# Simulating city growth by using the Cellular Automata Algorithm

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## Abstract

The objective of this thesis is to develop and implement a Cellular Automata (CA) algorithm to simulate urban growth process. It attempts to satisfy the need to predict the future shape of a city, the way land uses sprawl in the surroundings of that city and its population. Salonica city in Greece is selected as a case study to simulate its urban growth. Cellular automaton (CA) based models are increasingly used to investigate cities and urban systems. Sprawling cities may be considered as complex adaptive systems, and this warrants use of methodology that can accommodate the space-time dynamics of many interacting entities. Automata tools are well-suited for representation of such systems. By means of illustrating this point, the development of a model for simulating the sprawl of land uses such as commercial and residential and calculating the population who will reside in the city is discussed.

## Keywords

Cellular automata, transition rules, simulation, future population, future pattern

**Word count**

9.724

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**Table 1:** A correlation between Cellular Automata and Urban Cellular Automata

**Table 2:** The table illustrates what is the percentage, the number and the area that is covered by residential and commercial cells. Moreover the number of the population is depicted and also the years needed for the changes to take place.

*Sprawl is a relatively new form of urbanization, falling somewhere between Ebenezer Howard's ideas for Garden Cities and Le Corbusier's notions of a ubiquitous urban form, yet it is altogether different—a ''geography of nowhere,'' as authors have referred to it (Kunstler 1993)*

## 1. Introduction

Cities and urban development in general emerge from the bottom up and the spatial order we see in patterns at more aggregate scales can be explained only in this way. The way we simulate such emergence is by representing the basic elements or atoms of the city in two distinct but related ways: through cells which represent the physical and spatial structure of the city and trough agents which represent the human and social units that make the city work. This dissertation will investigate the first way; the cells, which is based on the simulation of the city by using the Cellular Automata (CA) algorithm. CA offer an interesting and innovative approach to the study of urban systems. In recent years there has been a prolific application of CA models to urban systems.

This process leads to surprising events to emergent structures not directly obvious of their process but hidden within their mechanism new forms of geometry associated with fractal patterns and chaotic dynamics-all are combined to provide theories that are applicable to highly complex systems such as cities. The employment of CA in urban simulations often entails substantial departures from the original formal structure of CA described by von Neumann, Ulam, Conway, and Wolfram. Although the application of CA to urban systems seems natural and intuitive, this is not in itself sufficient justification for their use (Couclelis 1985). Cellular Automata (CA) can be referred to as one of the Artificial Intelligence (AI) tools (Tsoukalas and Uhrig, 1997). The definition of CA rules is still a research issue, despite the emergence of CA as a powerful visualization tool in urban growth simulation (Batty, 1998). Urban CA is developed largely through trial and error which makes the CA models essentially heuristic (Wu, 2002).

The objective of this thesis is to survey theories and examples of city simulation models based on these concepts. In the second part of the dissertation an implementation of the CA concept to simulate the urban growth of a real city, the Salonica city in Greece in order to test number of modelling parameters that affect the urban growth simulation will be described. The initial idea is to re-create the city model based on different rules each time, rules related with land use or land cover etc. and compares the different patterns that emerge. Two experiments will be described with different results. Most related projects use GIS (Geographical Information System) and the CA algorithm, for creating such kind of simulation but in this thesis Processing language and CA algorithm is used to code the program and simulate the city. According to the official webpage, processing is an open source programming language used by students, artists, designers, architects, researchers, and hobbyists for learning, prototyping, and production. It was developed by artists and designers as an alternative to commercial software tools in the same domain.

As far as Salonica city is concerned, it is the second biggest city in Greece and it is the centre of development of the North Greece. Historically the city is the second industrial centre of the country. Moreover its central place in the transportation network makes Salonica a basic commercial centre. The great history of the city, the economy, its population, the great numbers of educational institutes, the health centres, its culture and the various amusement places have turned Salonica into a basic attraction area. Due to all the above the city, the last 15-20 years, has gone under various changes which are connected to its geographical position and its role in the area of north-east Europe. The changes that have happened the last years concern its rapid growth both of the population and the geographical transformation. This dissertation takes into account the important role of the city and tries to investigate how the city grows focusing on its population and its commercial uses which are the two important things that change as time passes. Moreover it tries to calculate distances from the new areas to the centre of the city.

# Part I

## 1. Related work of cities' simulation

A number of simulators have been proposed to address the simulation of the urban growth. Most of them are not available on the internet and that is because they are desktop applications. Furthermore, they are dependent on a proprietary GIS platform and data format. There are many examples of planned cities that can be generated by CA. It is not difficult to suggest rules that generate highly ordered forms such as the idealised utopias of great architects like Vitruvious, Palladio and Corbusier, and one of the most useful features of CA is to identify exactly what these rules are. But most cities are not regular, being based on organic growths, and to generate these using CA, some basis for historical accident and random decision must be invoked. (Batty 1997)

Urban CA have been developed rapidly for the simulation of urban complex systems since the late 80s. A number of interesting investigations have been documented (Batty and Xie, 1994; white and Engelen,1993; Clarke and Gaydos,1998). CA based approaches have applications in the study of urban and regional spatial structure and evolution. Modelling cities with CA is relatively new approach although it has its roots in geography and relates to the work of Hagerstrand(1965) and Tobler(1979)(Clarke and Gaydos,1998).

Urban CA models may be separated into three types. The first one uses CA models to generate results that can be explained by urban theories. This kind of models basically, are used to test ideas and assumptions for hypothetical cities. An example that illustrates this point is Western and Wu(1999) model which presents a CA model to implement urban theories concerning developers' profit seeking and communities welfare-seeking behaviours. In this example they explore the mediating effects of alternative systems of land use rights. The second type of CA is to apply them for the simulation of real cities. Clarke and Gaydos(1998) apply CA models to simulate and predict urban development in the San Francisco Bay region in California and the Washington/ Baltimore corridor in the United States. White et al(1997) provides a realistic simulation of the land use pattern of Cincinnati, Ohio. A constrained CA model is developed to simulate urban expansion and agricultural land use loss of Dongguan in the Pearl River Delta, a rapidly growing area in southern China. (Li and Yeh, 2000). An important example of this kind of simulation is which this thesis used as resource of information is the In the next example, the model is applied to the Midwestern Megalopolis region (Gottmann 1967) around Lake Michigan in the United States. The area provided some unique characteristics for applying the model, in particular, the boundary formed by Lake Michigan United States). In these simulations, it is assumed that the rate of growth is known *a priori*. The third type is to use CA algorithm to develop normative planning models to simulate different urban forms based on planning objectives. Yeh and Li (2001) use CA to generate different urban forms, ranging from monocentric to polycentric development. These urban forms can be assessed to meet selected criteria for sustainable development though minimising agricultural land use in an effort to achieve compact development. Ward et al (2000) also developed a constrained CA model which has been applied to an area in the Gold Coast, a rapidly urbanising region of Eastern Australia. They demonstrate that CA models can simulate planned development as well as realistic development by incorporating sustainable criteria in the simulation.

This thesis will implement the second type of CA in the second biggest city in Greece due to its rapid expansion and its important role in the north-east Europe.

## 2. General causes of city sprawl

At a broad level, sprawl can be considered as a mature stage in the evolution of a city toward a compact urban structure.

**Population growth** is one of the most important engines of change in any urban system. The expansion of a city beyond its periphery requires, at a minimum, population growth and/or spatial redistribution of that growth. There are at least three ways in which population growth has contributed to sprawl: absolute growth, increasing urbanization, and restructuring in the dynamics of household demography. First, city growth in terms of absolute population. Second, at the same time, the percentage of the population living in what can be classified as urban areas is also growing. Of that urban population, the numbers residing in small cities is swelling at a striking rate. Third, and in parallel, there has been an associated decrease in household sizes and a related increase in the number of housing units.

If urban populations swell, the city must expand, upwards or outwards and sometimes beyond its previous boundaries, stretching into agricultural or resource land. However, at the same time that urban population has been growing in absolute terms, the distribution of that growth has been allocated in a spatially distinct manner, largely on the urban fringe as sprawl. No longer indebted to central cities as interchange points for raw material and finished goods, industry has diffused rapidly through the city to the suburbs, following its labor forces and pursuing cheap land and easy access to an expanding network of interstate **highways**. Suburban highways have become the new centres of gravity around which urbanization has begun to orbit. Prolific use of automobiles makes lower densities possible because it facilitates dispersion of activities.

### 3. Cellular Automata

*Cellular automata are sufficiently simple to allow detailed mathematical analysis, but insufficiently complex to exhibit a wide variety of complicated phenomena- Stephen Wolfran, Cellular Automata and Complexity (1994).*

*The chess-board is the world; the pieces are the phenomena of the universe; the rules of the game are what we call the laws of Nature.-T. H. Huxley*

Take a board, and divide it up into squares, like a chess-board or checker-board. These are the cells. Each cell has one of a finite number of distinct colours - red and black. Now we come to the "automaton" part. Sitting somewhere to one side of the board is a clock, and every time the clock ticks the colours of the cells change. Each cell looks at the colours of the nearby cells, and its own colour, and then applies a definite rule, the transition rule, specified in advance, to decide its colour in the next clock-tick; and all the cells change at the same time. (The rule can say "Stay the same.") Each cell is a sort of very stupid computer --- in the jargon, a finite-state automaton --- and so the whole board is called a cellular automaton, or CA. To run it, you colour the cells in your favourite pattern, start the clock, and stand back

This is a concrete picture of CA. A more technical and more abstract description of CA is described below. CA is A DISCRETE DYNAMICAL SYSTEM that is composed of an array of cells, each of which behaves like a FINITE-STATE AUTOMATON. Any CA system is composed of four components – cells, states, neighbourhood (Moore, circle ...etc) and transition rules. All interactions are local, with the next state of a cell being a FUNCTION of the current state of itself and its neighbours.( G.W. Flake's, 2000 ) CA are models in which contiguous or adjacent cells, such as those that might comprise a rectangular grid, change their states- their attributes or characteristics - through the repetitive application of simple rules. The Figure below illustrates how CA work and what is happening as time passes. The initial automaton accepts the input and in time t and changes its status in time t+1.

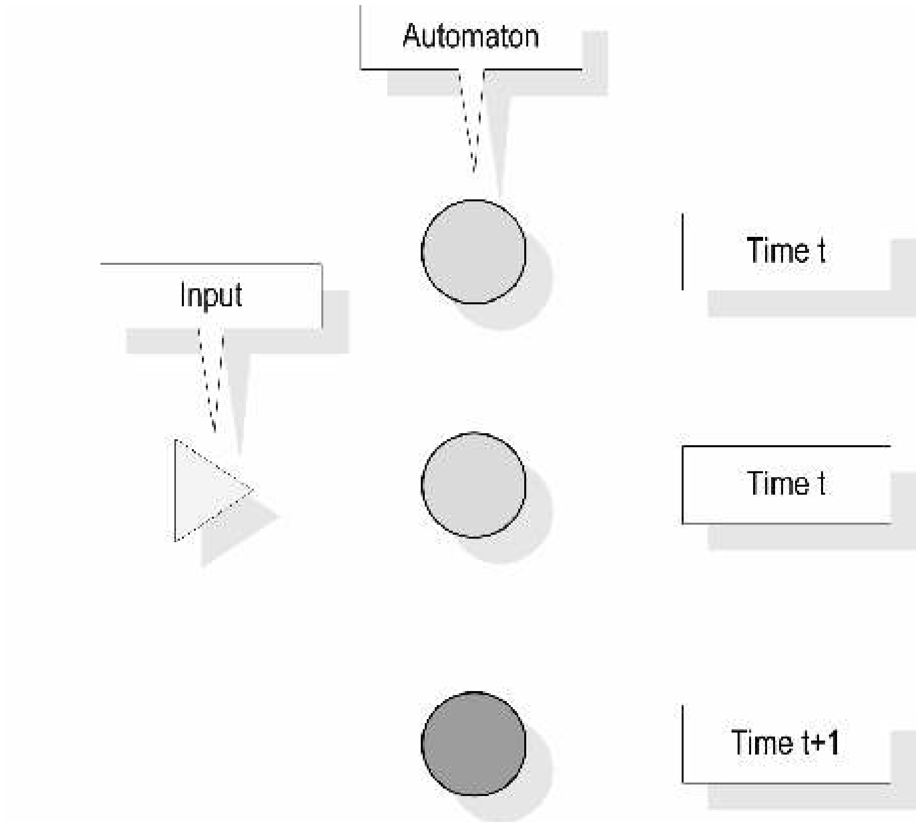



*Figure 1: An automaton changes state (colour) between two time steps, based on input*

CA models can be based on cells that are defined in more than two dimensions, but the 2d form that makes them applicable to cities is the most usual. The rules for transition from one cell to another can be interpreted as the generators of growth or decline, such as the change from undeveloped to a developed cell or vice versa. This change is a function of what is going on in the neighbourhood of the cell, the neighbourhood usually being defined as immediately adjacent cells, or cells that in some sense are nearby. Urban growth and decline in real city neighbourhoods provide excellent examples.

CA models were first suggested at the dawn of computer history. The mathematician Alan Turing, demonstrated the ideas in some early illustrations of computers that could “reproduce” themselves but it was John von Neumann, who set the field alight in the 1950s, initiating the scientific study of CA. In 1970, John Conway presented the Game of Life, in which a cell would be developed if it was adjacent to 3 already developed cells, would remain in the same state, that is survive, if surrounded by 2 or 3 developed cells, but would die otherwise.

CA embody a principal of generic development that fits with the ways systems in general and city systems in particular appear to develop, or might be developed. The states of the cell change if something does or does not happen in its neighborhood. The principle can be stated in its most general form as:

**If** something happens in the neighborhood of a cell

**Then** some other things happen to the cell

Another close is often added, dealing with the case where the conditional is not met-the else clause-but this complicates the logic, and in elementary expositions we can proceed without it.

