Outdoor Thermal Comfort And Shade : A Methodogy for Improving Thermal Comfort in an Urban Park using Agent based Modelling and Cellular Automata.

Computing Complexity
UBLLU1-15-M

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ABSTRACT

This project develops an algoritm and computational tool that integrates cellular automata (CA) as a generative design (GD) system for pedestrian behaviour prediction in response to thermal discomfort. The emphasis is on the measurement of perceived outdoor Solar radiation temperature and its optimization through shade trees in an Urban Park. A Cellular Automata model with specific rule-set was used to predict user behaviour in response to the high solar radiation with the MRT values as the evaluation Index. The aim was to find new points of interest for placement of shade trees, in order to improve the general temperature of the urban park during the summer.

Can trees mitigate the impact of Solar radiation?

Research suggests that shade from trees could go a long way to mitigate the urban heat island effect and make the thermal environment more comfortable..

Image Source: AP News Website, DANICA KIRKA and JILL LAWLESS, July 19,2022, https://apnews.com/article/

Introduction

Can trees really cool our parks down?

“Planting is regarded as one of the most effective methods to improve the outdoor climate”.(B. Lin et al. / J. Wind Eng. Ind. Aerodyn. 96 (2008) 1707–1718).”A tree affects the surrounding environment, including decreasing wind velocity, blocking sunshine and moderating air humidity.” ((B. Lin et al. / J. Wind Eng. Ind. Aerodyn. 96 (2008) 1707–1718)). These effects counteract with the pedestrian thermal comfort in summer. The urban environment is can be analysed adequately but it is very challenging to predict its behaviour. “Research studies suggest that there is a need for a method to predict the effects of different vegetation and landscape design configurations”((B. Lin et al. / J. Wind Eng. Ind. Aerodyn. 96 (2008) 1707–1718)), in order to access their impact on the comfort of users using the space from the concept design phase. A variety of interpretations could be made by learning more about the possible attraction of people’s interest in public spaces and knowing future interst points would help us to examine the efficiency of ammenities provided in the space. Based on this scope, The objective of this project is to use algorithmic design logic to find optimal points of interest for placement of shaded trees in order to improve the percentage of shaded area of the Queens Square park during summer.

Background

This project will aim to develop a method for optimizing the thermal comfort in an urban park by improving the average temperature to comfortable levels during the summer at the early stages of design. This method explores different configurations by addressing forces on the site.(i.e solar radiaiton and shade)

The proposed methodology highlights three main steps of execution:

1.) **Data Gathering:** Quantitavtive data will be obtained through a solar radiation analysis with on the project site,The evaluation Index will be the MRT values.

3.) **Shade optimization** using a CA based approach with multiple rule-sets and iterations to explore various scenarios of rules The most adaptive rule-set that responds to the context of a natural system will be chosen for further iterations.

4.) **Pedestrian Simulation:** To develop the results of this model further, an agent based simulation founded on the principles of the social force model will be used to carry out a live pedestrian simulation of the CA optimised configuration.

Generative Design

Generative design (GD), a computational and evolutionary system reflective of a specific design problem or characteristic determined by the designer(Herr 2002), has long been viewed as a paradigm shift by using rules to dynamically and autonomously generate complex outcomes unconceivable by humans alone (McCormack et al. 2004). By bringing the power of GD into existing design workflows and automating the process, high levels of accuracy, consistency, and efficiency can be achieved to strike a balance between subjective preferences and performance-based criteria. In performance-driven design, environmental factors such as solar (Lobaccaro et al. 2016; Zhang et al. 2016) and daylighting (De Luca 2017; Jalali et al. 2020; Pinto de Araujo 2018) are improved by simulating a building form's massing, orientation, etc. (Sams 2017). The iterative nature of GD makes it an ideal early-stage (ES) design approach by allowing for rapid exploration of countless design alternatives.

Cellular Automata

Cellular automata are discrete and dynamic computational frameworks. They are composed of a large number of simple elements called cells, arranged in a regular lattice. Every cell can have a finite number of states. Time is also discrete in CA and proceeds in iterative steps, i.e. t, t+1, t+2, t+4, etc. The states of the cells are updated in a parallel manner according to a local rule, commonly concerning just the cell in question and the neighbouring cells, at every time step, i.e. the state of a cell at time (t), depends on the state of the cell and the states of its neighbours at time (t-1). All of the cells are updated synchronously and the state of the entire lattice advances in discrete time steps. CA has since been used as a morphogenetic "bottom-up" design approach in which pre-determined results are avoided, and generated outcomes are complex and unpredictable (Herr and Ford 2016).

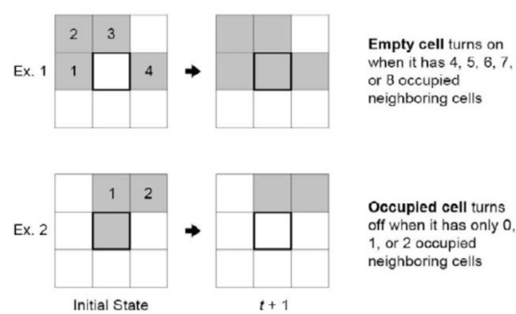


Figure 1: Cellular Automata

Conway's Game of Life

The GAME OF LIFE is a CELLULAR AUTOMATON devised by the British mathematician John Horton Conway in 1970. It is the best-known example of a cellular automaton. The universe of the Game of Life is an infinite two-dimensional grid of cells, each of which is either ALIVE (populated) or DEAD (unpopulated or empty). Cells interact with their eight NEIGHBORS, the cells that are directly horizontally, vertically, or diagonally adjacent.(M. Gardner 1970)

At each step in time, the following effects occur:

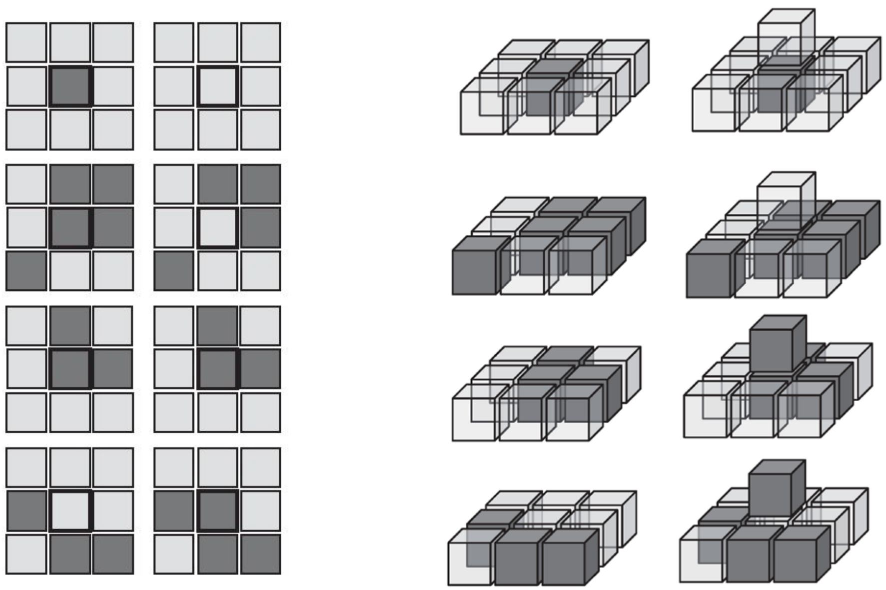


Figure 2: The rules of the Game of Life, 2D

LONELINESS: any live cell with fewer than two neighbors dies.

OVERCROWDING: any live cell with more than three neighbors dies.

STASIS: any live cell with two or three neighbors lives, unchanged, to the next generation.

REPRODUCTION: any dead cell with exactly three neighbors comes to life.

