past land use is known. This is a weakness of the method in terms of simulating urban growth since new influences on the urban structure cannot be evaluated.

However, for this model that in order to closely simulate the actual urban growth, the transition rules needed to be clearly defined over time. This is also dependent on the land use classification method used.

In regards to the spatial pattern of the simulated urban growth, it was clear that there was a close match. The growth of new urban cells has originally been observed to take on the five-finger shape. This imitates the famous five–finger plan, which has been a great influence in shaping the spatial pattern of the greater Copenhagen area.  This pattern can confirm a correlation between the urban growth and accessibility points. For this study the motorway junction on the E20, and E45 and the selected train stations were used and the clustering of urban cells mainly along the motorway and stations create a pattern that can be seen on figure 53.

The neighborhood window size and threshold are two important aspects in CA modelling. The choice of which size of window to use and what the threshold should be does take time to define based on factors like spatial resolution, objectives of the model, classification method for the data, among others. For this model, the 3x3, 5x5 and 7x7 window sizes were tested and based on the level of PCM and the kappa statistics the most suitable window size and threshold were chosen as shown in table  13 and 14.

The extent of the urban growth in figure 50 depicts an interesting phenomenon; the decline in the number of urban cells over the period could be a sign of what the future holds for the urban zone in this study area. The assumption in the study is that the area will not have enough urban zone left for further growth. This could be a general phenomenon of urban growth within a restricted zone whereby the extent of urban growth is controlled by planning and development legislations.

In the case of this study, the zoning map used in the model is a restricting factor, which ensures that the urban growth is contained within the zone marked out for such land use. There could be several explanations for this kind of growth. According to this study, the assumption made was that the area zoned for urban use in the study area is being saturated. This could also mean that there is not so much of this area in 2009 than in 1990, which should be expected if there is growth occurring in a given area.

# 8. Conclusion.

## 8.1 Research Question 1:

How has the five-finger plan model influenced spatial planning in the greater Copenhagen?

Based on the results from the land use maps modeled by the CA model in this study, the five-finger plan definitely seems to have influence. The areas with higher concentrations of urban forms seem to take the finger shaped pattern along the S- train railway lines within in the greater Copenhagen area. The five-finger spatial pattern also gets clearer as the years increase thus the pattern may not be easily recognizable from the land use maps 50 years ago but is more defined with time.

The results in page 105 seem to indicate that there is an influence considering the pattern of the actual 2009 land use data is morphologically taken the shape of the finger plan. The results from the spatial autocorrelation of the actual and simulated 2009 land use data showed a very close similarity in the pattern of the two datasets

## 8.2 Research Question 2:

How can potential urban growth factors be incorporated into a cellular automata model for the greater Copenhagen area?

Several factors may contribute to the urban growth of an area. Other than the fundamental necessities like political, social and economic stability of an area, the presence underlying factors also sometimes referred to as drivers of urban growth are a prerequisite.

According to the literature discussed in this study, some of the factors that have led to the urban growth in the Copenhagen greater area include:

- Good transport network (Accessibility)
- Proximity to the CBD
- Proximity of the suburbs to access points( train stations and junctions)
- Population growth

Good accessibility is a commonly known driver for urban growth. In the Copenhagen greater area, the S-train and the motorways generally are part of the main network. It should also however be noted that many people within this study area also ride bicycles as an easier way of getting around. There are also other types of roads running through the area that are not necessarily motorways and these greatly contribute in making the accessibility from point A to B much easier.

The above factors are can be incorporated into a model individually or in the case of this CA model, they were combined and used to make the suitability map. The population factor however was analyzed separately and not included in the suitability map. Instead, the population density and exponential population was extracted and compared to the results from the model. This is one way of incorporating the population; however, the other way could be to include it as a parameter in the suitability map.

The proximity to the CBD did show some correlation between the distances and the urban clustering and the population density. The urban clusters were majorly along the five-fingers plan thus along the rail lines but also the ten highest population density belonged to municipalities within a 3 km radius of the CBD as shown in figure 42. The 3 km radius is assumed good distance for commuters back and forth the CBD.

## 8.3 Research Question 3:

How can neighbourhood window size and threshold influence the Cellular Automata model calibration?

In this, study three window sizes were tested, 3x3, 5x5, and 7x7. According to the results, the different window sizes do represent the land use pattern rather differently. The PCM and the kappa statistics results from the trial and error method used to choose the window size proved that the 3x3 was the best window size because of its ability to capture a similar pattern of urban growth in comparison with the actual land use pattern. This of course does not mean that the other window sizes cannot be used. They can be used depending on the aim of the model and the land use classification applied.