To give the principle specific meaning, we need to define the things, the cells and the neighborhood. The cells might be sites for development; the things, “state” or types of development; and the neighborhood, regions where development might take place. The rules effecting transitions between states would thus imply growth, decline, or simply a change in state. Conway’s game of life can thus be translated into three decision rules:

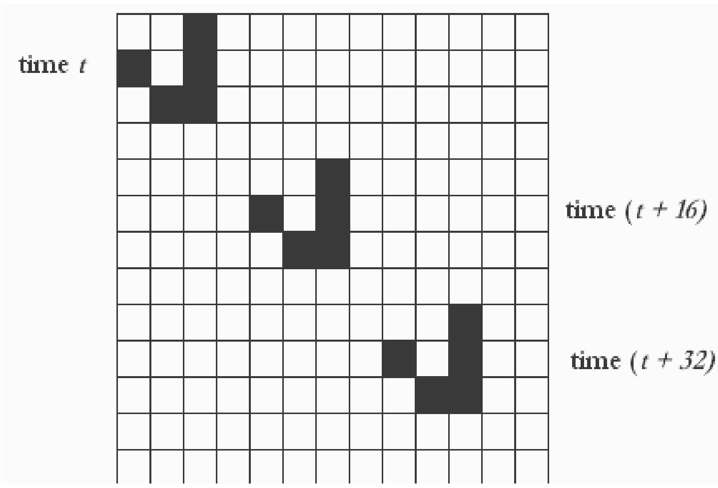


*Figure 2: Glider movement (Conway Game of life), diagonally from the upper left to lower right of the lattice.*

**If** there are 3 cells developed in the 8 cells neighborhood adjacent to the cell in question

**Then** the cell is developed

**If** there are 2 or 3 cells developed in the neighborhood

**Then** the cells remain in its existing state

**If** there are fewer than 2 or more that 3 cells developed in the neighborhood

**Then** the cells remain is emptied of any development

This implies that if there is no cell or only one cell developed in the neighborhood, development in the cell in question dies or the cell remains empty-through isolation; while if the cell has 4 or more developed neighbors, it also dies or remains empty-through overcrowding.

There are many ways this principle can be elaborated to achieve realism. Many **if-then** rules might be concatenated; the size and configuration of neighborhoods can be varied from the most local to the entire system; different types of state or development, such as different land uses and their attributes, might be characterized; and different configurations or starting points for these automata can be defined. The best way to explore possibilities is through examples.

The simple of all developments is that of contiguous growth. Imagine a city growing from one cell, the historic core of development. If there is any development in the 8 cells that form the square neighborhood around the cell (the Moore neighborhood) then the cell is developed. The principle is depicted in the figure below.

The figure depicts Neighbourhood structures considered for two-dimensional cellular automata. In the cellular automaton evolution, the value of the centre cell is updated according to a rule that depends on the values of the shaded cells. Cellular automata with neighbourhood (a) are termed ``five-neighbour square''; those with neighbourhood (b) are

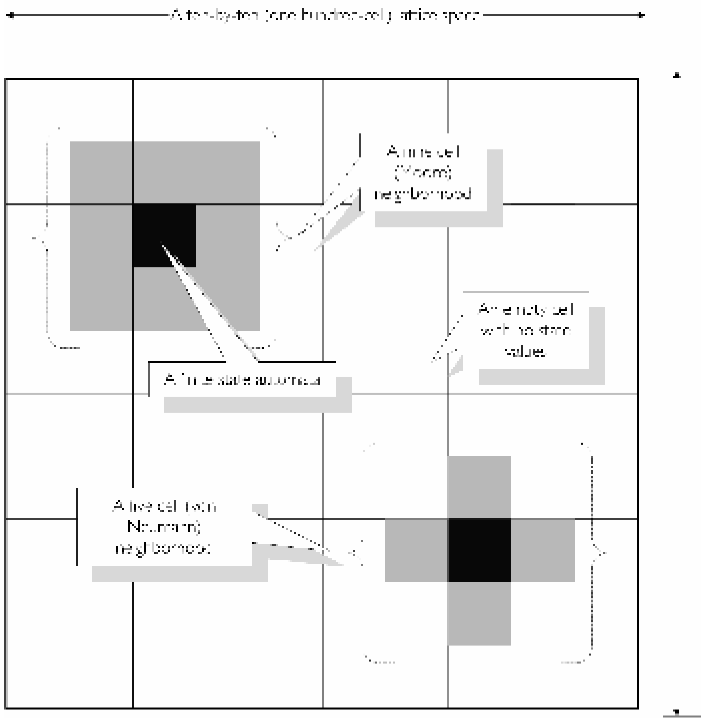


*Figure 3: Varying cellular automata neighborhood configurations in a 2D cell-space.*

termed ``nine-neighbour square." (These neighbourhoods are sometimes referred to as the von Neumann and Moore neighbourhoods, respectively.) Totalistic cellular automaton rules take the value of the centre site to depend only on the sum of the values of the sites in the neighbourhood. With outer totalistic rules, sites are updated according to their previous values, and the sum of the values of the other sites in the neighbourhood. Triangular and hexagonal lattices are also possible, but are not used in the examples given here. Notice that five-neighbour square, triangular, and hexagonal cellular automaton rules may all be considered as special cases of general nine-neighbour square rules.

**4. Urban Cellular Automata**

CA are based on the transformations caused from local action which generates global pattern: decisions made locally, which are not coordinated centrally in any way, generate patterns that appear to have been manufactured by some central intelligence (Couclelis 1987). This is an age-old conundrum. It is currently one of the most debated topics in science, and reflects the notion that systems are self-organising. It also reflects the idea that systems organise themselves from the ground up, thus generating hierarchical or fractal organisation. Self organisations that is to say the phenomena by which a system self organises its hierarchical structure independent of external causes,  is a fundamental property of open and complex systems. Such systems exhibit phenomena of nonlinearity, instability, fractal structures and chaos – phenomena which are intimately related to the general sensation of life and urbanism at the end of the 20$^{th}$ century. (Portugali, 2000).

It is relatively easy to generalize the basic specification of CA to represent urban systems. The cell space on which a cellular automaton operates might be considered equivalent in an urban sense to an environment, a landscape, or a territory. The CA lattice can also be generalized to represent urban spatial structures, networks of accessibility, or the physical infrastructure of the city (particularly when the lattice is specified as an irregular tessellation). CA cells operate just like the pixels that comprise a television screen, except that each cell is capable of processing information, as well as visualizing its state. Cells can be used to index any kind of object or attribute such as population or building but the crucial feature is that cells cannot move thus constitute the backdrop on which urban change takes place. Cells can correspond to any zonal geography within a city: parcels of land, administrative boundaries, traffic analysis zones, etc. The cell state offers a flexible framework for encoding attributes of a city into the simulation model. In an urban context the cell state can be made to represent any attribute of the urban environment, e.g., land use (residential or commercial), density (high density or low density), land cover (forested or concrete), etc. Neighbourhoods in urban CA represent spheres of influence or activity within the city, e.g., market catchment's areas, the walking radius of individual pedestrians, the commuting watershed, etc. The rules of a CA drive the dynamics of change in the model. CA rules can be devised to mirror how phenomena in the real world operate, and can then be coded as algorithms within the simulation. In the table in page 49 a correlation between CA and urban CA is presented.

The discrete spatial structure of real cities, makes CA models with their discrete cellular structure a natural tool to represent cities, The same applies to the fact that in both cities and CA models, the properties of a given local spatial unit (a building, parcel of land or a CA cell) are determined, to a large extent, in relation to their immediate neighbors. This is apparently the reason for the growing wave of urban and regional CA models that we see in the last few years. (Juval Portugali,2000).

City is a typical system in self-organization. Self-organization as Juval Portugali (2000) has mentioned is the phenomena by which a system self organizes its internal structure independent of external causes. Also, that kind of systems exhibit phenomena which are intimately related to the general sensation at the end of the 20th century. It is an open and complex system; open, in the sense that it is part of its environment through a flow of immigrants from the environment inward into city and from it outward to the environment. This flow and the fact that the properties of every place (i.e. cell) in the system are a derivation from the properties of the neighboring places and thus change with every move in city, keep the city in a far equilibrium situation. It is a complex system in the sense that it involves interaction among a large number of places whose properties are changing with every new iteration. In this thesis the aim is to model a real city as a self organization system, we do not determine the internal rules, which lead from local interaction among individuals and places to the global pattern and structure of the system. Given various configurations of initial conditions the aim of this thesis is to study such processes.

Despite the advantages that CA offer in the exploration of the growth of a city a number of errors during the modelling and the simulation may happen. These errors may affect the results of the program. A series of inherent model errors can be identified for CA models in simulation of city growth. They are related to the following aspects:

- Discrete entities in space and time;(cell size and time for each generation)
- Neighbourhood definitions (types and sizes);
- Model structures and transition rules;
- Parameter values and variables(according to the variables and the values the simulation takes into account, some assumptions should be made);

(Nagaratna P Hegde, *Dr I V MuraliKrishna, **Dr K V ChalapatiRao)

## 5. The example of Salonica city

### Area of Study

Salonica city is in Northern Greece and has been selected for this study due to its importance and its role both in economic and social life of Greece. This result in large urban development over the last decades making the city grows from a small part to


*Figure 4: Map of Greece*

cover most of the part of the nomarcy. The accelerated urban development raises the need of simulating the growth pattern to help the municipalities in planning the proper distribution of infrastructure services. The social importance of this work is to understand the urban growth pattern over Salonica city and its surroundings.

The city with its surroundings covers 5.500 Ha and its population in 2001 was 862.562 people. The population of the surroundings was 181.169 people in 2001 but it keeps growing the last years due to the fact that many people who used to live in the main city move there. As far as the population of the main city is concerned it remains steady. That is because many immigrants from other countries choose Salonica in order to make their new life. Another point worth mentioning is that there is rapid a growth in the number of companies that invest in Salonica, and this is the other factor that attracts

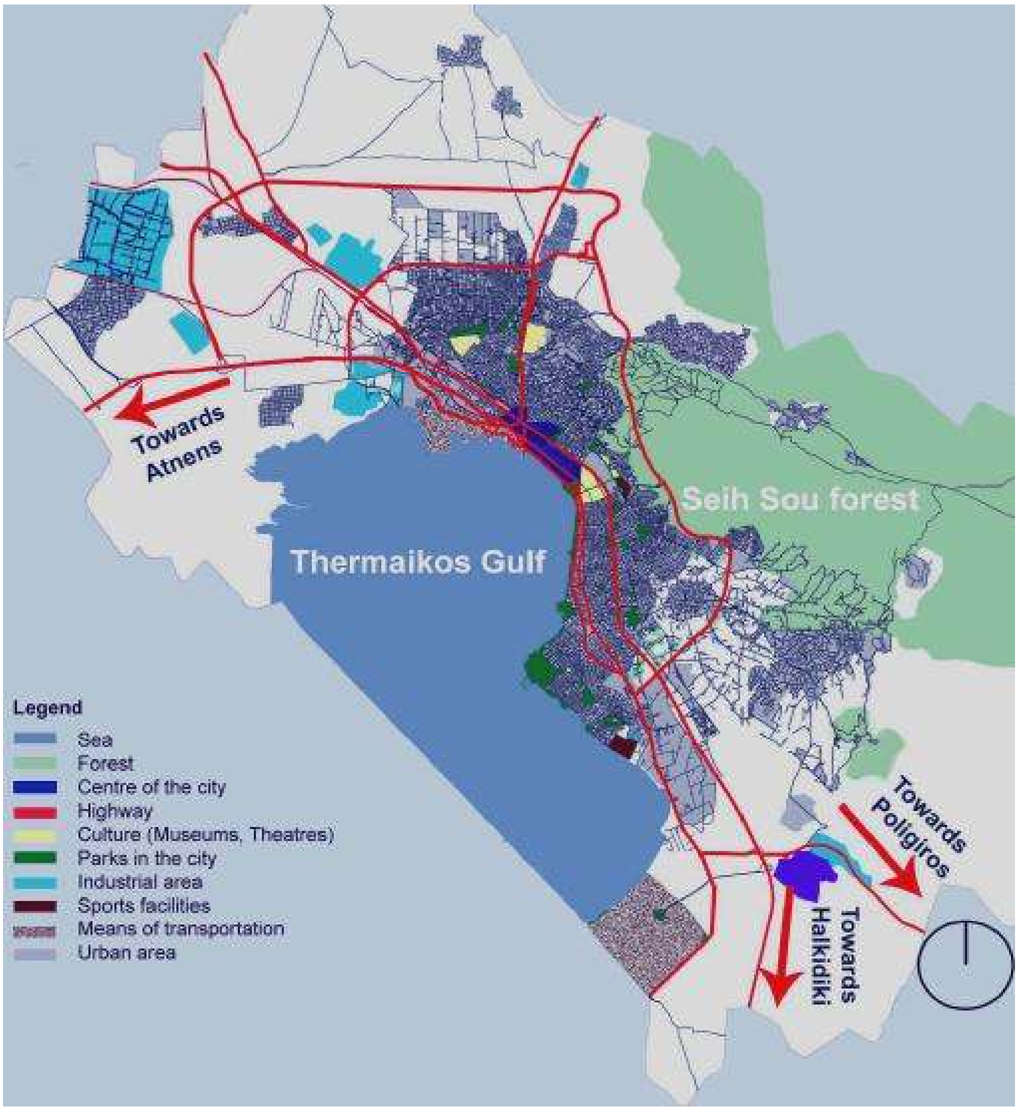



*Figure 5: Map of Salonica city*

people from other regions of Greece. The last 20 years the population has increased at about 20%, this percentage is quite higher than the increase of the percentage of the rest of the country.

The last years specific areas of the city change. What I mean by claiming this is that population has the trend to move only is specific areas that are far from industrial areas and near by the forest or the non urban areas. Moreover commercial uses tend to sprawl next to the main highways that lead to Athens or Halkidiki. All these, change the pattern of the city as time passes.

The investigation of how this city sprawls become more interesting due to its geographical position. On the south there is a sea, the Thermaikos gulf. On the North part of the city there is a forest, The Seih Sou Forest. This fact makes the city grow mainly on the east and west part and in some occasions in the North part next to the boundaries of the forest.

This thesis takes all the above into consideration and tries to predict the sprawl of the city by simulating it. The design and implementation of CA algorithm to simulate the urban growth of the city will be discussed.

### *6. Aim and objectives*

Based on the general framework presented, a simulation the city of Salonica in Greece is developed that attempts to satisfy the need to predict the future shape of the city, the way land uses sprawl in the surroundings of the city and its population. Previous researches related to Salonica's growth are only on a theoretical level and the predictions do not offer the opportunity of having a visual result of the city's future shape. Furthermore, the rapid growth of the city makes this simulation important in order to help planners to organise the expansion of the city.