Conway's Game of Life

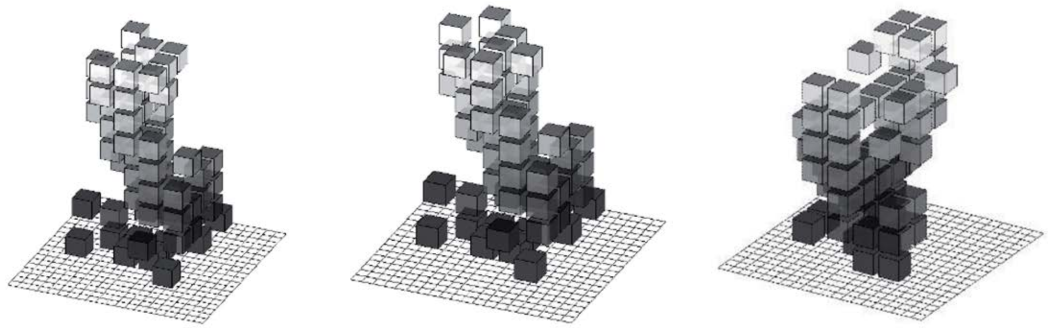


Figure 3: Typical CA spatial forms based on the rules of the Game of Life

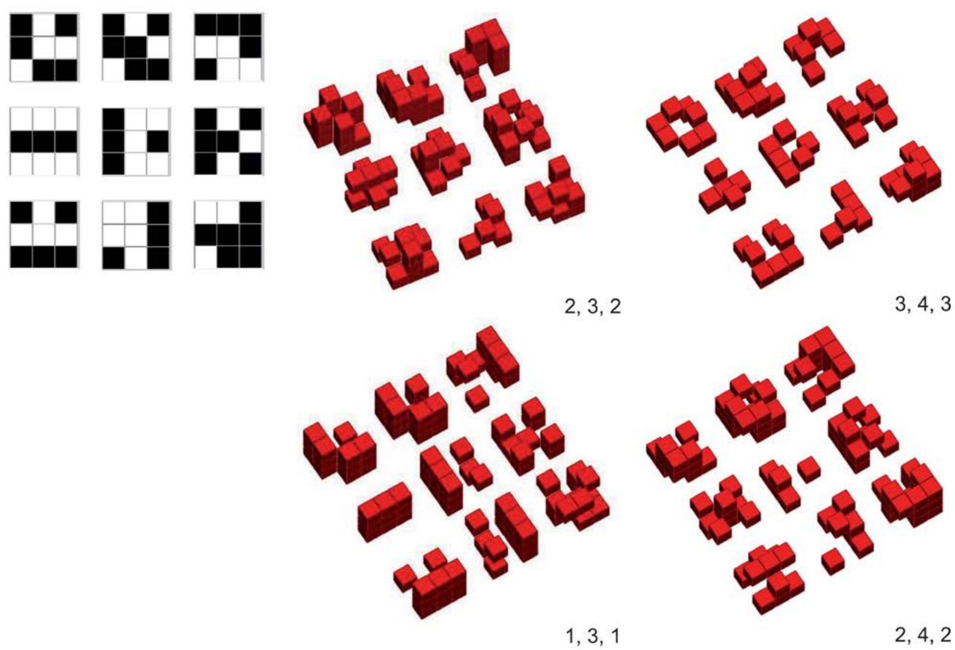
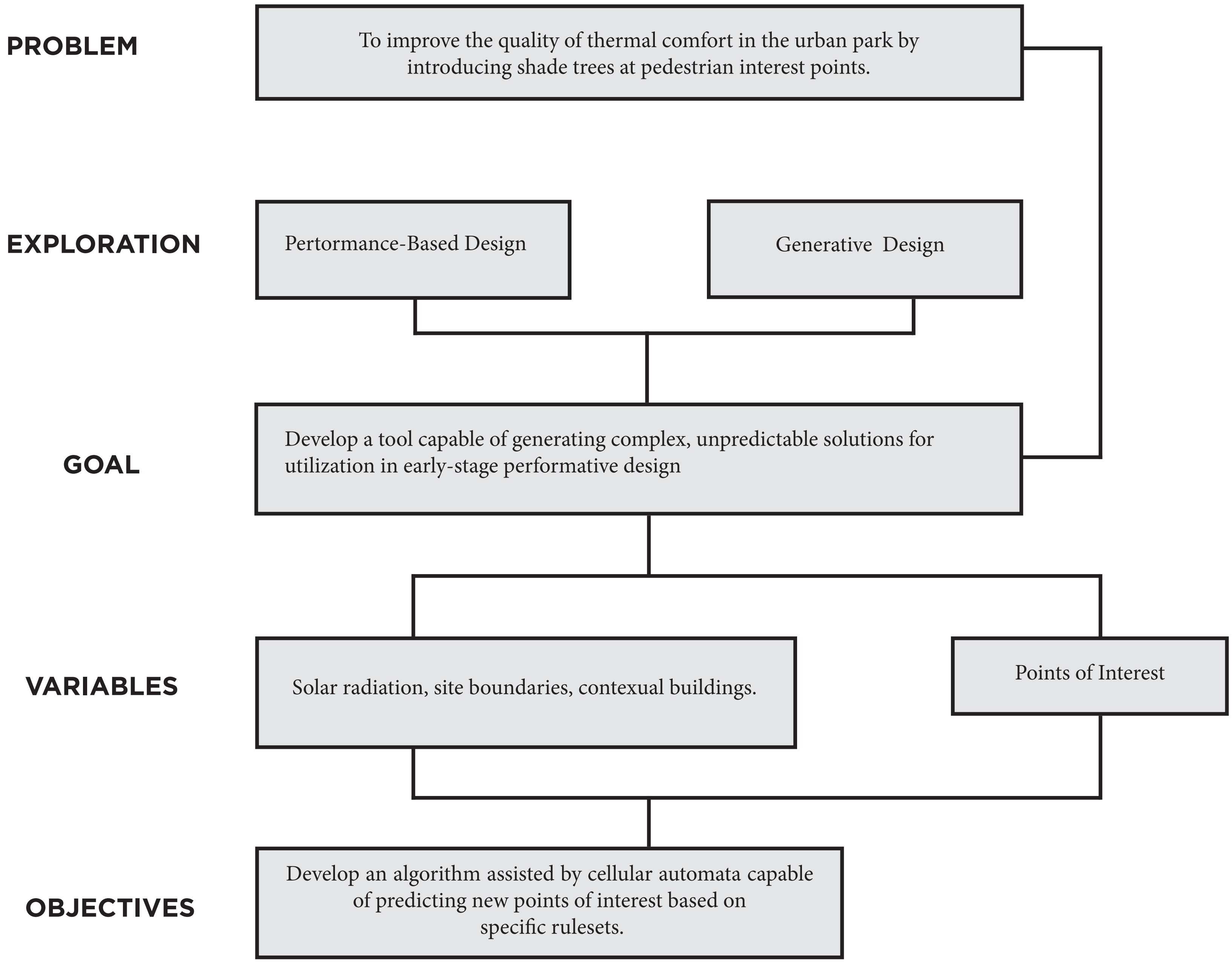
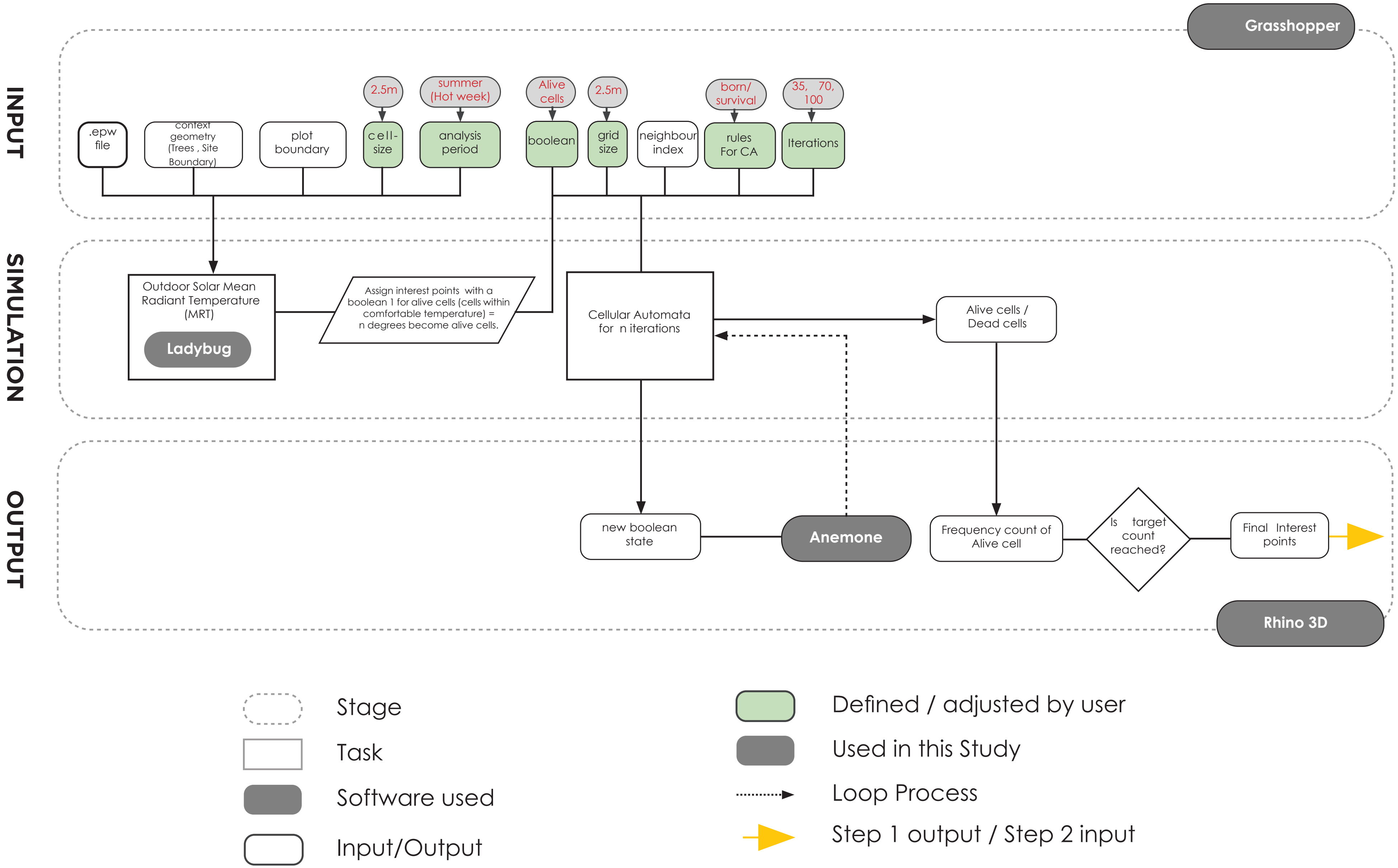


Figure 4: Variations of a single CA system based on the same rule (2,3,2)