## 8.4 Research Question 4:

How can Cellular Automata (CA) help in modelling urban growth in the area?

The use of CA to model urban growth is a known method as earlier discussed in the theory chapter of this study. CA can be used to model urban growth by defining the parameters under which the model should operate. For this study, the parameters defined where:

- The type of land use classes
- The transition rules
- Window size and threshold
- The suitability map input

Depending on the parameters used in this model, the model results were able to depict a spatial pattern, a 50% goodness of fit, and make a future prediction for the next 20 years. These results could be better improved upon and one of the ways to do this is by refining the calibration and validation process.

Additionally, it was also noted that measuring the extent of urban growth based on only the spatial pattern is not enough but a more detailed analysis is necessary to determine the rate of growth over time. (Yeh and Li 2001), further clarify on this issue adding that the feasibility and the plausibility of a model should be equally considered. In the results of this CA model shown in figure 48, it was noted that as much as the spatial pattern of urban growth was spreading out, the actual number of pixel cells being transformed to urban land use were actually decreasing over time. As the area for growth decreases over the years so does the number of pixels. This pattern however does change if more area is opened up for urban landuse.

In conclusion, considering the ability of this CA to simulate urban growth, its performance was considered satisfactory although the model can be greatly improved upon. Additionally the simulation result for 2010 shows that even with a selection of only a few train stations and motorway junctions, the urban growth in the Copenhagen greater area like many metropolitan areas is on the rise.

# 9. Perspectives

As noted in chapter two previous studies by known modelling researchers like Batty, Torrens, and White to mention but a few the use of Cellular Automata has been considered effective in modeling the dynamics and complexities of urban growth and as such, this method will be explored further in this chapter. The CA method is also considered somewhat straight forward because of its ability to apply the neighborhood rules of transition, which question the state of each cell based on its neighboring environment.

The original idea of the CA as a self- organizing system is the ability to simulate urban growth without any interference from the outside. This however seems contrary to the how urban growth is formed. Urban growth is usually dictated upon by outside factors like policies, politics, social and economic status governing a given area. In this case, the greater Copenhagen area and Demark in general have defined areas for urban growth and other types of land uses. This is further supported on municipality basis by the plans that the municipalities have in place in regards to land use allocation. The land use allocation process, based on the ABCD model for land use allocation determines in detail how the land in the municipality is to be used.

During this study, it was noted that sometimes the accuracy of the model could be overstated for example in a situation where the number of the non-urban cells are more predominant than the urban. In the case of this study, there is a reasonably large amount of non-urban cells in comparison to the urban thus another method was necessary to eliminate any inaccuracies.  Since the visual observation method used earlier may not be too reliable and cannot identify the pixel fit, the kappa analysis is considered more reliable. The method identifies the goodness of fit, which generally shows how effective the model has been in simulating the urban growth in comparison to the original data. However basing on only the 'goodness of fit' to determine urban growth as already mentioned in the previous chapter is not enough. More methods are recommended in order to attain a good result.

Furthermore, the five-finger influence on the urban growth pattern. In the recent land use, maps it can noted that in as much as the pattern has continued along the fingers, it has also gone beyond the fingers. What is seen now is a clustered kind of urban pattern in the greater

Copenhagen area. In the analysis of the results on urban growth and population density in figure 44 and 45, it was noted that some of the areas outside the Copenhagen municipality like Roskilde and Gentofte had high populations and dense urban clusters. The question raised then is, “will the urban growth pattern in the Copenhagen area change in the future with an increased demand of new territory for growth?”

The use of the CA model to in the planning of urban growth in the Copenhagen greater area can definitely be used when all the necessary factors are incorporated. One of the ways to use the model could be to predict the future urban growth pattern of this area. Since the urban growth is growing beyond the fingers, this calls for another plan to structure the growth pattern and accommodate the slow but steady population growth. This may require that the existing social and economic models be revised after approximately every five to ten years.

Finally, the use of mainly the ArcGIS processes like buffering, statistical, proximity and overlay analysis among other methods was used. As much as these processes are able to quantify the spatial dynamics of the model, for example the density, entropy, and accessibility it is not enough to capture the complexity of urban growth. In order to capture, the spatial and temporal factors of the study area, detailed spatial and analysis is necessary in other programs other than in ArcGIS. However, ArcGIS platform was mainly used because it was readily available and easily applicable to this study. It is a recommendation for further study in urban growth modelling that a combination of other platforms and programs be used to effectively process, analyze and interpret the result of the cellular Automata modelling.

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