This thesis proposes that a model of a city can be structured based on the relationships between elements-land uses (in this model land uses will be represented by the cells which have a specific size that represents a piece of area) that constitute it. Representation of land uses can be outlined as choosing different colours for every different type of land use. The structure of the city to be represented can be nothing more than cells which define its new pattern.

The model should respond to up to date urban theories by being able to represent both land uses and areas. **Conway Game of Life** seems suitable to be used as the basic program for the representation of the urban model of the city, as one of their inherent qualities is **two-dimensional simplicity and simple rules that can produce complicated patterns.** Based on that program a more complicated one will be structured.

The model should also be simple enough, developed for a limited number of parameters, user friendly and efficient in terms of speed.

Previous representation of cities and an effort to predict their future size and pattern so far have been quite successful although they have been done only by designing and implement the CA algorithm in ArcGIS (Geographical Information System) programming environment for the simulation.

This thesis is developing such a system by constructing a program in Processing language and attempts to address a context of enquiry.

- It explores the power of CA algorithm and its ability to be applied in the investigation of the growth of urban systems such as the urban system of Salonica. What are the advantages offered when urban design is based on such a kind of algorithm?
- What is going to be the future pattern of the city and how the land uses are going to be placed according to the applied rules?
- Is such a model structured in Processing programming language and environment able to predict the urban growth and calculate the future population of this specific city, the Salonica city?

To answer these questions a Cellular Automata Algorithm based on transition rules is created, according to the criteria that were pointed out above related with the growth of population and the way the land uses are distributed in the area in and out of the city. The model is compared to previous approaches and the results were evaluated and correlated.

Obviously the simulation of real city is very complicated. This is due to the fact of the complex structure of it and the complex interaction of many development factors resulting in the overall development pattern. The simulation process will go through many processes starting from analyzing the area of study, CA algorithm design and implementation and finally evaluation of the simulation results. All of these steps will be discussed in details in the following sections.

# Part II

## 1. Methodology

### 1.1 Artificial City Simulation

Simulation is regarded as essential to the study of the city growth. Our assertion is based on several motivations. In this section we will implement the CA algorithm in the simple version of the Conway Game of Life in order to create an artificial city. The concept to simulate the urban growth of an artificial city that starts from scratch in order to test number of modelling parameters that affect the urban growth simulation is described. The parameters include the size and shape of neighbourhood and the effect of different constraints on the simulation process.

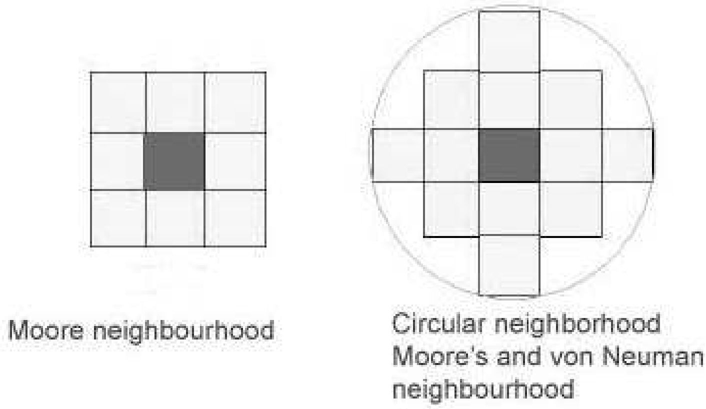



*Figure 6: CA Neighborhoods that are used in the experiments*

Two experiments with different type of artificial cities are presented. The size and shape of neighbourhood has an effect on the urban growth rate and results. Moreover the cells' state affects the emerged pattern. Different cell states represent different land uses. In order to test the effect of size and shape of the neighbourhood and the emerged patterns from different cell states on the simulated growth results, an example of 2-state land use binary image (urban vs. non urban) is used as an example. The total size of the image is 500x500 pixels. CA simulation is implemented on the input image using two different neighbourhood configurations (a. Moore (3x3) and b. Circular- like which is a combination of the Moore's and the Von Neuman neighbourhood). Simple **IF…THEN** rules are used to drive the simulation using the two different types of neighbourhood:

- **IF** the tested cell is non-urban(white cells) surrounded by 3 or more urban cells, **THEN** change it to urban
- **IF** the tested cell is urban, **THEN** keep it urban (red cells).

The images below summarize the simulated urban growth results for Moore and Circular-like neighbourhoods after specific number of growth steps. The results indicate important remarks related to the growth rate which is higher for Circular-like neighbourhood as compared to Moore neighbourhood. By using the Moore's neighbourhood, cells seem to sprawl smoother and the emerged pattern is closer to the way real cities sprawl. The images illustrate the results as the generations grow. Moreover these first

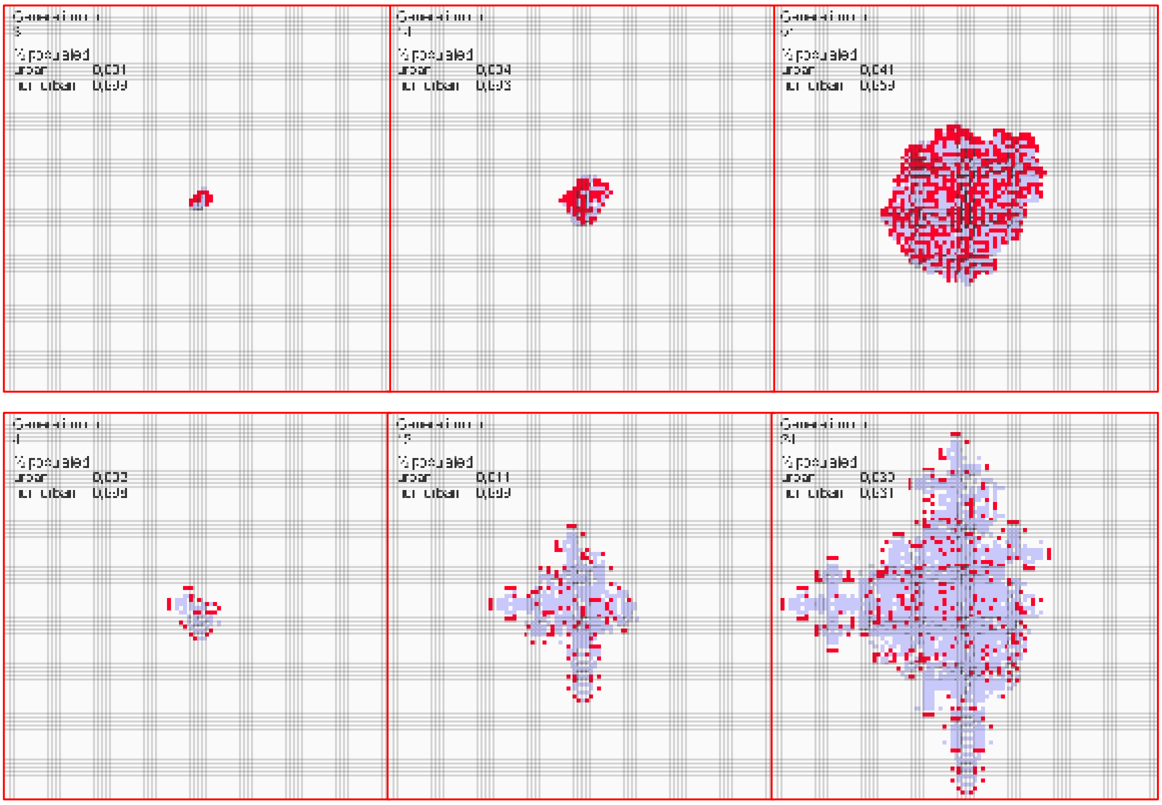


*Figure 7: the first row is an artificial city that is created with the Moore's neighbourhood while the second row is the one that is created with the circular-like neighbourhood*

experiments give results related to the percentage of urban and non-urban cells that cover the image (virtual city)

In the second simulation the same code is implemented but some obstacles are placed in the city. These obstacles represent areas of the virtual city that cells cannot grow in them. That kind of areas may be areas such as the sea or the forest in a real city. The code is working according to the rule:

**IF** there is a grey area in the neighbourhood, **THEN** no cell growth is allowed there. In an actual city this grey area will represent a specific land use.

The code that is implemented in the city of Salonica is based mainly on such a kind of rules. It is obvious from the figures that in every generation the ratio between urban and non-urban changes.

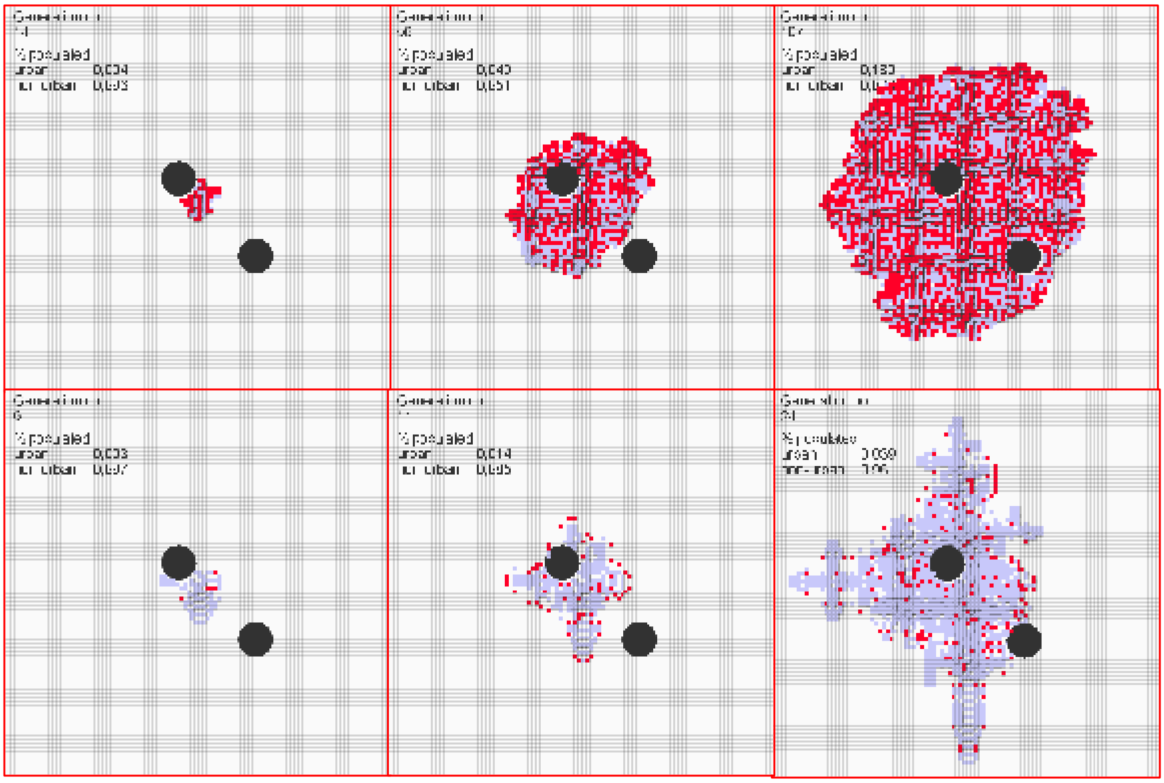


*Figure 8: the first row is an artificial city that is created with obstacles with the Moore's neighbourhood while the second row is the one that is created with the circular-like neighbourhood*

### 1.2. Development of the program

The final program is based on the previous experiments of the Conway Game of life. What I mean by claiming this is that starting with the simple Conway game of life a more complicated code based on a real city, the Salonica city, and controlled by specific rules is developed. Two experiments with two different types of neighbourhood and some changes in the rules that drive the program will be discussed. The program is developed according to the graph below:

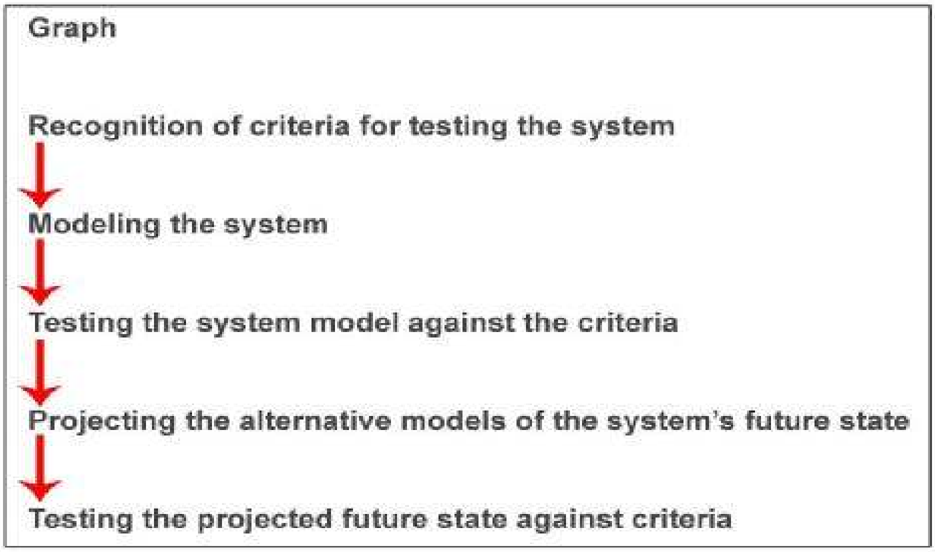



*Figure 9:Grafh of the procedure of the work*

To begin with, the first important is to recognise the criteria for testing the system. The criteria are the rules that drive the model and produce either a numerical result, for example square meters of an area or a pattern. Secondly, the system (the city) will be modelled by using the CA algorithm and beginning with the Conway game of life a more complicated code will be written. Afterwards the model will be tested against the criteria and the emerged alternative models of the system's future stay will be discussed and tested.