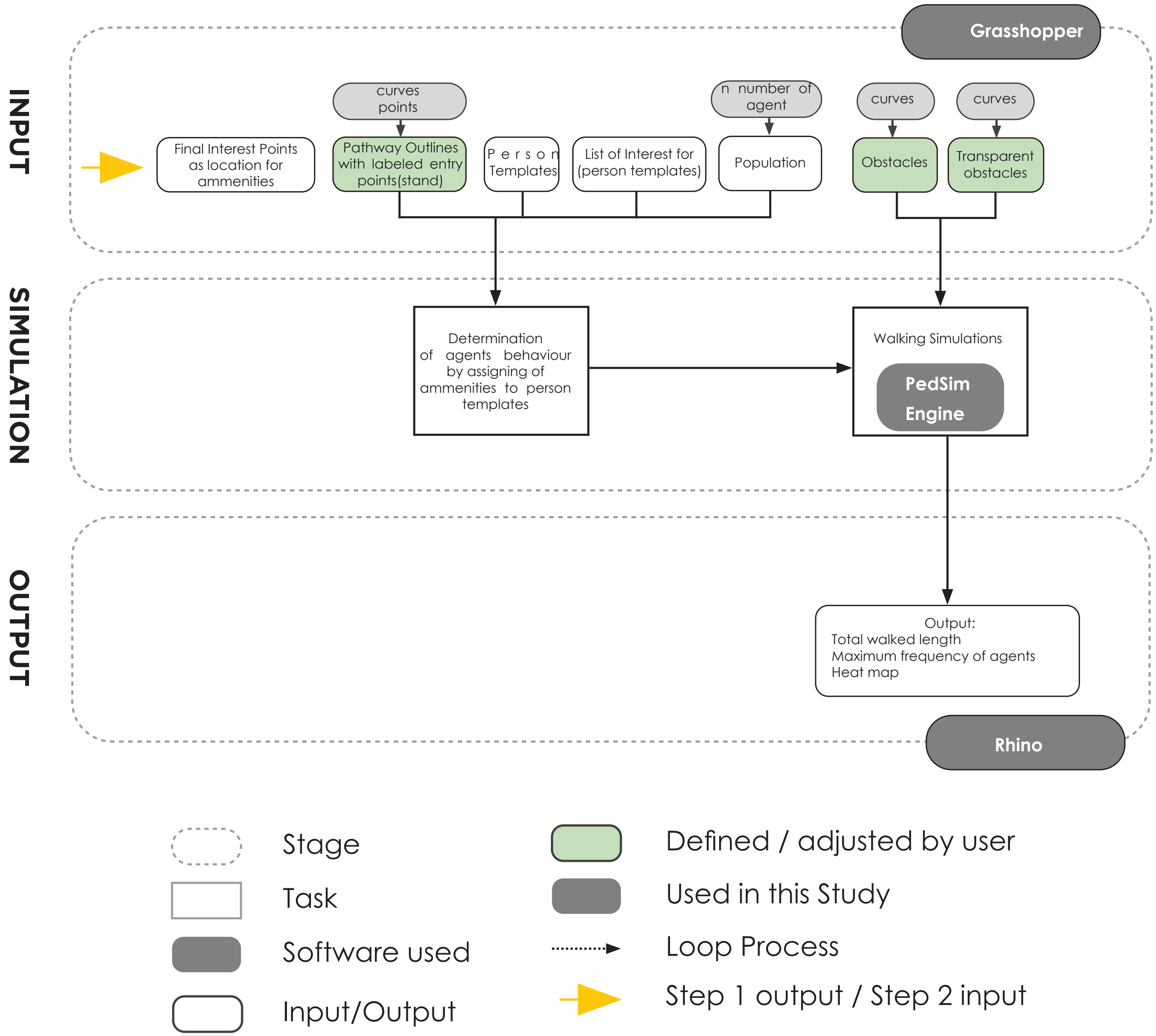

PROBLEM
To improve the quality of thermal comfort in the urban park by introducing shade trees at pedestrian interest points.
EXPLORATION
Pertormance-Based Design
Generative Design
GOAL
Develop a tool capable of generating complex, unpredictable solutions for utilization in early-stage performative design
VARIABLES
Solar radiation, site boundaries, contexual buildings.
Points of Interest
OBJECTIVES
Develop an algorithm assisted by cellular automata capable of predicting new points of interest based on specific rulesets.

Materials & Methods Flowchart

STEP 1 Cellular Automata Algorithm Methodology



STEP 2 Flow Chart of Pedestrian Simulation



Queens Square Park

“Queen Square is a magnificent Georgian park area in the heart of Bristol, surrounded by trees and cobbled streets. Nestled amongst Bristol’s Harbourside and Old City areas, Queen Square is a popular retreat for nearby workers and visitors to the city who are looking to relax. The square also regularly hosts outdoor theatre, concerts and other major events, all against the backdrop of the magnificent Georgian town houses that dominate views across the square”(https://visitbristol.co.uk/)

Figure 12: Queens Square Park Bristol. Credit: Google Maps

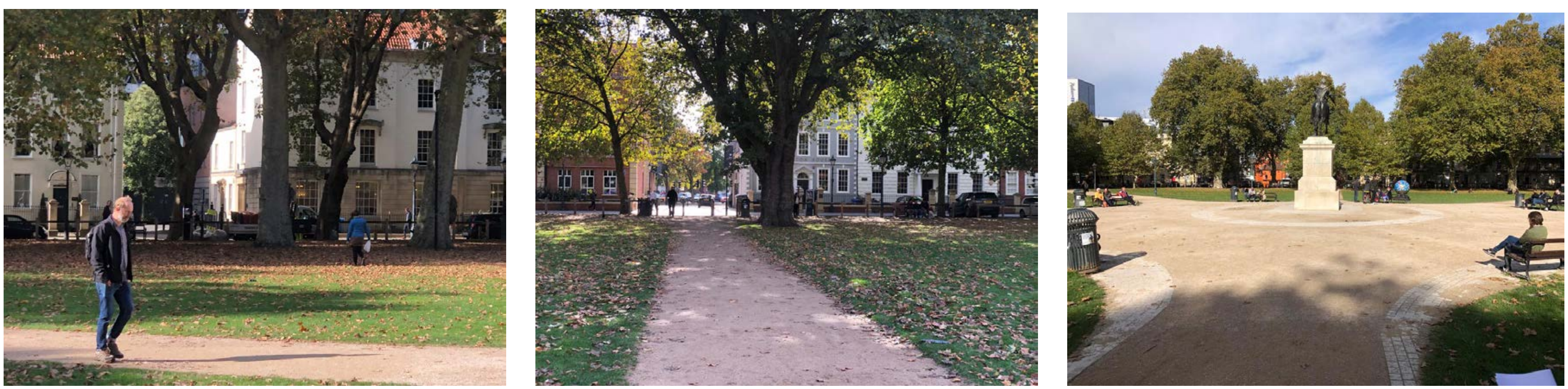


Figure 13: Queens Square Park Bristol. Credit: Author

Annual Average Temperature for Bristol

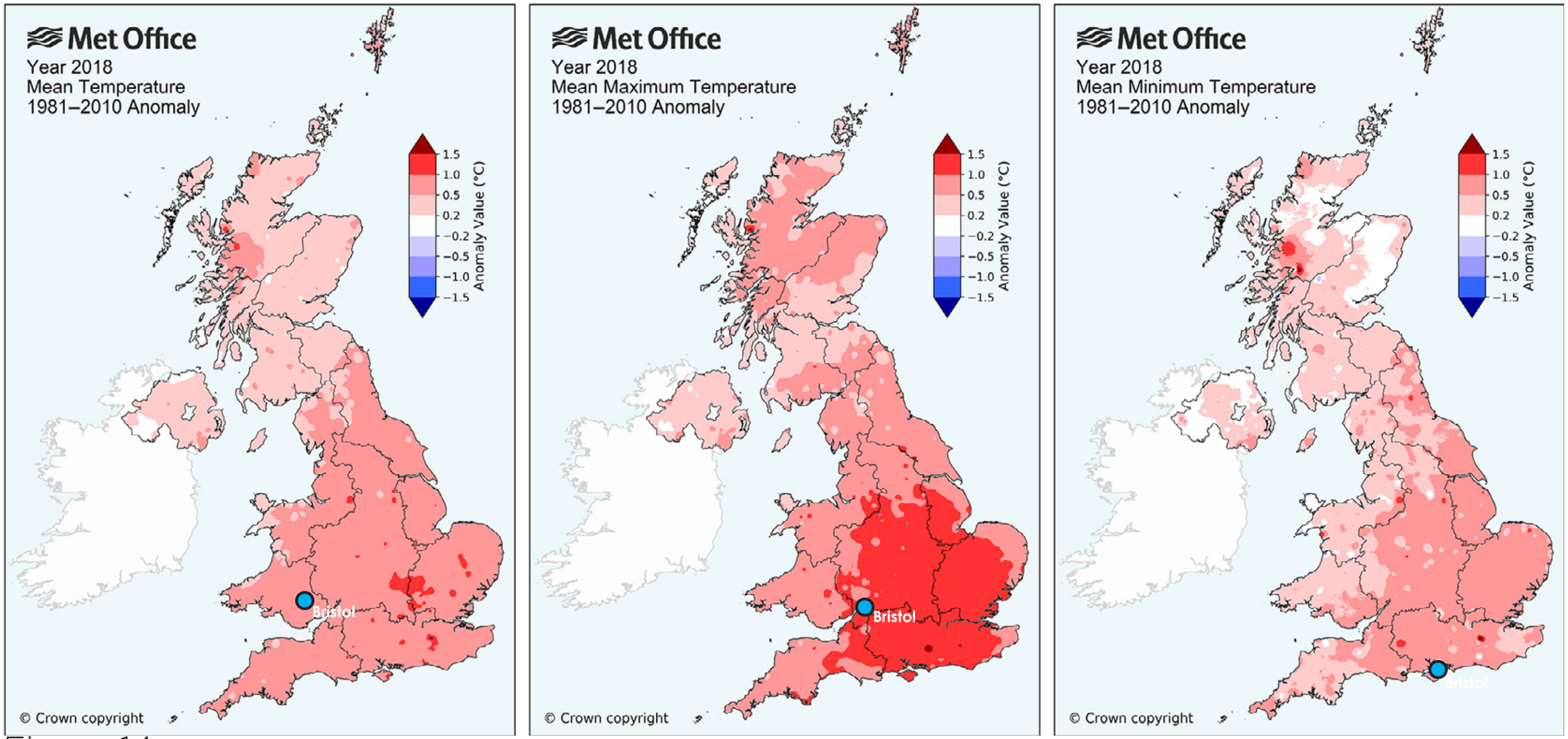
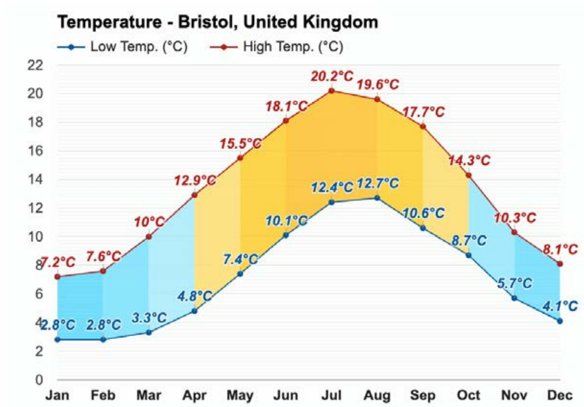


Figure 14

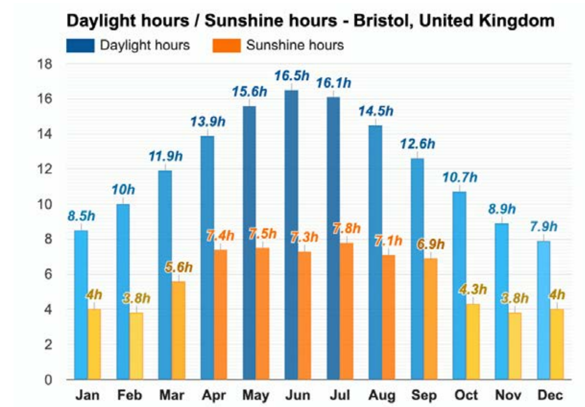
Figure 14 : Year 2018: annual average temperature anomalies (°C) relative to 1981–2010 average for mean,

Source: Intl Journal of Climatology, Volume: 39, Issue: S1, Pages: 1-55, First published: 30 July 2019, DOI: (10.1002/joc.6213)