### 1.3. Rules for the program

In order to model the system some parameters that affect the growth of the city should be taken into account. According to researches that have been done from the faculty of Architecture, School of Technology of Aristotle University of Salonica Greece there are specific parameters that affect both the growth of the residential and commercial land uses in the city. Those parameters should be integrated in the CA algorithm in order to write the rules in the program that create the sprawl of the city and have, after some generations of the algorithm a view of the future pattern of the city. The main parameters that affect the residential and the commercial sprawl are the parameters described below:

- Increase of the population the last 20 years due to the Immigration
- Population movement to the periurban space-cheap residential areas-better environment

- Population in the city remains steady although many people move to the periurban area. This is because of the immigrants that move to the city reside in the main part of it
- Blooming of commercial uses on the main highways mainly in the east side of the city
- Industrial area: In the west of the city and the north-east. (From Thessaloniki to Poligiros,see map page 20)
- The periurban area has a lot of crop and pasture areas including the forest

Moreover, Geography is essential to understanding the factors that drive sprawl. Sprawl operates within the space-time dynamics of the city and its inhabitants. It is prevalent in some cities, but not others. Sprawl is present in distinct locations within a metropolitan area or systems of cities. In this specific case, there is a **sea** in the south part of the city. In this way Salonica can sprawl only in the North, East and West part. Moreover, the **forest** on the North –East part of the city is another factor the affects the direction of the city's expansion. This forest is under protection and under no circumstances humans will reside in it. In addition to that, the forest is an attractor for residential uses, due to the better environment next to it, and the last years many people are moving to areas that are close to it.

Furthermore, it is assumed that the main industrial areas in the city remain steady and do not change in the time. Those areas neither grow nor diminish. According to researches the industrial area of the city has moved to the Western part of the it and remains there. Of course there is a chance of growing but the algorithm does not take into account this factor since the main concerns of this thesis are the residential and commercial land uses.

The cells on this city check their neighbors and according to the used type of neighborhood another pattern emerges. Taking all the above into consideration and for all the above mentioned reasons the rules that drive the program are:

- **IF** tested cell state is sea, **THEN** no growth is allowed at this cell.
- **IF** tested cell state is road, **THEN** no growth is allowed at this cell.
- **IF** tested cell state is highway, **THEN** no growth is allowed at this cell.

- **IF** tested cell state is industry, **THEN** no growth is allowed at this cell.
- **IF** tested cell state is forest, **THEN** no growth is allowed at this cell.
- **IF** the number of residential cells in the neighbourhood around the tested cell is equal or more than 3, **THEN** change it to residential if there is no sea or forest or industry cell in the neighbourhood.
- **IF** the number of commercial cells in the neighbourhood around the tested cell is equal or more than 3, **THEN** change it to commercial if there is no sea or forest or industry cell in the neighbourhood.
- **IF** one or more of the neighbourhood cells is road **AND** one or more residential, **THEN** change the state of tested cell to residential
- **IF** one or more of the neighbourhood cells is road or highway **AND** one or more commercial, **THEN** change the state of tested cell to commercial
- **IF** state of tested cell is urban, **THEN** keep it urban
- **IF** tested cell under consideration is residential **OR** commercial, **THEN** keep this cell the same without any change.
- **IF** tested cell under consideration is either (forest OR pasture OR row crops) **AND** there are 4 commercial cells and a highway in the neighbourhood, **THEN** change tested cell to commercial.
- **IF** tested cell under consideration is either (forest OR pasture OR row crops) **AND** there are 4 residential cells in the neighbourhood, **THEN** change tested cell to residential.
- **IF** commercial uses in the neighbourhood are more than the residential uses, **THEN** the tested cells changes into commercial use.
- **IF** residential uses in the neighbourhood are more than the commercial uses, **THEN** the tested cells changes into commercial use
- **IF** there is an industrial area next to the tested cell **THEN** no growth either for commercial nor residential use is allowed

### 1.4. The program

The cell state offers a flexible framework for encoding attributes of a city into the simulation model. In this urban context the cell state is be made to represent an attribute of the urban environment the land uses. In Conway game of life a binary state automaton is used (dead or alive, urban or non urban) in this research multi state CA are used. The states of the cells depend on the various land uses. Every land use has a different cell state. The cell states are: the residential state (state 1), the commercial state (state 2), the road state (state 3), the highway state (state 4), the free area state, crops and pasture, (state 0). Forest area, the sea and the industrial area are not represented with cells since cells cannot grow in such areas. The states that this thesis investigates are the commercial and the residential cells.

To begin with, an image of the map of the city was created in Photoshop CS2. The image was captured from Google map and was coloured in Photoshop. Its size is 1500*1632 pixels. Different land uses on the map have different colours. Seven classes are defined based on Anderson classification system (1976): water (sea), road, commercial, forest area, residential areas, pasture and row crops (free area). The land uses have different colours based on this classification. Processing program first loads the image of the map and then reads the RGB (red, green,blue) values from the colours of the land uses on it. The code extracts the red, green, blue value from a colour, scaled to match the current **colorMode()**. This value is always returned as a float. Afterwards it places or does not place the cells in the areas on the map according to those RGB values. Initially, before the first run of the algorithm, the cells are placed in areas with specific colours at the same time they obtain specific states. Both the states and the areas represent specific land uses. For example **IF** there is a blue colour on the map (blue represents the sea) the program is told not to draw cells on blue areas. **IF** there is a black colour on the map, the program is told to draw cells in state 1 (residential cells) and blue colour. The program works with the same way for all the above mentioned states and land uses.

To illustrate these points, an example from a small part of the map is described. The map depicts how the cells are distributed on the map according to the RGB values they read before the algorithm starts running. Moreover every time a cell reads the RGB value from the map and it is placed on the specific area simultaneous it obtains a specific state that represents its land use. The blue cells represent the residential uses while the green ones represent the commercial uses. As it is obvious from the image below the cells are not created on the area of the forest, the streets, the highways and the sea. Moreover they are not allowed to sprawl on those areas due to the implemented rules.  They are only able to grow on the free areas as the

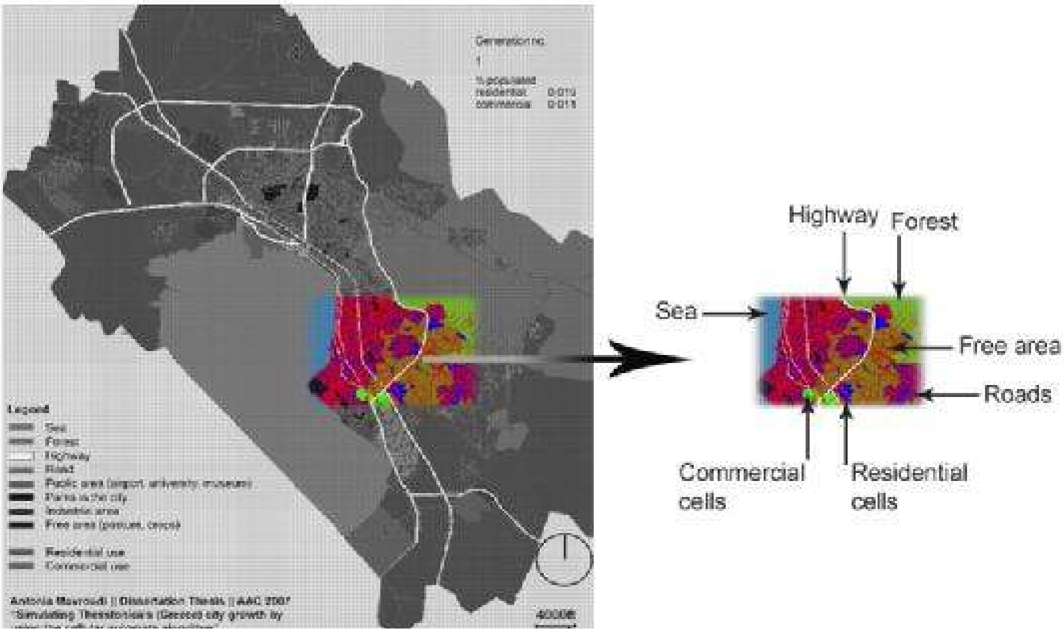



*Figure 10: Detail sketch of how the program works*

algorithm runs on the computer. The figure below depicts how the cells are distributed on the image of the map according to their states. It is clearly illustrated where the free area is, in which the cells will spread, the streets, the forest and the land uses.

The cells have specific sizes that represent a real area. The cells' size is one pixel big (1*1 pixel) and the area that occupy is 280, 9 $m^2$ (16, 76m * 16, 76m). Those numbers will be useful later in the evaluation of the results and the calculation of the area that is created and the population that will reside in it.

The image of the map is populated by the updated pixel values after implementing CA crisp rules defined in subchapter 1.3. A 3*3 Moore neighbourhood in the first experiment and the circular like neighbourhood in the second is used in the simulation process. The neighbourhoods represent spheres of influence or activity within the city, e.g. market catchments areas a good. The updated centre pixel is determined as a function of current state of centre pixel and the states of the neighbourhood pixels. The output image of one growth step is used as input for the next growth step to have accumulative urban.

The program keeps running and the cells are sprawling according to the applied rules mentioned above. As the generations grow the cells keep growing. Different patterns emerge in every generation. The program calculates in every generation the numbers of residential and commercial cells witch increase after the end of every loop. Those numbers will be used in order to calculate the area that the cells occupy, the population and the time that this area will be occupied by those cells. In order to calculate the area the cells occupy, the number of cells (the code in Processing calculates the numbers) is multiplied by the area that one cell occupies (280,9 $m^2$ or 0,02809 Ha).

**Cells' area (Ha) = number of cells * 38,069/10000 (1)**

The average density of the people who exist in one Hectare in the city of Salonica is 160 people/Ha. Having the area that the cells occupy in each generation we can calculate the population that will reside in every generation in the new areas according to the mathematical equation:

**Number of people = 160people/Ha * Cells' area (2)**

In addition to all that, we have to take into consideration that the algorithm starts running from 2001. The initial population of the city is the population the city had in 2001. The program calculates the cells and the increase of the population in every generation. In order to find the number of the whole population of the city the 2001 population should be added to the number of population of every generation.

After calculating the population and the area it is easy to calculate the time that the increase in the population and the area that the city covers will take place. Every generation represents a time period. From the data collected from researches of the Aristotle University of Salonika it is known that the population of the city in 1991 was 792.258 people and it was increased to the number of 862.562 in 2001. There was an increase of 70.304 people that decade. For calculating the time the below mathematical equation is used:

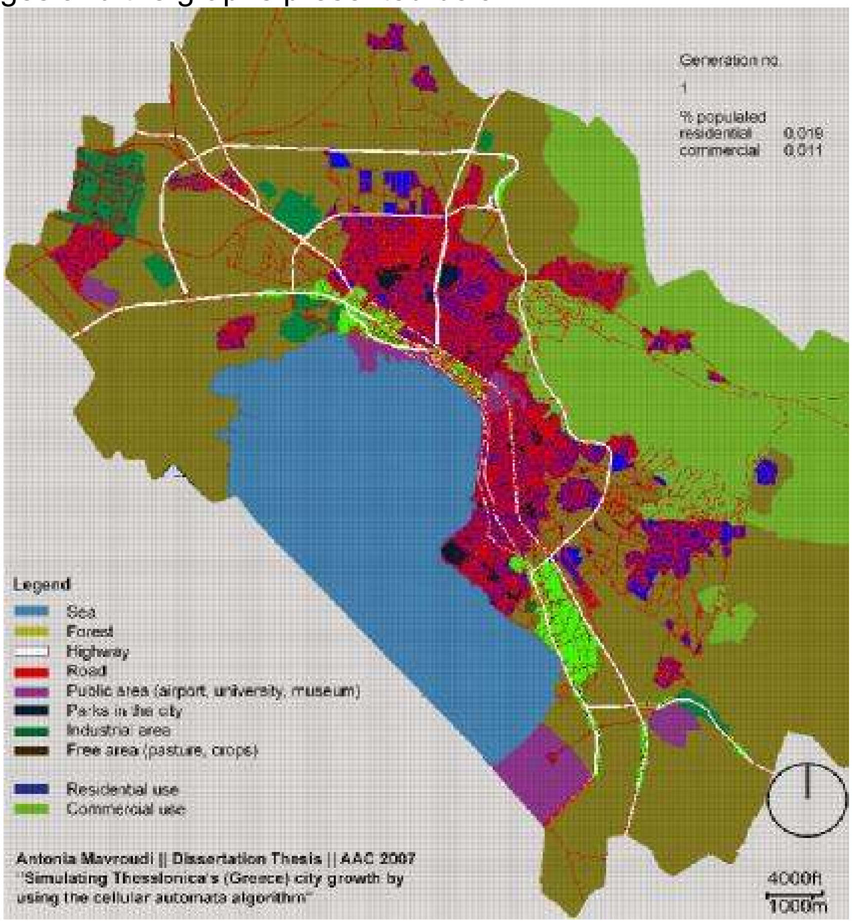
**Time = (Number o people (from the program)) * (time that the increase of the population in the city took place)/(increase of population between 1991 and 2001)**

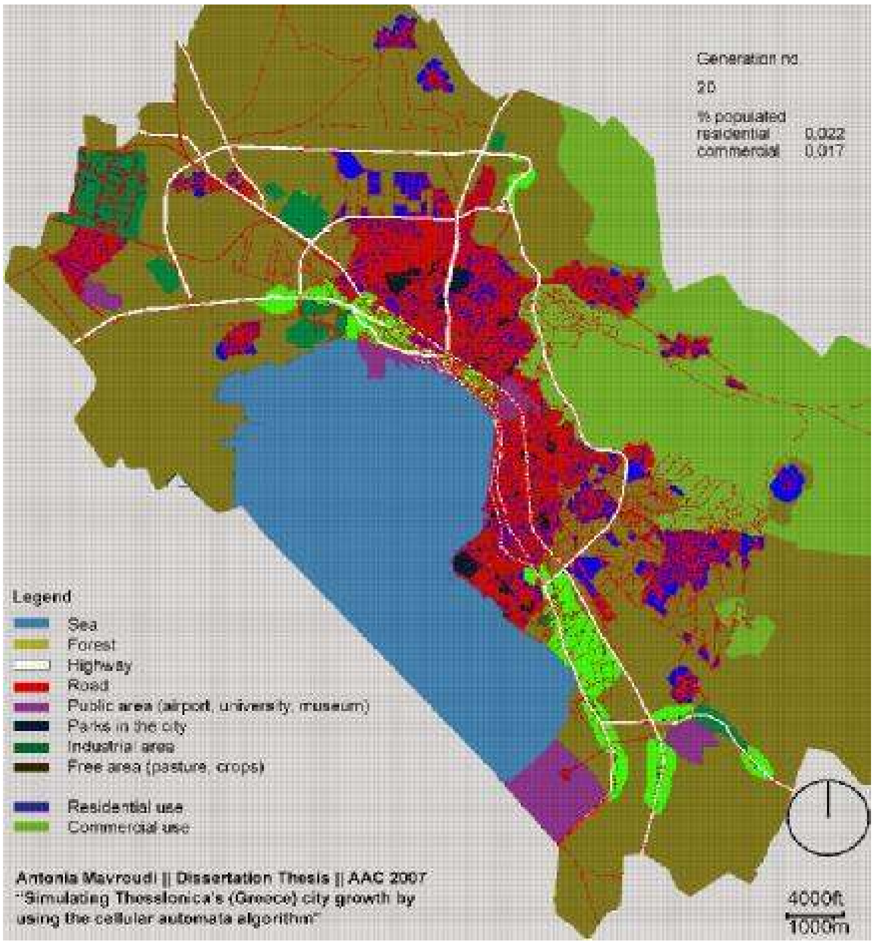
So **Time (years) = (Number of people (from the program)) *10 / 70.304** (**3)**

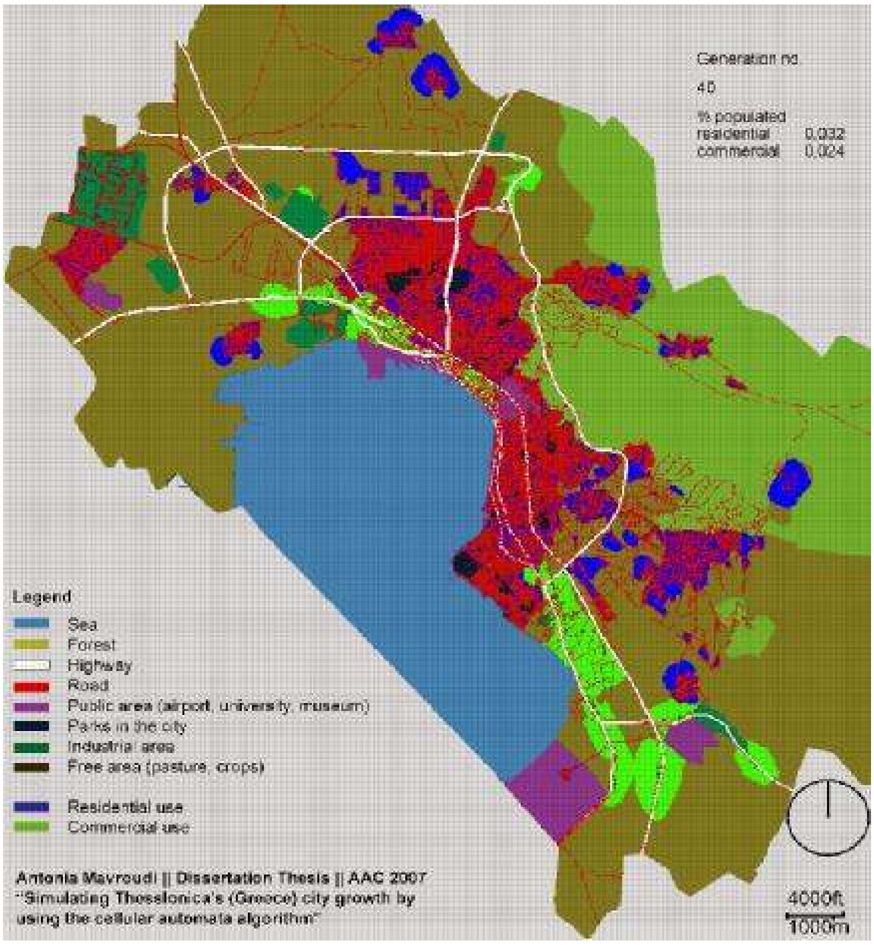
### 1.5. Representation of the city

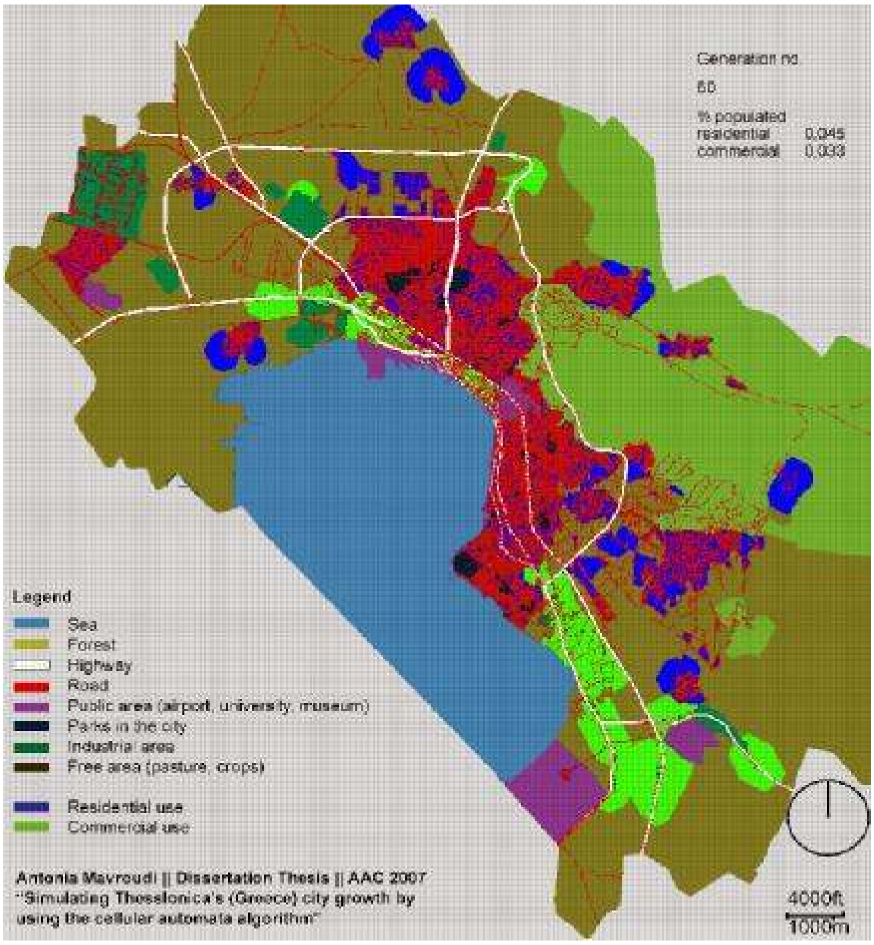
After defining how the program works and how the results will be evaluated this section will introduce the visual and numerical results of the implementation of the CA algorithm in Salonica city.

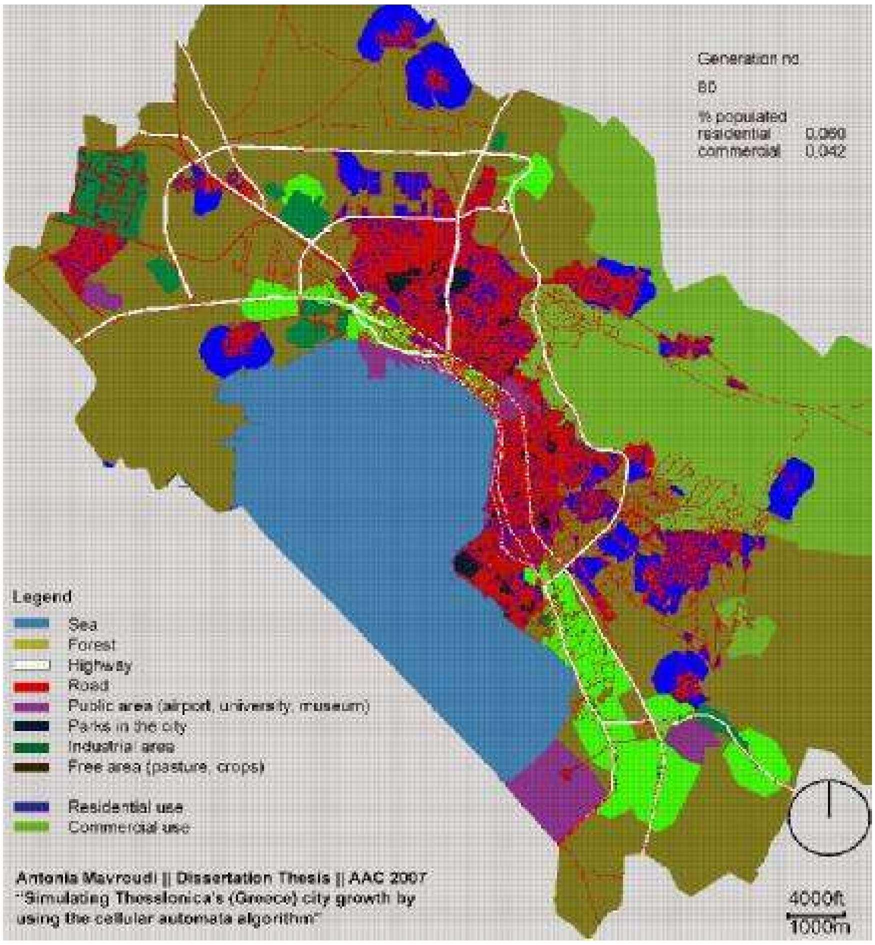
In the first experiment a 3*3 Moore's neighbourhood the rules for the program are the rules mentioned in paragraph 1.3. One can realize that there are specific areas in the periurban area of the city that grow. Those areas are next to the forest (better environment), near by the roads (for easier approach to means of transportation) and of course far from the industrial areas. Commercial uses sprawl close to highways and next to areas that already exist commercial cells. Results from different generations of the algorithm are presented below. Moreover, a constant increase both of residential and commercial cells is observed. The city as it has already been mentioned, the last 20 years is growing due to the large number of people that move to it. The algorithm takes into account this fact and predicts the future population and the future shape of the city. All these observations are clearly illustrated in the images and the graphs presented below.

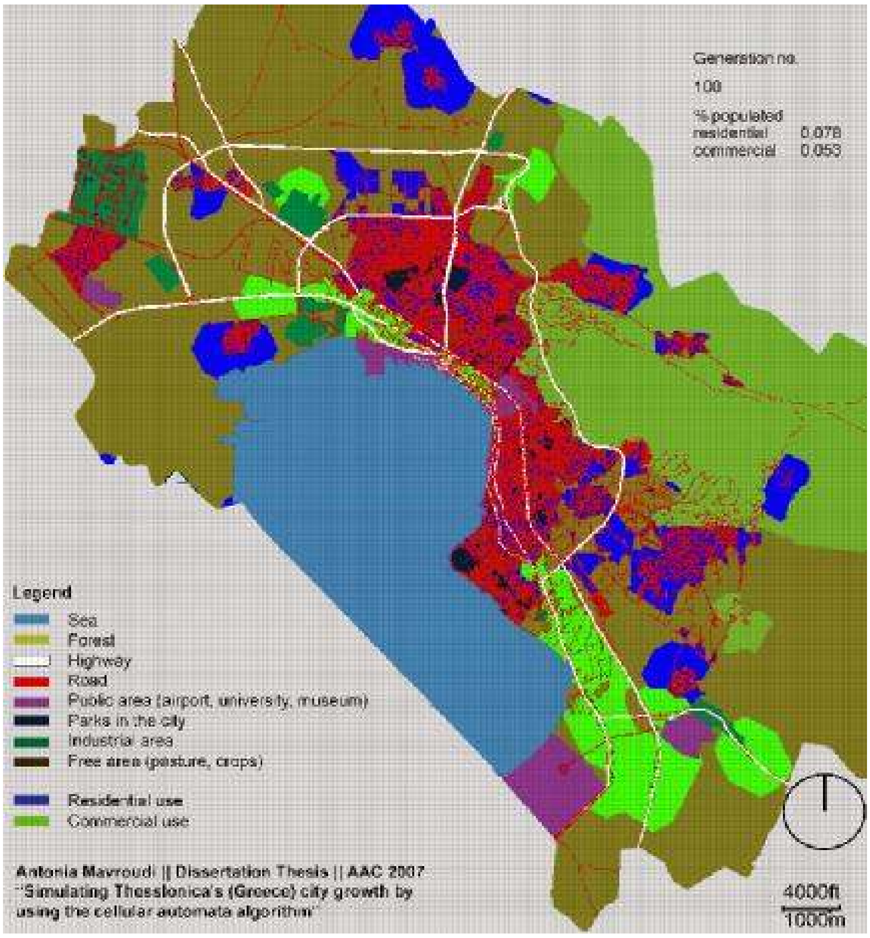



Generation no
20
% populated
residential 0,022
commercial 0,017
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by
using the cellular automata algorithm"
4000ft
1000m


Generation no
40
% populated
residential 0,032
commercial 0,024
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by
using the cellular automata algorithm"
4000ft
1000m


Generation no
60
% populated
residential 0,045
commercial 0,033
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by
using the cellular automata algorithm"
4000ft
1000m


Generation no
80
% populated
residential 0,060
commercial 0,042
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by
using the cellular automata algorithm"
4000ft
1000m



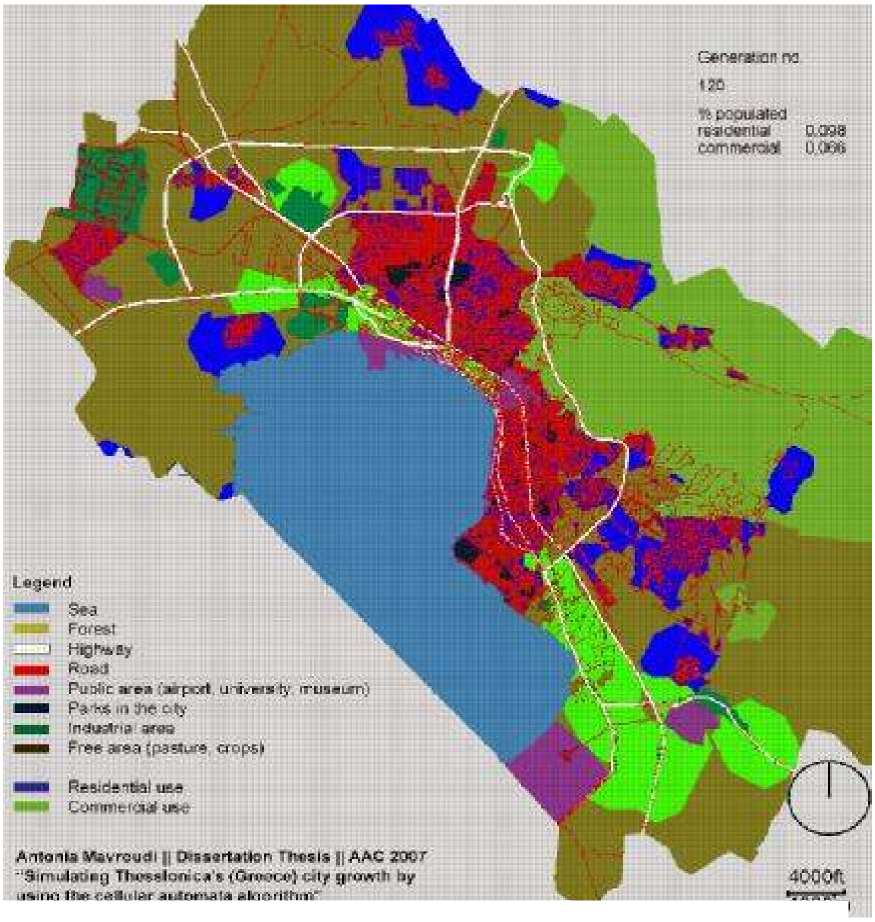




*Figure 11: Emerged results of the program. Generations 1, 20,40,60,80,100,120 (1st experiment)*

This graph shows the increase in the percentage of the area that cells occupy during the simulation from the 1st until the in 120th generation. Both commercial and residential areas are becoming larger. The amount of the area both os residential and commercial cells is increased steadily reaching the peak of 0,076% of the whole map of the city for residential cells and 0,066% for commercial cells.