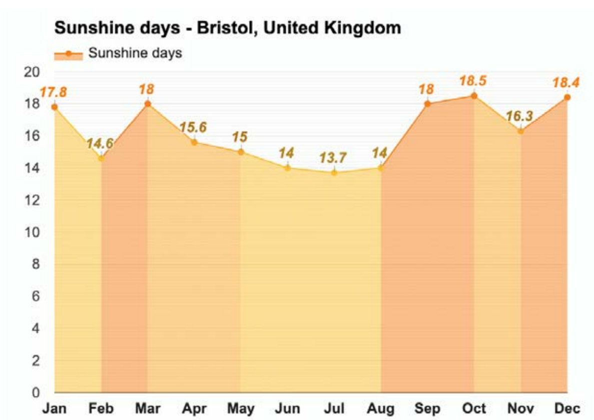
Monthly Average Temperature for Bristol



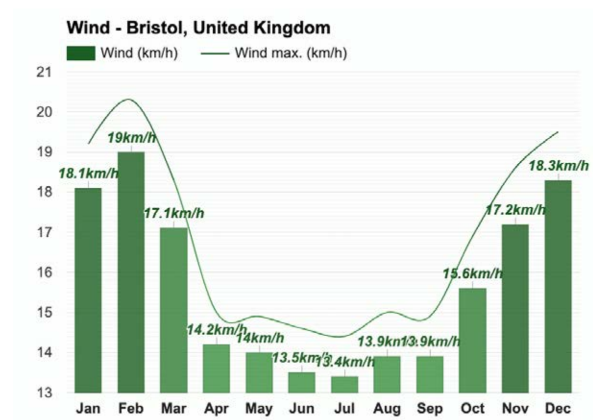
Average Monthly Temperatures
Source: https://www.weather-atlas.com



Average Monthly Sunshine hours
Source: https://www.weather-atlas.com



Average Monthly Sunshine
Source: https://www.weather-atlas.com



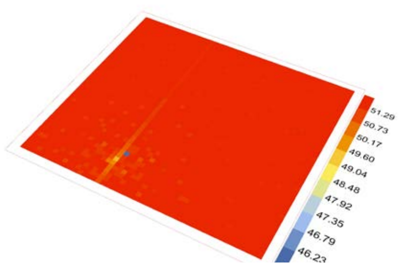
Average Monthly Wind Speed.
Source: https://www.weather-atlas.com

Ladybug Analysis

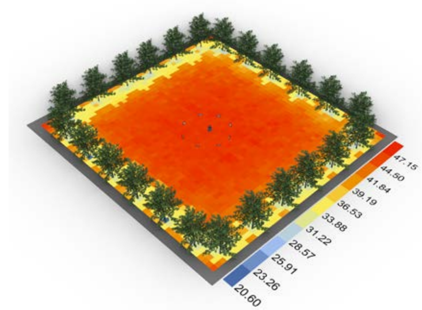
Inputs

The radiation analysis is created in using parametric methods in Grasshopper, along with open-source plugins Ladybug and Elk. The workflow requires A) an EPW file for the specified location, B) the site context geometries gotten from Open Street Map using the Elk Plugin for grasshopper, and C) the site plot boundary, each of which are plugged into Ladybug. 3D models for context geometries are trees which were generated using Lands design Plugin for Rhino. The trees on the queens square park were identified as plane trees(planatus occidentalis), The plugin contains a large collection of plants out of which plane trees were obtained from. The height and spread of the trees were also modified to best match what is existing.

Summer

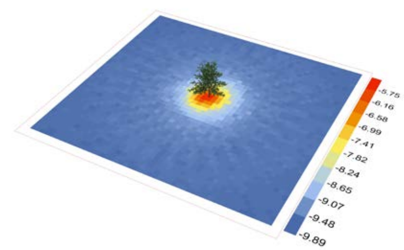


Map showing Mean Radiant Temperature (MRT) values on the site with no shade trees during summer.

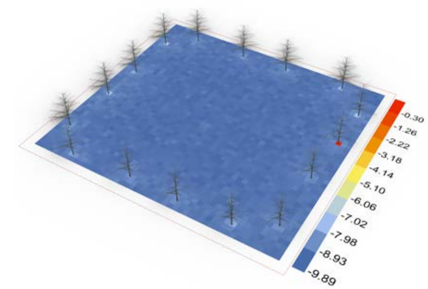


Map showing Mean Radiant Temperature (MRT) values on the site with shade trees during summer.

Winter



(MRT) values indicate that during winter tree shade could have significant effect on the MRT. This is a subject of further research and is not discussed within the scope of this project.



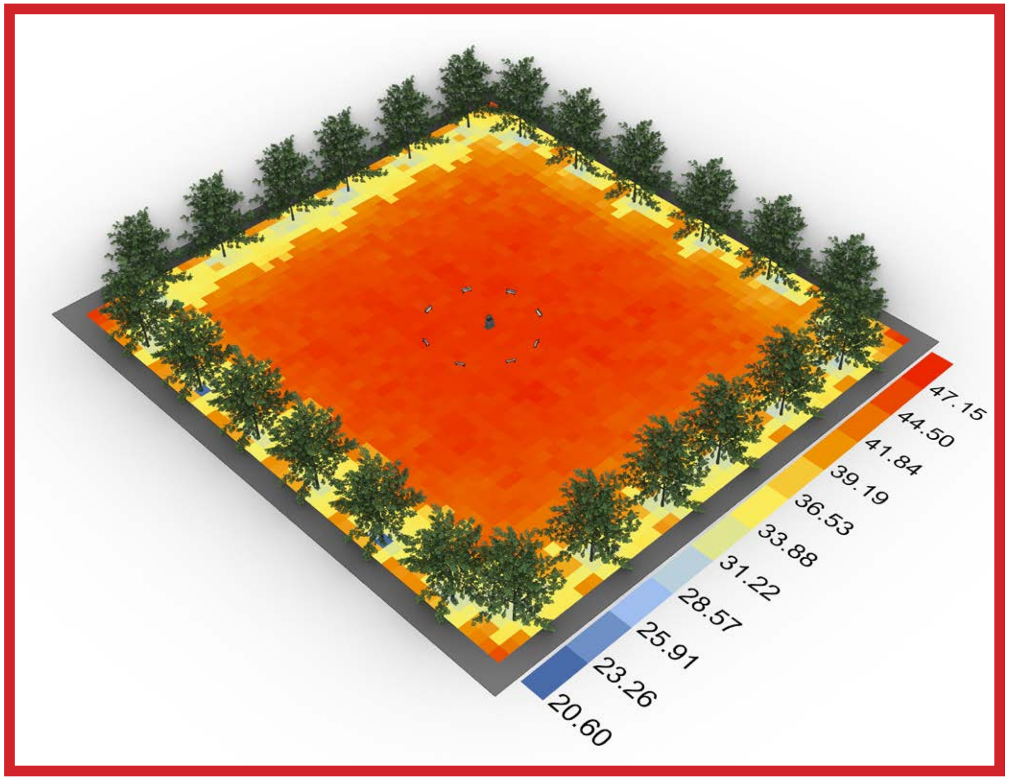
During Winter shade Trees have no significant effect on the temperature. The trees are without leaves as this is the typical conditions of trees during winter.

Outputs

The (MRT) values are sorted in ascending order, with the lowest values at the bottom. Then, based on the user-input target treshhold, comfortable temperature(x) for thermal comfort is extracted for (y) number of cells. The cells become Alive cells in the cellular automata simulation and the other values are considered as dead cells.

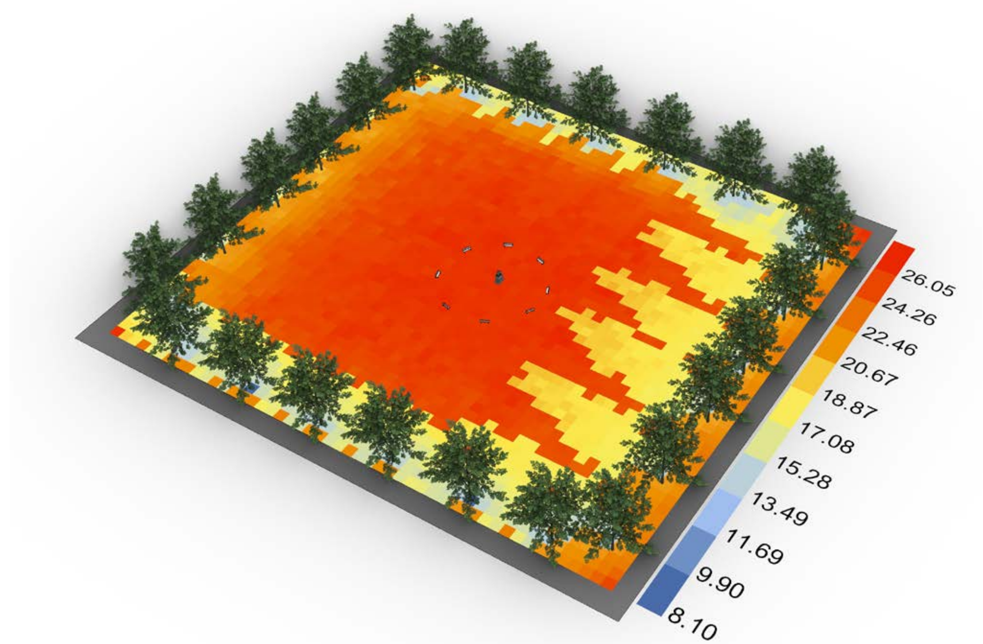
Mean Radiant Temperature (MRT) Analysis

Summer



Single cell: 2.5m x 2.5m
Cell grid size: 50(2.5) x 46(2.5)
No of Trees = 24
Total area of cells :14,375m2
Area of cells under shade: 1375m2, 9.6%(<35degrees)