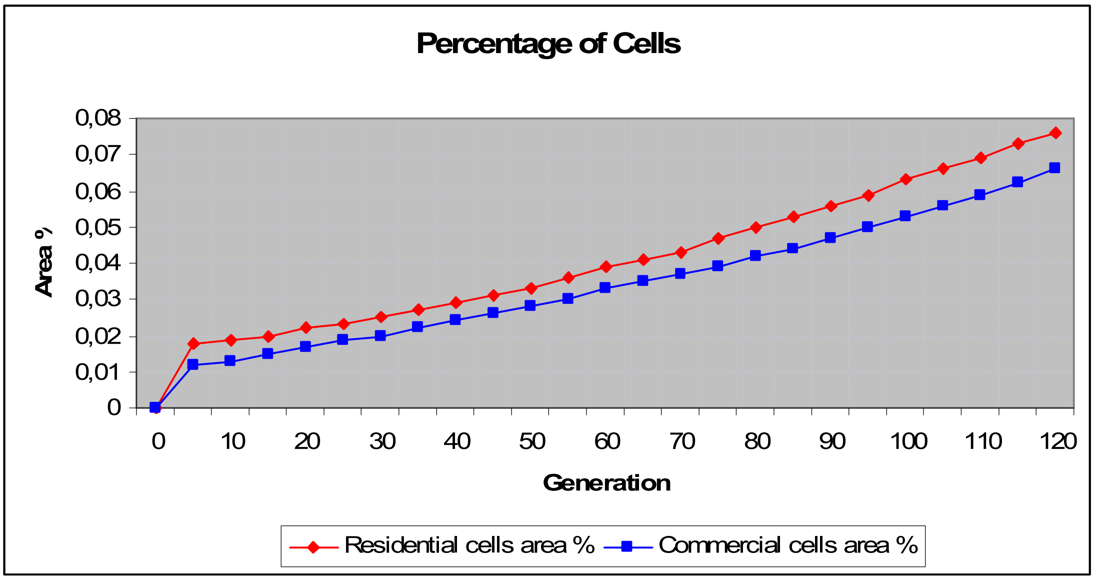



*Figure 12: Graph: Percentage of cells that cover the image (map) in every generation 1-120*

According to the number of residential cells it is not difficult to calculate the population for every generation and the years that this number will reside in the city with the help of the equation 2 and 3 from subchapter 1.4.

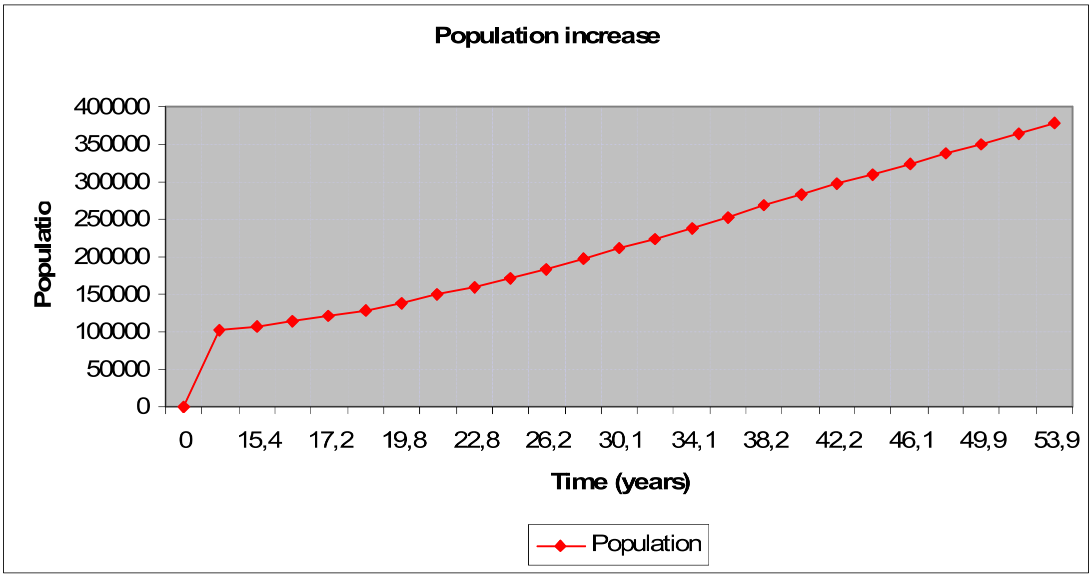



*Figure 13: Population graph*

The above graph illustrates the steady increase of the population as the time passes. The time was calculates from the equation 3 in subchapter 1.4. Every generation represents a specific time period in years. At about 54 years (120$^{th}$ generation) from the time that the algorithm started counting (2001)(0 generation) a rise of 378.245 people will take place. The algorithm was running for 15 minutes in order to create the pattern in the 120$^{th}$ generation. Allowing the algorithm to work at about 4 hours the emerged results were quite strange and difficult to predict whether they are close to reality or not. The picture above illustrates the 570$^{th}$ generation.

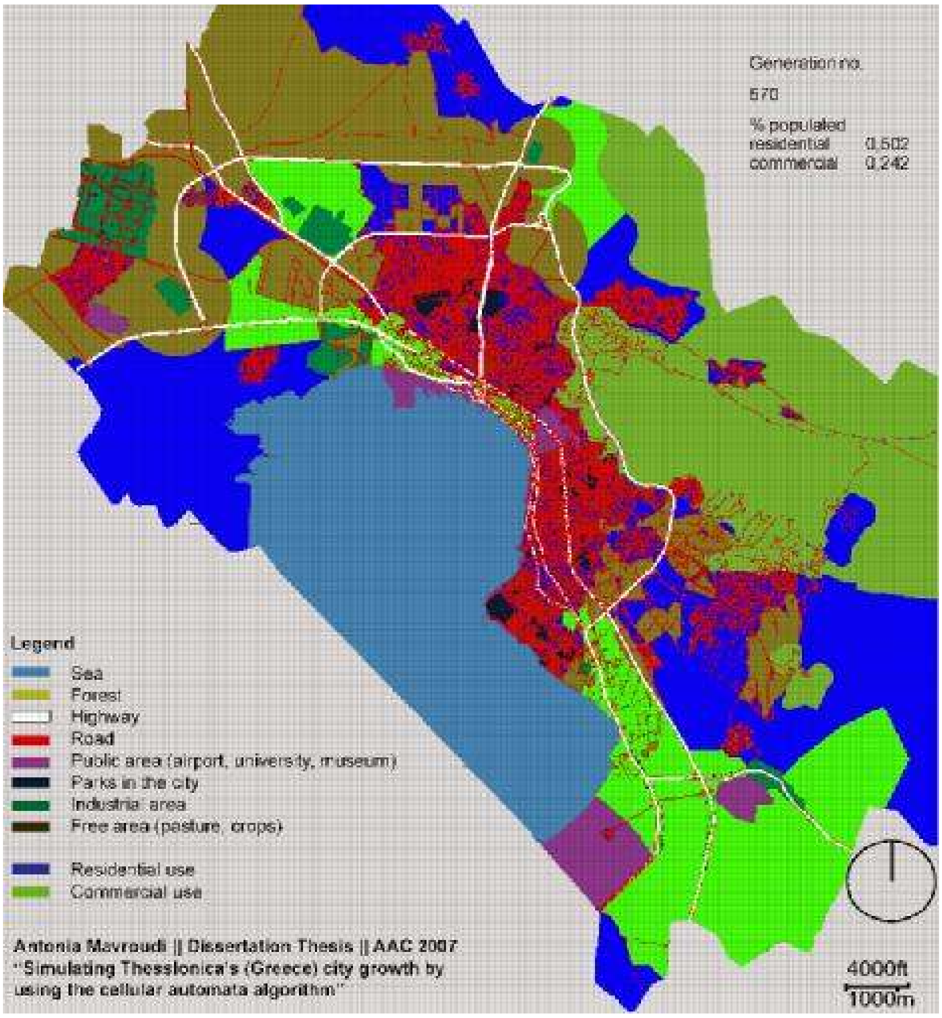



*Figure 14: Emerged result of the program. Generation 570*

The table in appendix page 52 shows all numbers that were calculated from the results of the algorithm. Those numbers are related to the population and the years those changes will take place. In addition to that, the area that residential or commercial uses cover in every five generations in calculated. That table has the advantage of collecting all the results and provides numbers.

As it is clearly illustrated in both graphs and the table the population and the area that the land uses cover is increasing. No decrease in all those numbers is observed. This is because the rules that drive the algorithm coded in this way. Those rules are based on observations from the last 20 years and show that the Salonica city keeps growing and as time passes more and more people invade in the city. In 1981 the population was 738.977 while in 1991 was 792.258. In 2001 the number of the population was raised to the number of 862.562 people. The equation that is used in order to calculate time takes into account only the increase between 1991 and 2001. This assumption is due to the fact that the factors that changed the city between 1991 and 2001 are the factors that drive the city's change nowadays.

Having the final output (image) of the program not only the user may have a visual idea of how the city will be and how many people will reside in it but also he or she may count various distances in the new city. Moreover it is

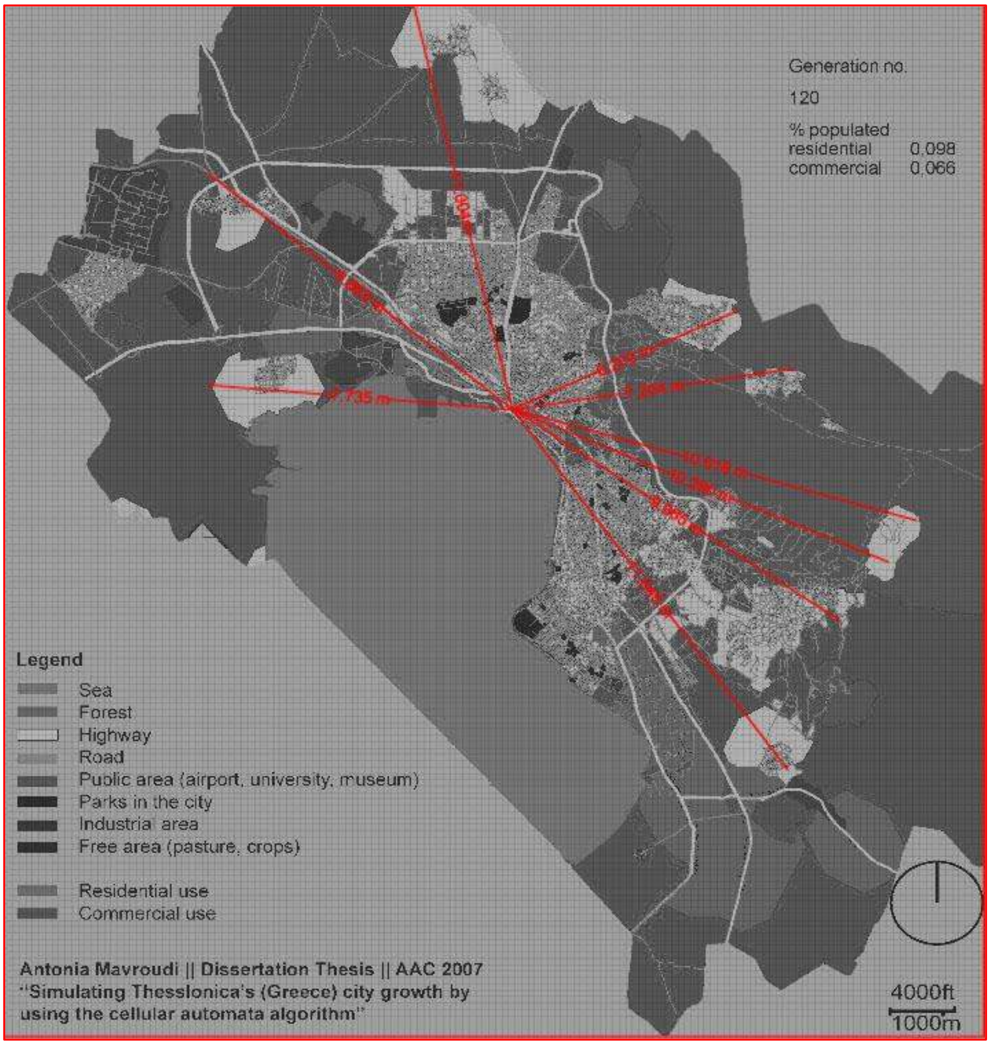
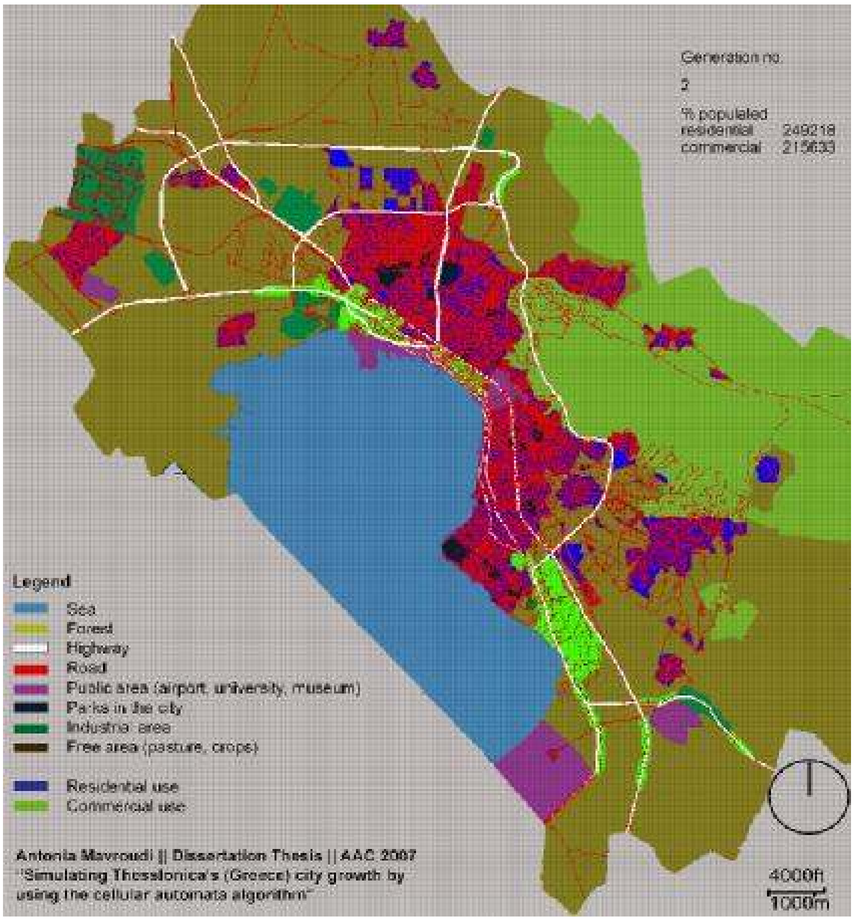
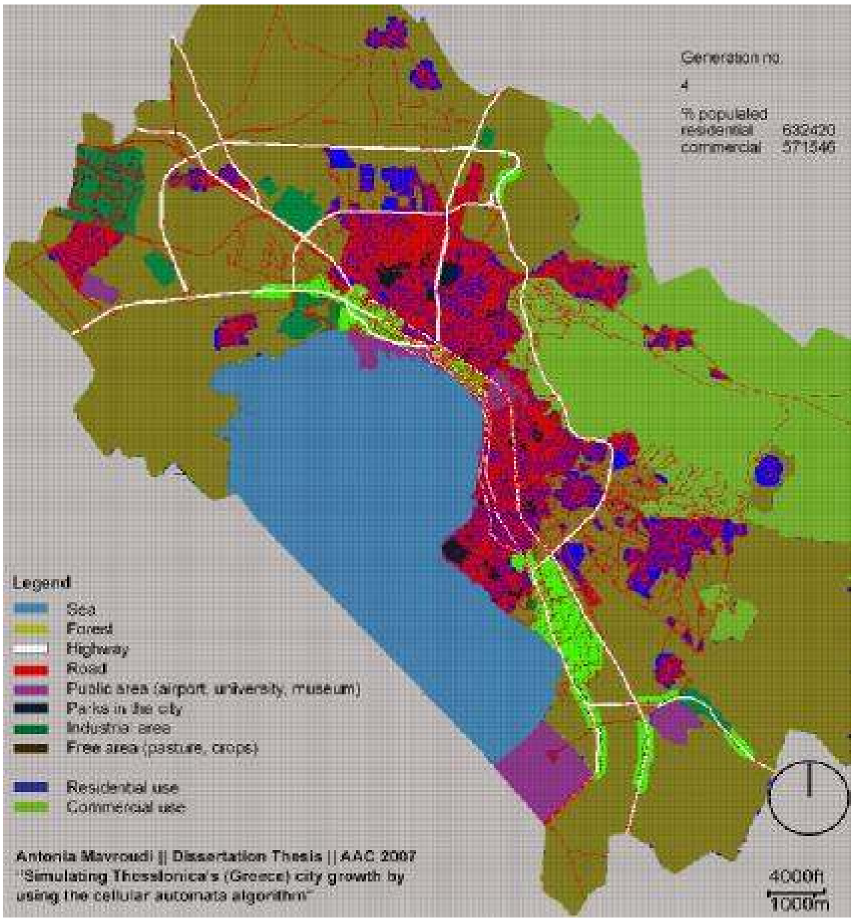



*Figure 15: Illustration of the distances between the new areas and the centre of the city*

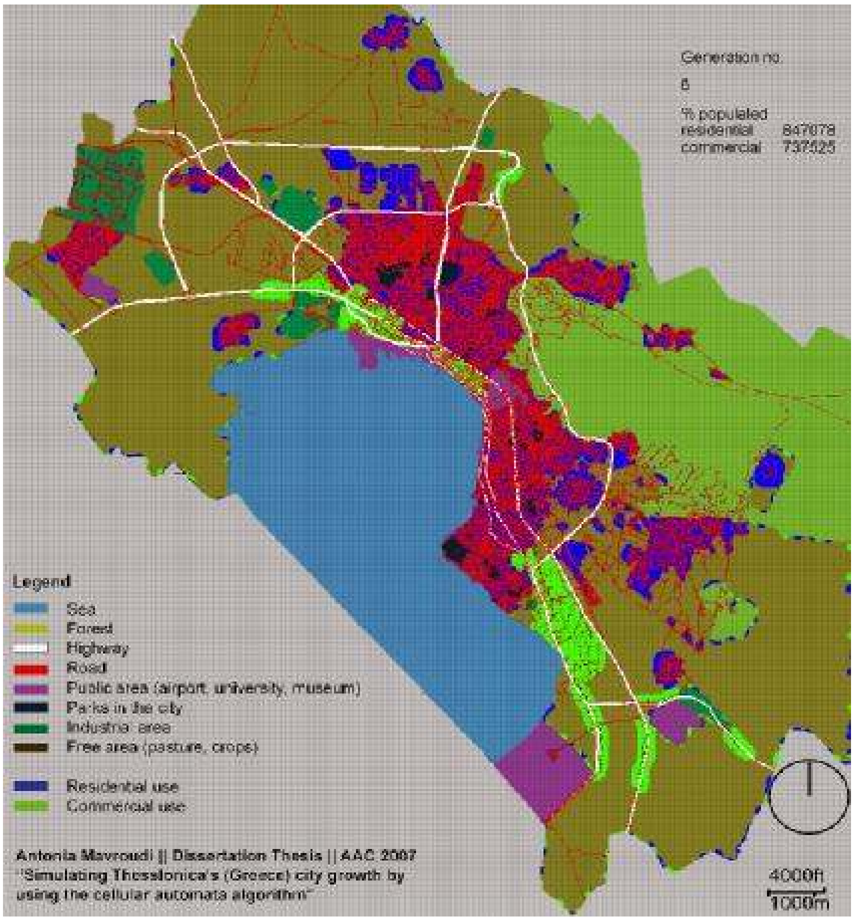
not difficult to calculate routes in order to move from one new area to another. The example in the figure above illustrates the distances between the new areas from the centre of the city. In order to do so, Autocad was used. The image of the map was imported in Autocad and it was adapted in the right scale, then the distances were calculated. The distances are calculated in meters.

In the second experiment a circular like neighbourhood is used and the rules for the program are the same rules like those used in the first example. The images in the first runs of the algorithm seem the same as the previous example but the city grows quicker than before. Specific areas in the periurban area of the city sprawl as before but after the first ten runs, the algorithm does not work as it was supposed. There is a rapid increase in the number of cells. This rapid increase in the number and the increase in their growth speed create patterns that are far from reality. Moreover, cells are created in forbidden areas such as the forest’s area. The program does not work properly and those results cannot be considered as accurate and realistic. The results from the different generations of the algorithm are presented below.

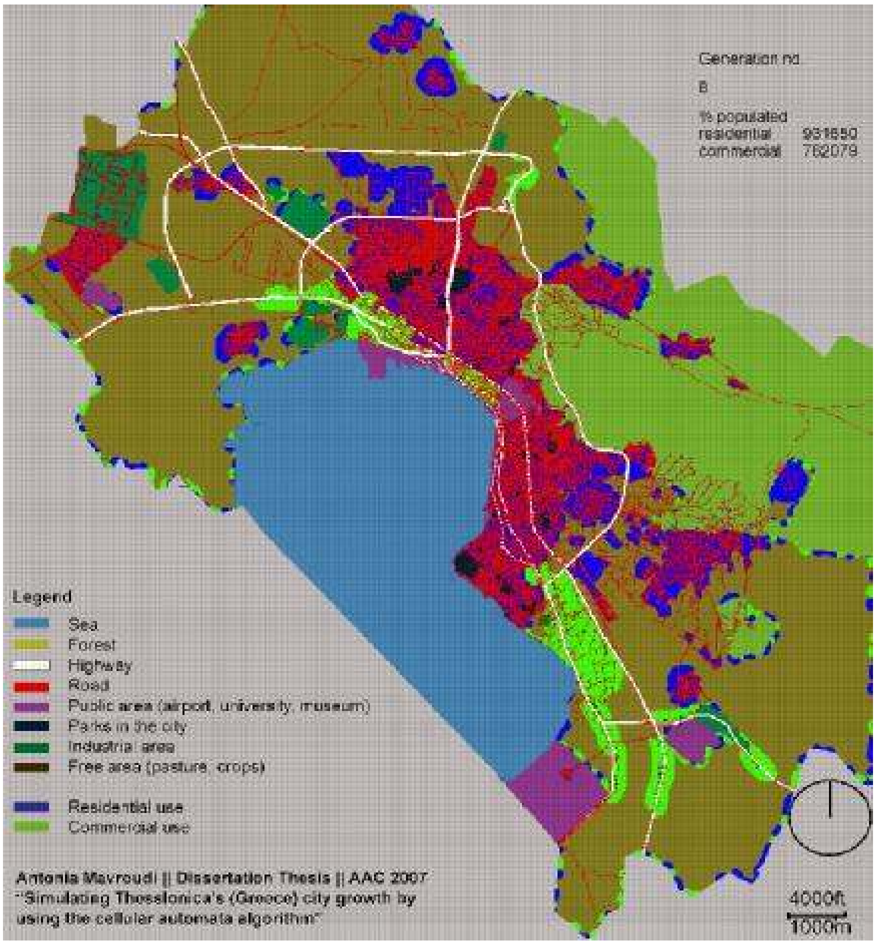




Generation no.
4
% populated
residential 632420
commercial 571546
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by using the cellular automata algorithm"
4000ft
1000m

Generation no.
6
% populated
residential 847878
commercial 737525
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by using the cellular automata algorithm"
4000ft
1000m


Generation no.
8
% populated
residential 931650
commercial 762079
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by using the cellular automata algorithm"
4000ft
1000m

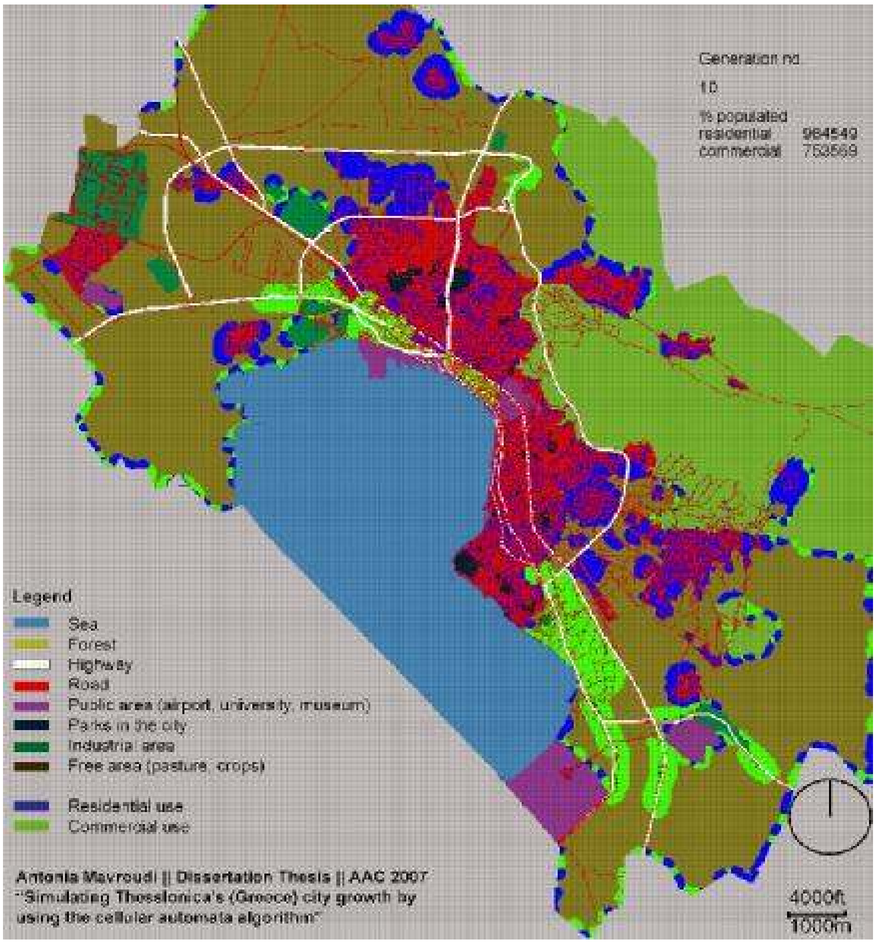

Generation no.
10
% populated
residential 984549
commercial 753569
Legend
Sea
Forest
Highway
Road
Public area (airport, university, museum)
Parks in the city
Industrial area
Free area (pasture, crops)
Residential use
Commercial use
Antonia Mavroudi || Dissertation Thesis || AAC 2007
"Simulating Thessalonica's (Greece) city growth by using the cellular automata algorithm"
4000ft
1000m

***Figure 16:*** *Emerged results of the program. Generations 2, 4, 6,8,10 (2nd experiment)*

It is clearly illustrated in the figures that the algorithm does not work properly. After these simulations one can realise that in order to simulate a city and its growth, the first experiment gives reliable results.