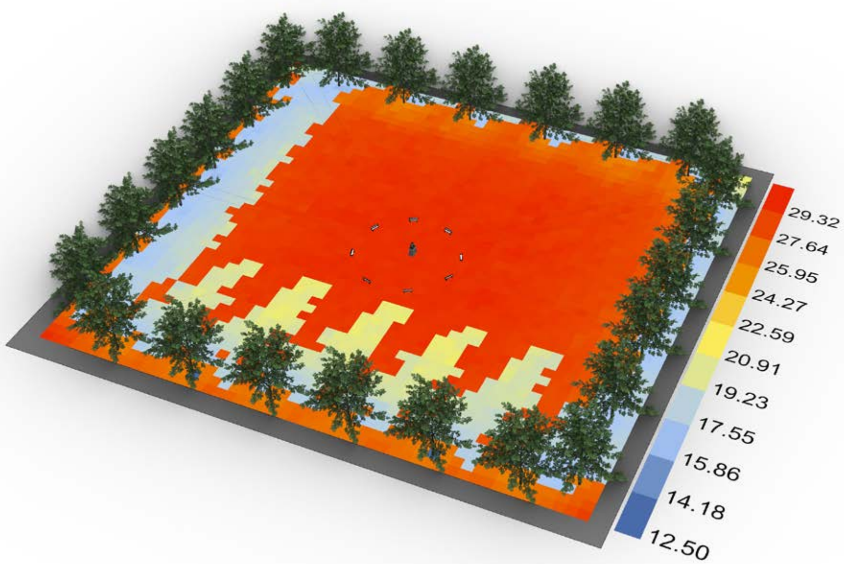
Autumn



Single cell: 2.5m x 2.5m
Cell grid size: 50(2.5) x 46(2.5)
No of Trees = 24
Total area of cells :14,375m2
Area of cells under shade: 1869m2 13%(<18degrees)

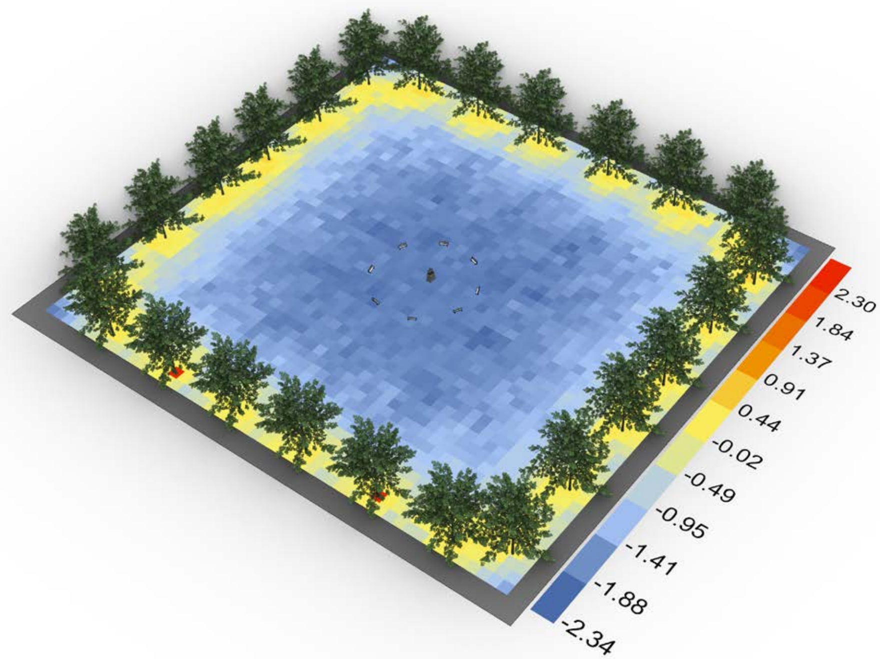
Mean Radiant Temperature (MRT) Analysis

Spring



Single cell: 2.5m x 2.5m
Cell grid size: 50(2.5) x 46(2.5)
No of Trees = 24
Total area of cells :14,375m2
Area of cells under shade: 1475m2 10%(<22degrees)

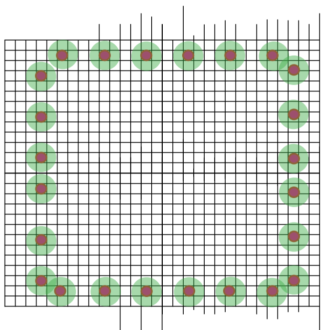
Winter



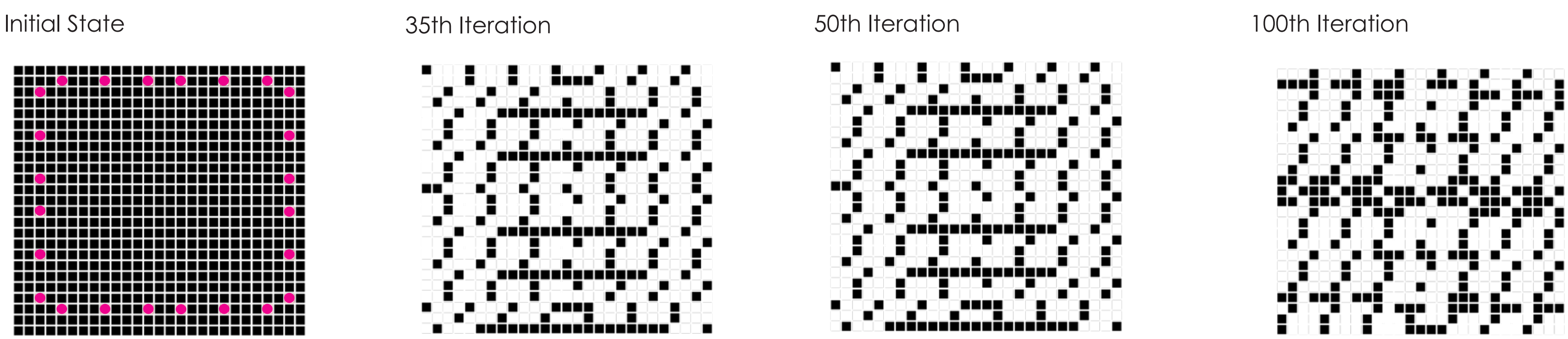
Single cell: 2.5m x 2.5m
Cell grid size: 50(2.5) x 46(2.5)
No of Trees = 24
Total area of cells :13,1375m2
Area of cells under shade: 1764m2, 7%(<-0.4 degrees)

CA Rules Devlopment

The genetic solver Galapagos was used to explore rules as genomes and to optimize the cellular automata simulation for closest proximity of alive cells from initial starting cell to the alive cell after 100 iterations. . A number of rule combinations were tested to visualize their behaviour but the results were very regular and did not show the desired intuitiveness of the Cellualar Automata. The rules for the simulation were developed through testing different conditions to find the rules that best fit a natural self organizing behaviour.



Shade areas at the site boundary have been considered at starting point of shade interest points for the cellular automata simulation.

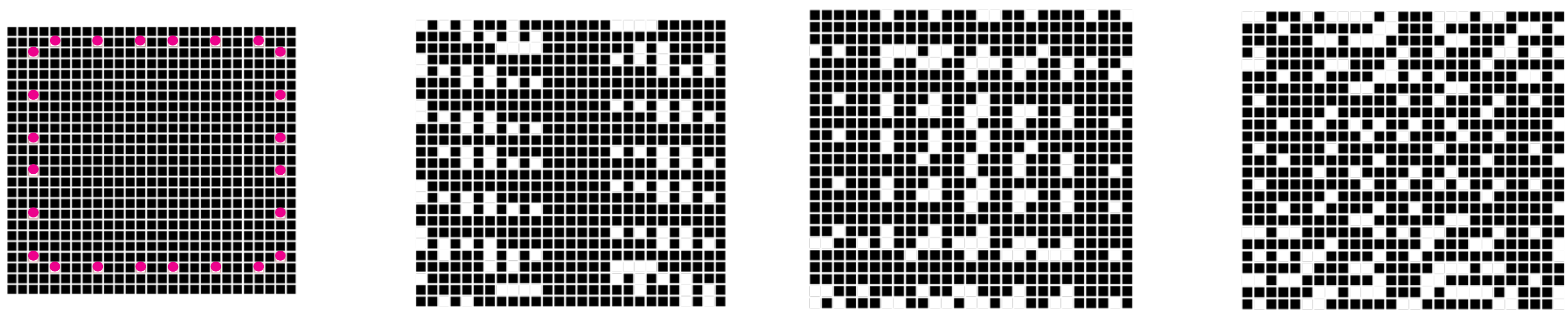


Ruleset 1:

1.Every dead cells with 3 or 6 live neighbour becomes alive.
2.Every live cell with 2 or 7 neighbours survive
3.Every dead cell with 0,1,2,4,5,7,8 live neighbours die.

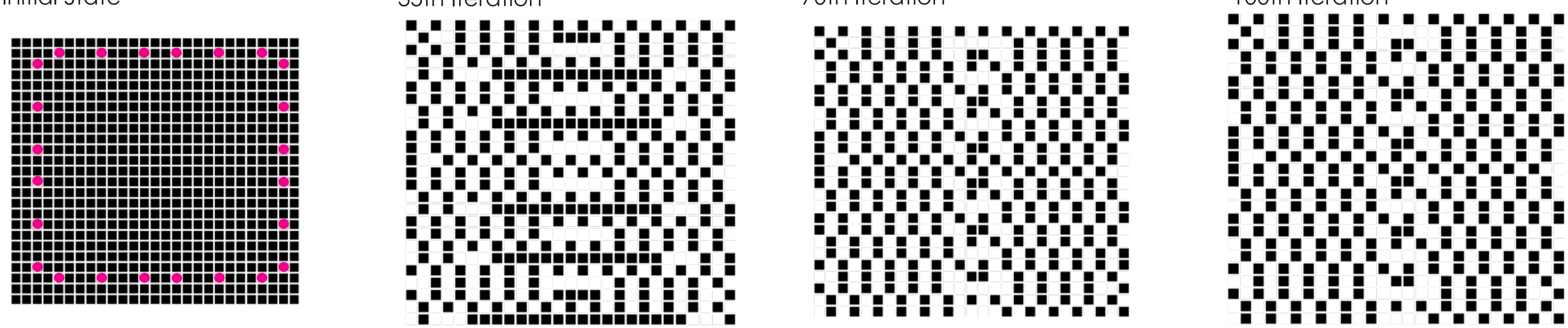
CA Rules Devlopment

Initial State | 35th Iteration | 70th Iteration | 100th Iteration



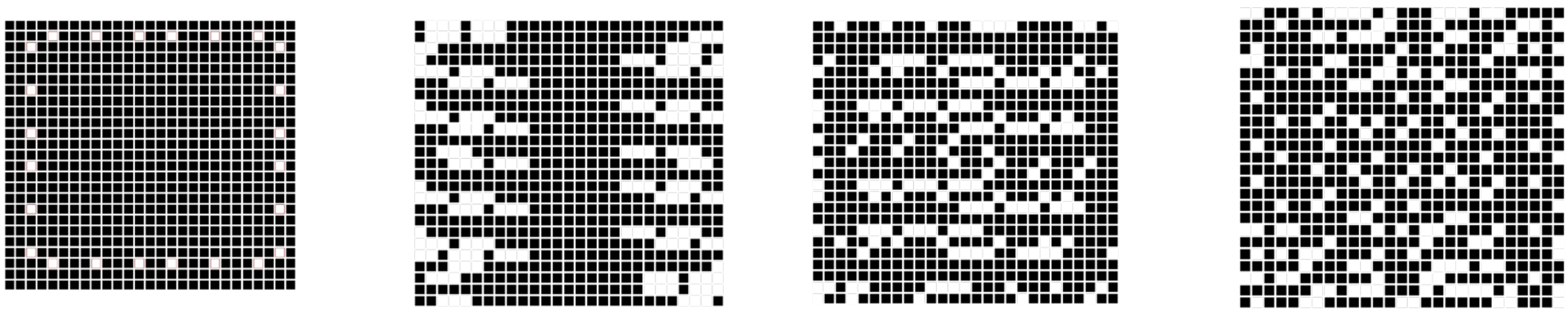
Ruleset 2:
1.Every dead cells with 2 ,3 or 7 live neighbour becomes alive.
2.Every live cell with 4, 5 or 7 neighbours survive.
3.Every dead cell with 1,4,5,6,8 remains a dead cell.