# Part III

## 1. Further work

Although this program gives a flavour of how the city will be after some years it does not create a city. This code is not used as a design tool. A possible next expected step for this model would be for the program to play the role of the "designer". What I mean by claiming this is that by re-creating the rules the code would be able to draw streets cells, residential cells and commercial cell. In this way a network that would represent a real city may be created. This is a quite interesting view that needs further discussion and work both in the program and the rules that create the new city.

In addition to that, in a more detailed research of the growth of the city the results would be more accurate if social and economical parameters were incorporated in the applied rules. By saying this, I mean for example companies that arrive in the city may attract more people from areas outside the city due to the job opportunities those companies offer. This factor creates an economical attractor for the city. Also more correct results may derive from corrections in the program. Those corrections may concern the cell size and the transition rules.

One more important factor that should be taken into account in a further, more detailed analysis of the city is whether or not the industrial areas expand or diminish, in what way and how they affect both commercial and residential uses. This algorithm is only affected from industrial areas in a way that now cell growth is allowed close to those areas.

Another point worth mentioning is that the systems behaviour may be controlled by the user in order to create a specific patterns and produce a specific result for example control the growth of the city and its population and also the emerged pattern.

The results of the run of this algorithm may be quite helpful both for urban designers and the municipalities in order to distribute the infrastructure services and organise the city. Despite the fact that Processing gives results, it proved to be restricting in terms of drawing new cells after some runs of the algorithm. Cells are created in forbidden areas such as forest. Use of an appropriate program is compulsory in order to produce graphic representations that bring out the system's potential.

## 2. Discussion

Modelling and simulation may serve as generative science (Epstein 1999). We can gain understanding of the phenomenon of sprawl, and the factors that combine to produce it, by piecing elements of sprawling systems together in simulation, and studying the ways in which they interact to form system dynamics. Moreover, sprawl is not easily experimented with on the ground. It is infeasible to think that sections of the city could be reduced in density or set upon alternative growth regimes *en masse* without popular upheaval. Realistic but synthetic computer simulations can be built, however, as a laboratory for exploring ideas and plans that we would not otherwise be able to effect on the ground. Modelling can be used as a planning support system, to pose what-if questions and evaluate likely or alternative outcomes.

Simulation may also be used to examine future, unforeseen consequences of actions. The implications of urban policies and plans may take decades to manifest. However, in simulation, time can be accelerated or decelerated, into the past or the future, at will. Models may also be used as tools to think with. They can help to convey key properties of a problem or phenomenon to affected parties, stakeholders, policy-makers, students, and other researchers. Moreover, this can be done in an interactive and visual context. (Paul M. Torrens,2006)

Apart from the general observations for Urban CA, this thesis confirms the usefulness of the algorithm in predicting the pattern and the population of a city. Although the error is possible, the results from this case study may be considered as accurate and close to the future shape of the city due to the fact that the rules that had been taken into account and drive the program are rules that were selected from readings and are those who affect the shape of the city the last years. What I mean by claiming this is that those rules represent the real forces that drive the city's sprawl.

While researching in other similar works that use CA in order to predict the sprawl of the city it was obvious that using Porcessing language and Java was a new approach. Most previous works use the GIS programming environment. Those modelling procedures are very advanced and the results are very close to the reality although there are some restrictions. One advanced model that simulates sprawl is the model that Paul Torrens created. That sprawl model is based on a conceptual model. The model is applied to the Midwestern Megalopolis region as it is mentioned in the first part of the thesis around Lake Michigan in the United States. The model includes exogenously- and endogenously-considered growth, which is distributed over a simulated landscape using mechanisms designed to represent geographic drivers of sprawl: geographical inertia, diffusion, and mobile agents of change. The methodology is based around an automata core, extended as geographic automata (GA). The model also includes historical, autoregressive functionality to represent geographical inertia in urban dynamics and functionality for representing growth or decline that originates within the system. The simulation of Salonica city uses geographical inertia such as sea and forest areas and also is based on historical functionality which means that the algorithm takes into account the history of the forces that drive Salonica's growth. The model uses the same techniques in the code, techniques that are related with the way the program reads the pixels of the map or what the cells represent (land uses and area that they occupy).

The purpose of Torrens work was to explore the geography of sprawl through simulation. Simulations evolve a city-system in a realistic fashion, with emphasis on the processes driving space-time dynamics, the patterns generated by the simulation, and the rate of simulated urbanization.

The model generated sprawl-like cities in each of the simulation scenarios, and by varying the influence of rules within the model, facilitated exploration of the potential drivers of sprawl. The simulations discussed in this paper were designed to explore geographic dimensions of sprawl, focusing on mimicking the spatial distribution of growth in dynamic contexts such as

Torrens did. In the literature on sprawl, however, it is clear that there are other important components to the phenomenon that these simulations have not addressed— namely, preference-based drivers at within-neighbourhood geographies.

As far as this thesis is concerned it is obvious although it is based in previous works such as the one Paul Torrens did, it introduces a new approach of simulating cities. This work is the first steps of approaching cities' growth with Processing and it is not as advanced as others. That is why the results may contain an error possibility.

In conclusion, the simulation of the urban growth aids the urban planners to choose the best options for the sustainable development of the city. CA are proved to be quite efficient in simulating the urban growth over time. The strength of this technology comes from the ability of urban modeller to implement the growth simulation model, evaluating the results and presenting the output simulation results in visual interpretable environment. (Sharaf Alkheder and Jie Shan). The results of this thesis may be helpful for planners since they give a flavor of the future of the city. Also no similar approaches that predict the shape of Salonica and produce such a kind of results were made. Previous approaches are theoretical. It is worth mentioning that those approaches were used for the better understanding of elements that drive the changes of the city.

## 3. Conclusions

In the first part, CA were approached from a broader perspective to a more specific use of them in simulating the city growth by using the Urban CA. The thesis has then gradually developed as to define Urban CA, and eventually construct a model for simulating a real city, the city of Salonica, in the second part. This implementation was the basis for the methodology which was followed to validate the hypothesis of the current thesis.

This thesis takes advantage from the algorithm of CA and its power and implies it in Salonica which is a city that changes constantly the last years and predictions like the ones observed may shed light to planning of the city. The observations made may be quite helpful for planners. The results of this dissertation are concluded in the list below:

- Calculation of the population
- set the time as a parameter, calculate the years that these changes will take place
- visual results, the emerged pattern of the city
- count distances from the new areas to the centre of the city

The two type of neighbourhoods described in this thesis illustrate the various ways to approach a simulation of the city. It is clearly presented that in the first experiment the pattern and the results are close to the reality while in the second simulation there are some problems with the way the code works.

Although this research is only verified on a theoretical level, the produced model demonstrates the potential of this type of analysis as a mean to explore more sophisticated models, perhaps with a longer research agenda of supporting decision-making for policy-makers, urban planners, developers, and residents.

More over the new approach of using Proccesing language and Java is quite interesting, since the previous approaches and simulations were programmed in GIS. This thesis introduces a new way of simulating cities' systems.

Taking everything into consideration, it has been demonstrated how a simple CA model based on IF….THEN rules and using limited amount of data can be developed as a useful tool to predict a growth of a city.

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# Appendix

**Table 1:** A correlation between Cellular Automat and Urban Cellular Automata:

| Basic CA | Urban CA |
|---|---|
| The cell space on which a cellular automaton operates | equivalent in an urban sense to an environment, a landscape, or a territory |
| The CA lattice | represent urban spatial structures, networks of accessibility, or the physical infrastructure of the city |
| Cell state | The cell state offers a flexible framework for encoding attributes of a city into the simulation model. In an urban context the cell state can be made to represent any attribute of the urban environment, e.g., land use |
| Neighborhoods | • represent spheres of influence or activity within the city, e.g. market catchments areas a good<br>• encapsulation of interaction amongst system elements<br>• region that development might take place |
| The rules of a CA | • drive the dynamics of change in the Model<br>• imply growth, decline or a change in state<br>• devised to mirror how phenomena in the real world operate<br>• can then be coded as algorithms within the simulation |
| The patterns they generate | exhibit many of the signature trademarks of complex adaptive systems, such as phase shifts, power laws, self-organization, self-similarity, and fractal dimensions |
| Rank-size rules or power laws (as they pertain to complexity and CA) | link the frequency of occurrence of phenomena to their unit size with linear, consistent relationships across scales. The distribution of cities of various sizes of population follows a rank-size rule |
| Self-organization is one of the characteristics of | Self-organization can occur in both spatial and temporal dimensions. |

| | |
|---|---|
| complex adaptive systems and also of CA. | |
| CA develop over time, the patterns that they generate often exhibit a degree of self-similar regularity in structure. With self similarity, portions of the evolved pattern of a structure are indistinguishable from the whole; essentially, the structure of the pattern is scale-independent (Wolfram 1994). Often these patterns are fractal and can be characterized using fractal dimensions. | In cities, as well as in CA, the recursive local-scale dynamics that generate well-defined geometrical structures in two-dimensional space often generate similar structural geometries at higher scales as the structure grows and changes. In particular, cities often exhibit a bi-fractal structure, characterized by two or more zones. Inner zones—the well-developed core of a typical monocentric city, for example—can generally be characterized with a fractal dimension of 1. This means that they have a dimensionality that lies between one (a linear city) and two (a city completely occupying a plane). Inner cores often comprise compact built environments. In terms of system dynamics, transition is stable and ordered; the system is well organized and the urbanization process is essentially complete. Outer fringe zones, on the other hand, have a characteristic fractal dimension of just greater than one—they are sprawling. In such examples system dynamics are still quite stochastic, as urbanization is still underway. This bifractal pattern also characterizes cities on lower-level scales, for example at the level of individual land uses Many of the structures that CA generate also exhibit self similarity and are fractal in dimension.(Paul M. Torrens, 2001) |

**Table 2:** The table below illustrates what is the percentage, the number, the area that is covered of residential and commercial cells. Moreover the increase in the number of the population and the total populations is shown and the years that need for these changes to take place.

| Generation | Residential % | Commercial % | No Residential cells | No Commercial cells | Area Residential (Ha) | Area Commercial (Ha) | Total Area | Population (increase) | Population total | Time (years) |
|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | 0,018 | 0,012 | 22882 | 9413 | 642,756 | 18,055 | 660,811 | 102841 | 965403 | 14,7 |
| 10 | 0,019 | 0,013 | 23934 | 10850 | 672,307 | 18,886 | 691,193 | 107569 | 970131 | 15,4 |
| 15 | 0,02 | 0,015 | 25233 | 12310 | 708,795 | 19,911 | 728,706 | 113408 | 975970 | 16,2 |
| 20 | 0,022 | 0,017 | 26894 | 13820 | 755,453 | 21,221 | 776,674 | 120873 | 983435 | 17,2 |
| 25 | 0,023 | 0,019 | 28780 | 15404 | 808,431 | 22,709 | 831,14 | 129349 | 991911 | 18,4 |
| 30 | 0,025 | 0,02 | 30903 | 17107 | 868,066 | 24,384 | 892,45 | 138891 | 1001453 | 19,8 |
| 35 | 0,027 | 0,022 | 33140 | 18959 | 930,903 | 26,15 | 957,053 | 148945 | 1011507 | 21,2 |
| 40 | 0,029 | 0,024 | 35603 | 20980 | 1000,089 | 28,093 | 1028,182 | 160015 | 1022577 | 22,8 |
| 45 | 0,031 | 0,026 | 38221 | 23173 | 1073,628 | 30,159 | 1103,787 | 171781 | 1034343 | 24,5 |
| 50 | 0,033 | 0,028 | 40980 | 25506 | 1151,129 | 32,336 | 1183,465 | 184181 | 1046743 | 26,2 |
| 55 | 0,036 | 0,03 | 43890 | 27932 | 1232,871 | 34,632 | 1267,503 | 197260 | 1059822 | 28,1 |
| 60 | 0,039 | 0,033 | 46940 | 30427 | 1318,545 | 37,038 | 1355,583 | 210968 | 1073530 | 30,1 |
| 65 | 0,041 | 0,035 | 50036 | 32956 | 1405,512 | 39,481 | 1444,993 | 224882 | 1087444 | 32 |
| 70 | 0,043 | 0,037 | 53212 | 35491 | 1494,726 | 41,987 | 1536,713 | 239157 | 1101719 | 34,1 |
| 75 | 0,047 | 0,039 | 56412 | 38049 | 1584,614 | 44,512 | 1629,126 | 253539 | 1116101 | 36,1 |
| 80 | 0,05 | 0,042 | 59657 | 40661 | 1675,766 | 47,073 | 1722,839 | 268123 | 1130685 | 38,2 |
| 85 | 0,053 | 0,044 | 62859 | 43335 | 1765,71 | 49,599 | 1815,309 | 282514 | 1145076 | 40,2 |
| 90 | 0,056 | 0,047 | 65994 | 46058 | 1853,772 | 52,073 | 1905,845 | 296604 | 1159166 | 42,2 |
| 95 | 0,059 | 0,05 | 69057 | 48870 | 1939,812 | 54,49 | 1994,302 | 310370 | 1172932 | 44,2 |
| 100 | 0,063 | 0,053 | 72085 | 51771 | 2024,868 | 56,879 | 2081,747 | 323979 | 1186541 | 46,1 |
| 105 | 0,066 | 0,056 | 75031 | 54776 | 2107,621 | 59,204 | 2166,825 | 337220 | 1199782 | 48 |
| 110 | 0,069 | 0,059 | 78026 | 57875 | 2191,751 | 61,567 | 2253,318 | 350681 | 1213243 | 49,9 |
| 115 | 0,073 | 0,062 | 81062 | 61056 | 2277,032 | 63,962 | 2340,994 | 364326 | 1226888 | 51,9 |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| 120 | 0,076 | 0,066 | 84159 | 64313 | 2364,027 | 66,406 | 2430,433 | 378245 | 1240807 | 53,9 |