Initial State | 35th Iteration | 70th Iteration | 100th Iteration

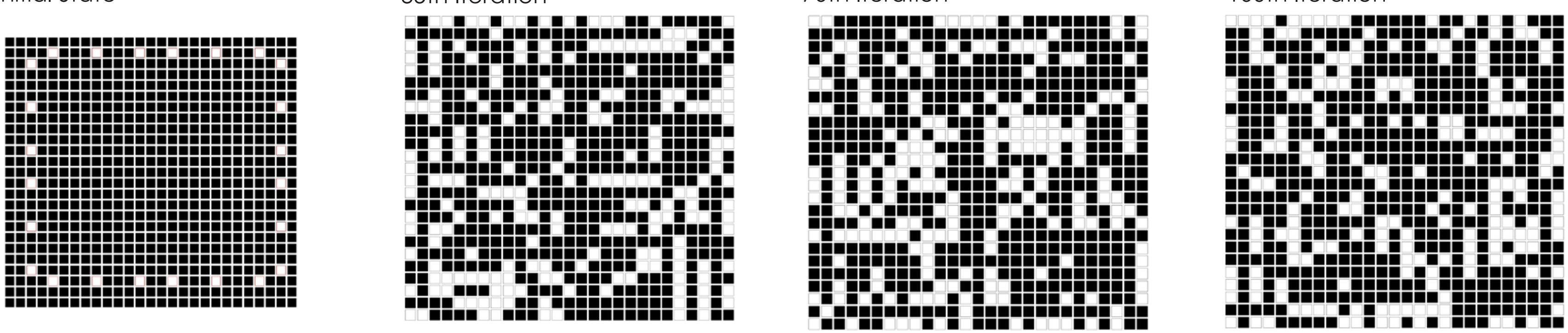


Ruleset 3:
1.Every dead cells with 3 or 7 live neighbour becomes alive.
2.Every live cell with 5 or 2 neighbours survive.
3.Every dead cell with cell with 0,1,2,4,5,6,8 dead cell remains dead.

CA Rules Experiment



Ruleset 4:
1.Every dead cells with 3 live neighbour becomes alive.
2.Every live cell with 3, 2 or 7 neighbours survive
3.Every dead cell with 0,1,2,34,5,6,7,8 remains a dead cell

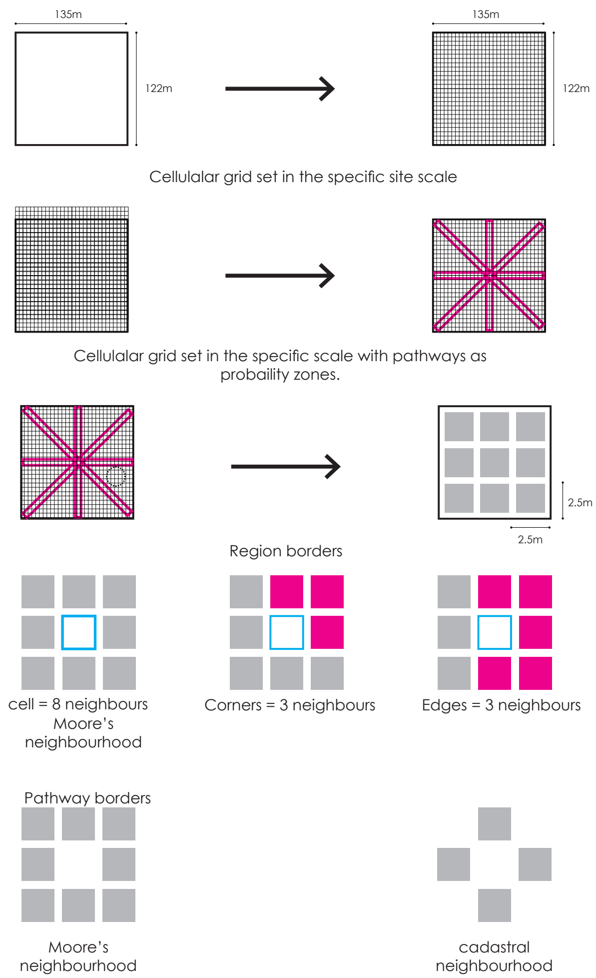


Ruleset 5:
1.Every dead cells with 2 or 7 live neighbour becomes alive.
2.Every live cell with 3,4 or 5 neighbours survive
3.Every dead cell with 0,1,2,,6,7or 8 becomes a dead cell

Figure 4: Cellular Automata Rules

CA Rules Devlopment

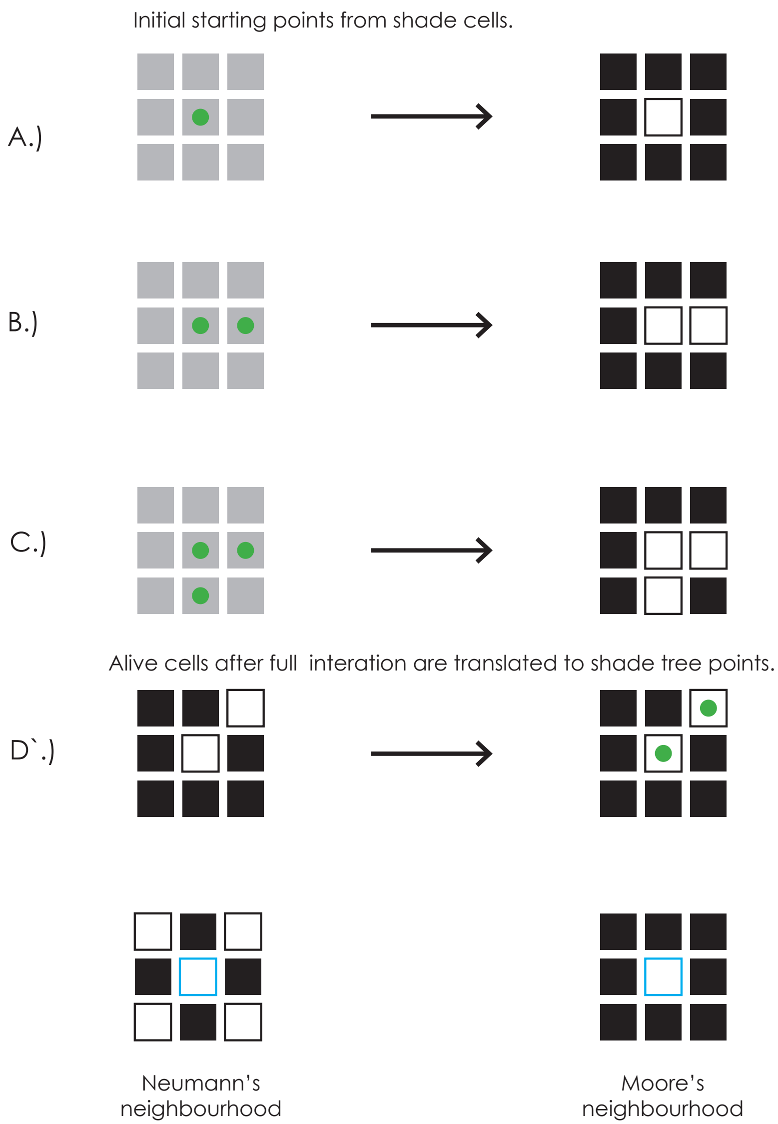
Existing Site Insert in the Cellular Automata grid



The interest points(shade attractor) acts as a movement foci for people walking in the space. We can distinguish between interest points that do not result in alive or dead cells and those that do. A different rule that is probabilistic applies to the cells in the pathway; these cells only have a 30% chance of surviving. which is consistent with a normal situation since the majority of people won't be eager to cross the path in search of shade. The initial alive cells are the cells that fall within the allowable temperature threshold under the shade trees. For this project the temperature chosen was 20degrees Celsius. The site's pathways are included in the square grid and a cell is 2.5 metres by 2.5 metres using the Moore's neighbourhood, which consists of 8 neighbourhood cells.

The state of the cell is analysed by either 0(dead cell) or 1(life cell).

Rules are divided into four types:
1. Analyse the dead cell and transform to life cell
2. Analyse the life cell and stay life cell
3. Analyse the life cell and transform to dead cell
4. Analyse the dead cell and stay dead cell



Translation of shade cells into life cells

1.)Born Rule: The first rule brings the life from dead. This rule type is applied when 2 or 7 cells are life neighbours. it is the optimal location for new shade cells.

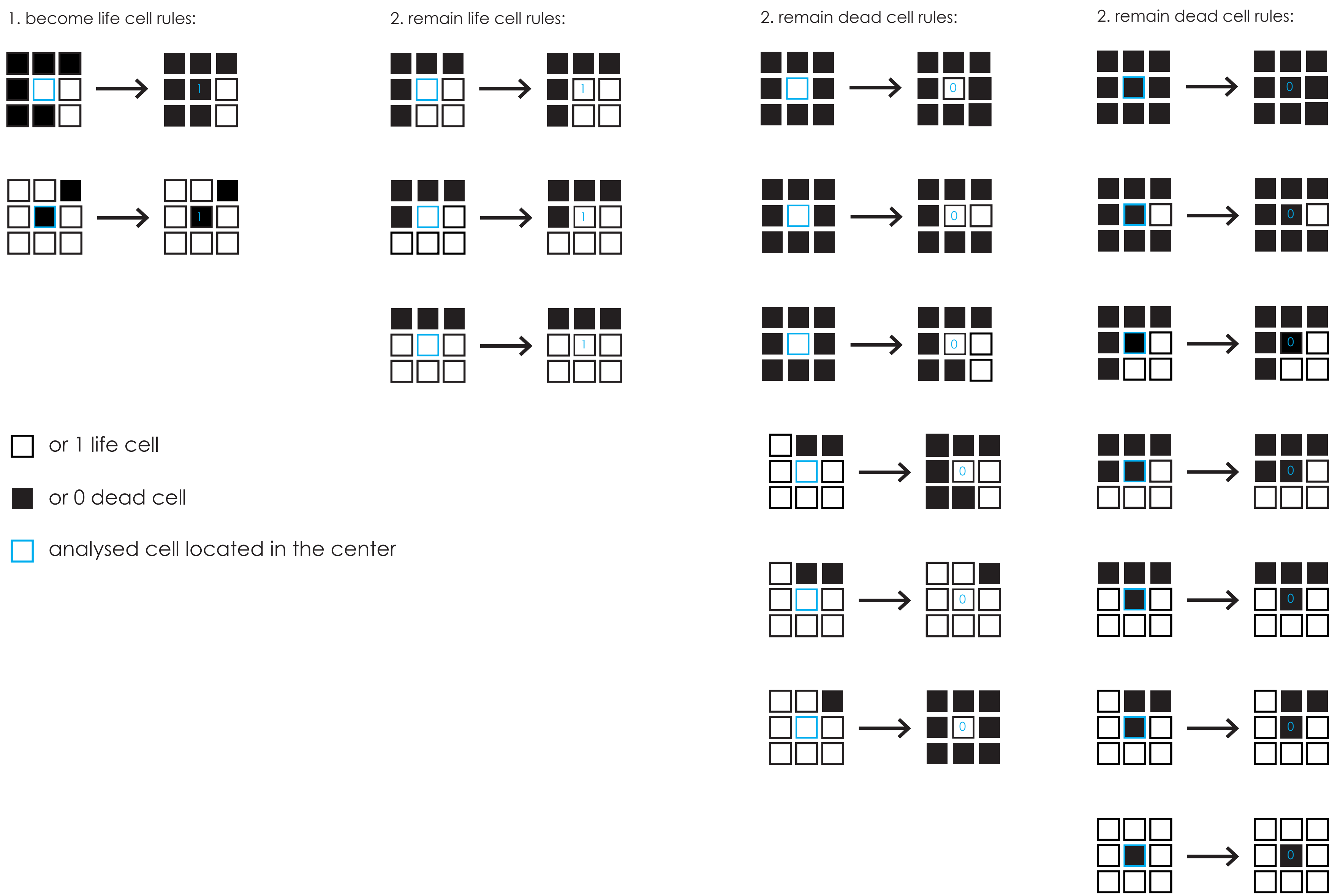
2.)Survival Rule: This rule is applied when amount of the alive cell neighbours is 3, 4 or 5. It shows the thermal environment is balanced and the cells are well shaded and are able to sustain life.

3.)Death Rule:This rule transform a life cell into a dead cell when the amount of life neighbor is 0,1,2,6,7 or 8.in this case it shows there is insufficient amount of shade or suffecient amount of shade but overpopulation exist within the shade so hence it is unable to attract more life.

4.)Probalistic rule: Alive cells that make it to the pathway have a 20% chance of survival.

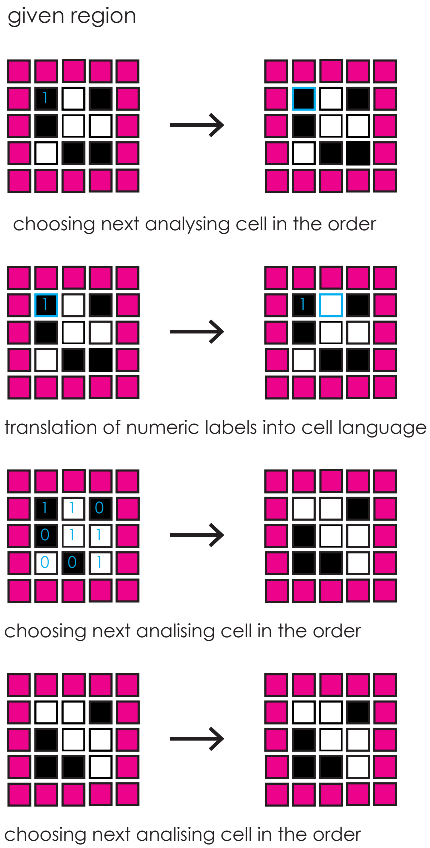
After testing multiple rules, a certain unpredictability, randomness and intuitive behaviour was realised with this ruleset and it was used to obtain the final results.

Transition rules

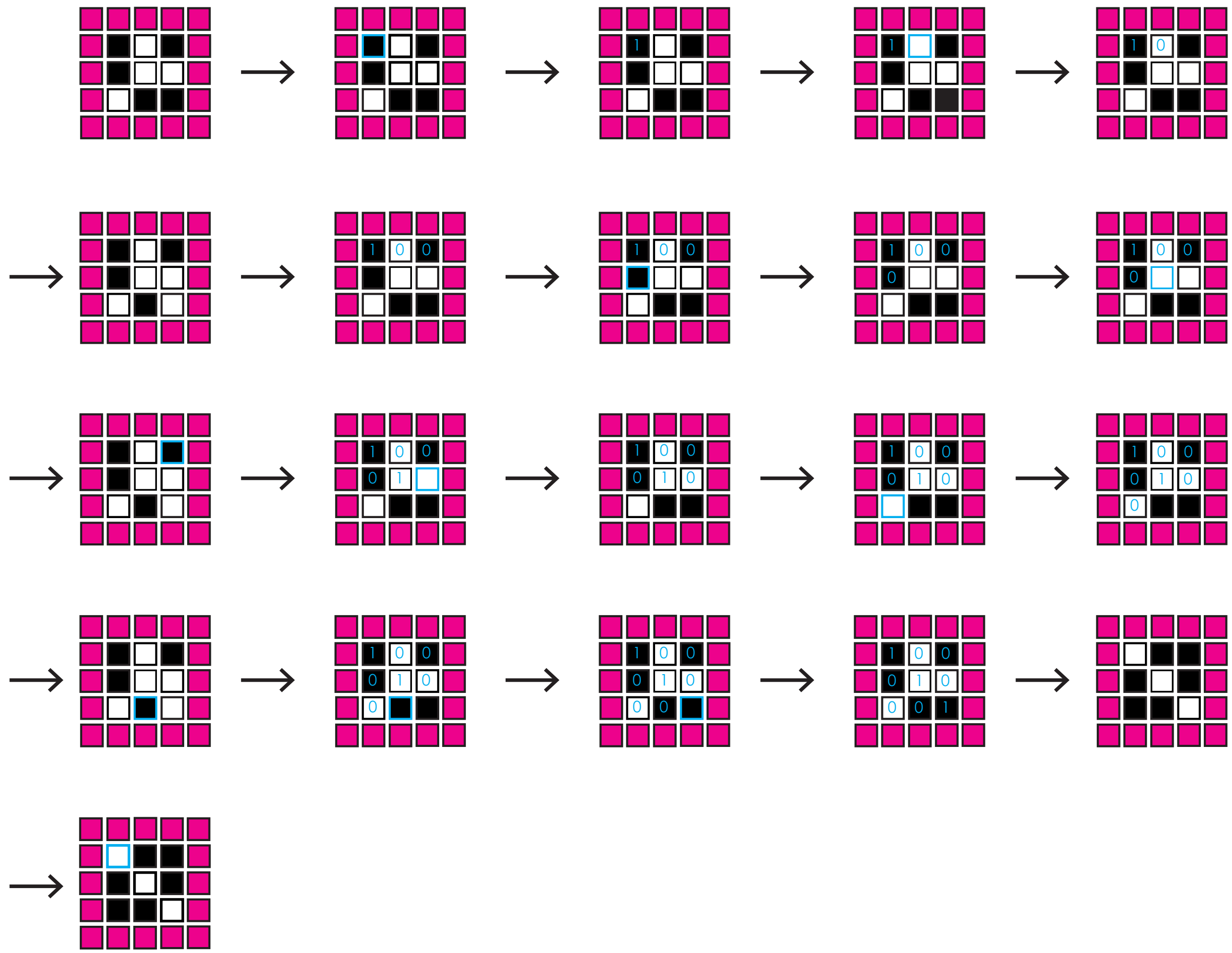


Materials & Methods Rules Development

Example of a global Iteration Process

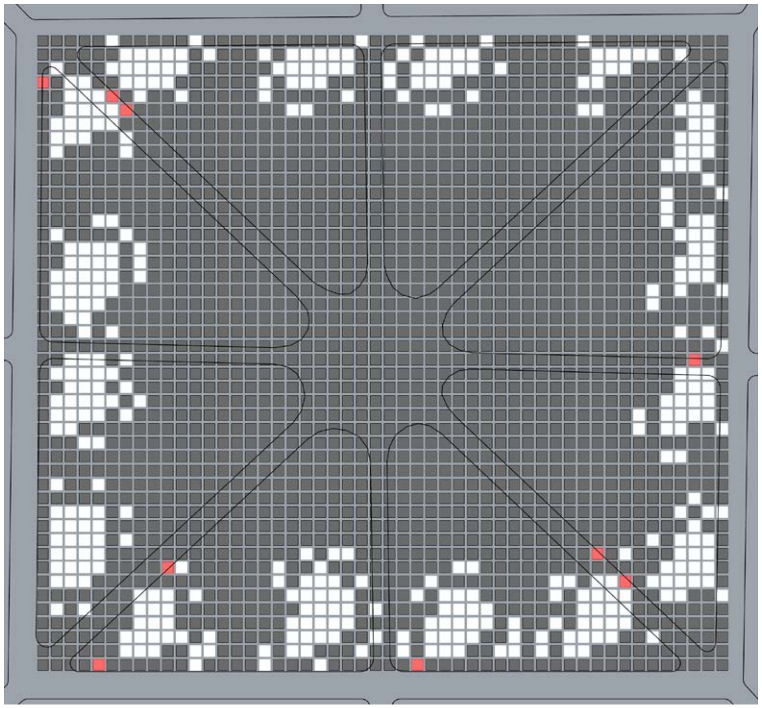


An example of a full iteration process

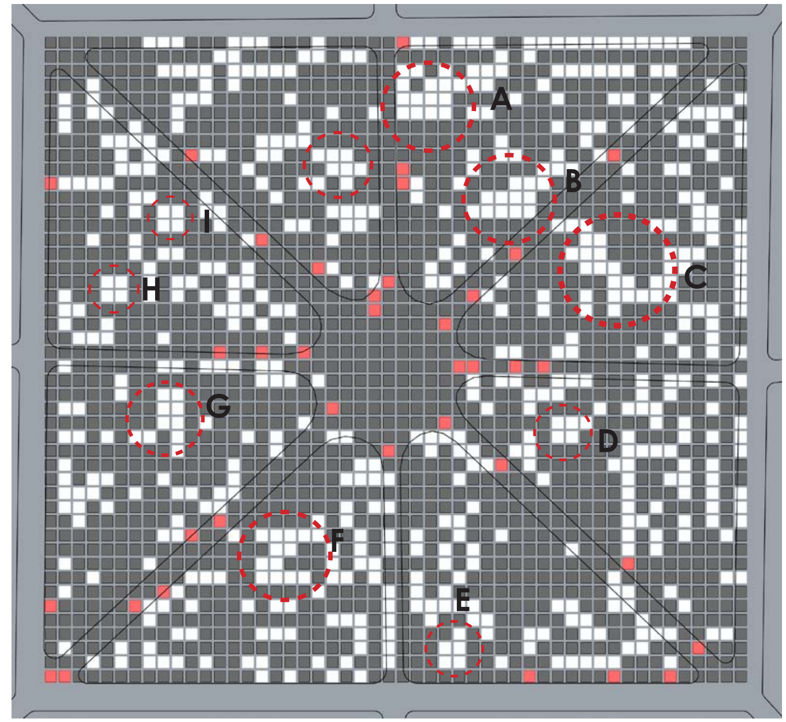


Simulation of the starting cells after n iterattions

Initial state

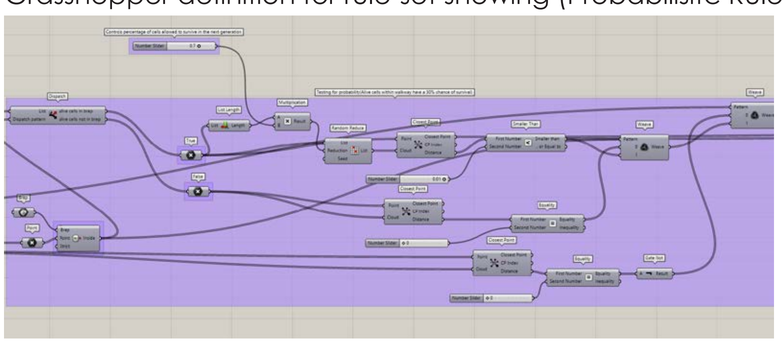


35th Iteration

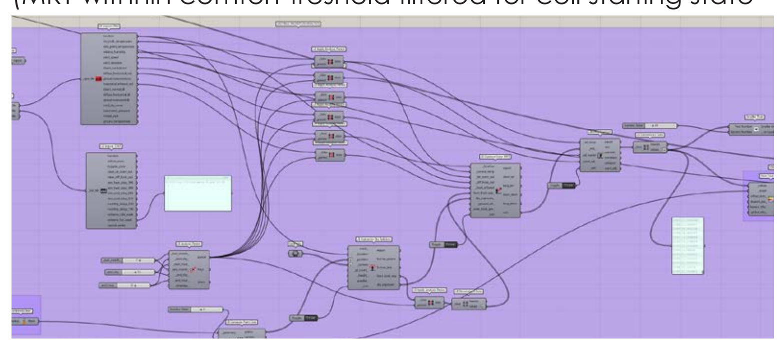


Points of interest behavior prediction of the cells

Grasshopper definition for rule-set showing (Probabilisitc Rule)

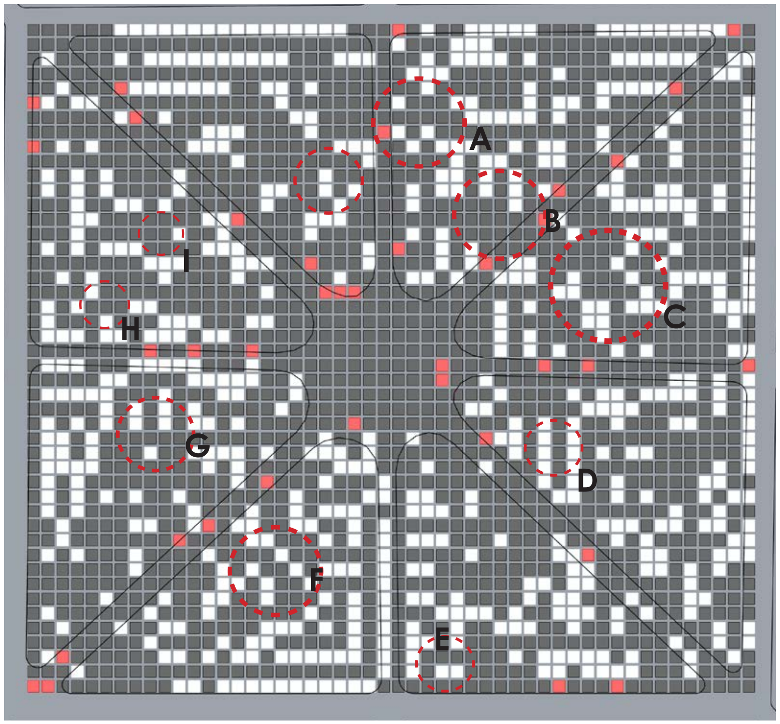


(MRT withnin comfort treshold filtered for cell starting state

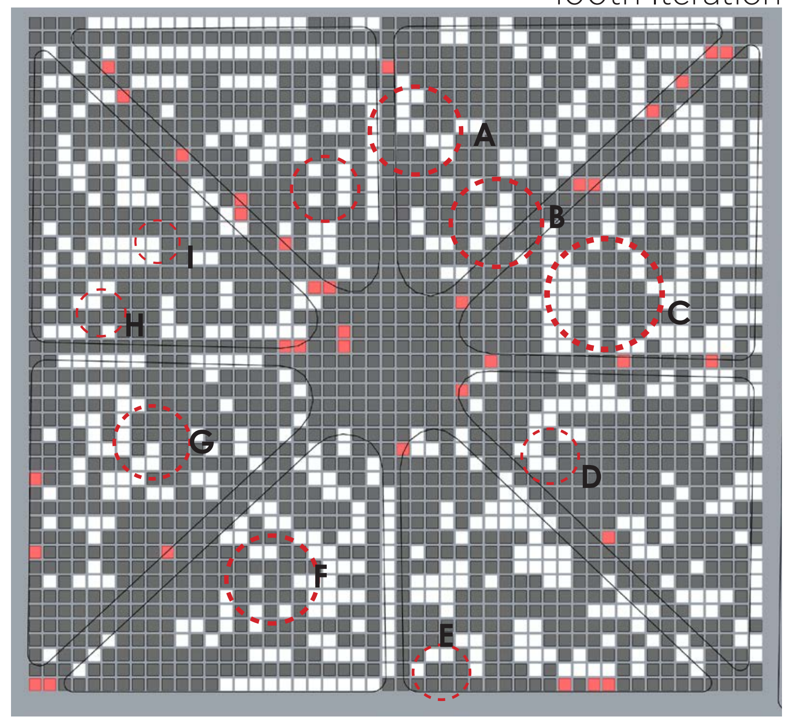


Simulation of the cells after n iterations

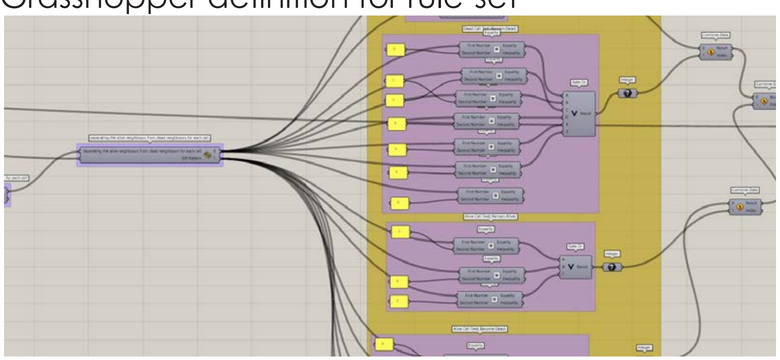
70th Iteration



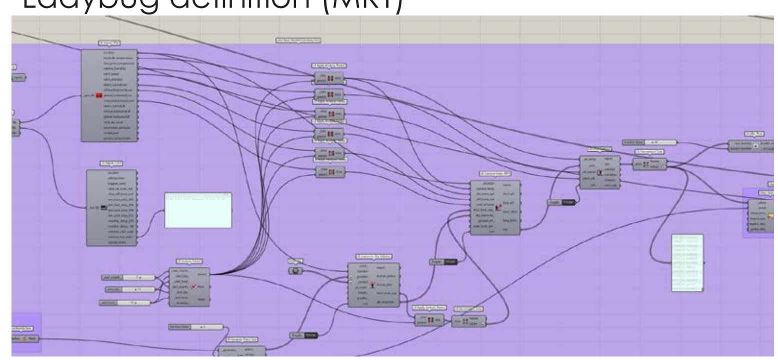
100th Iteration



Grasshopper definition for rule-set



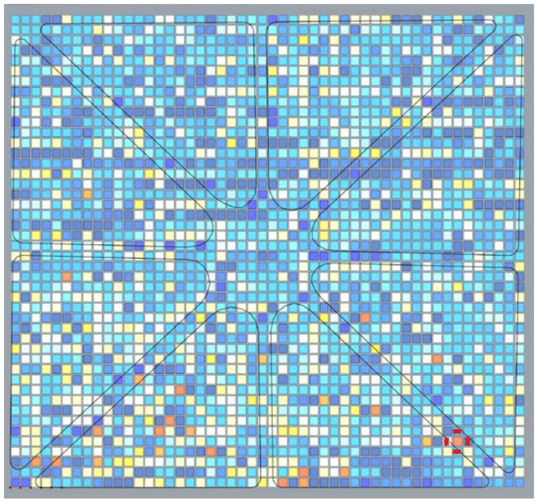
Ladybug definition (MRT)



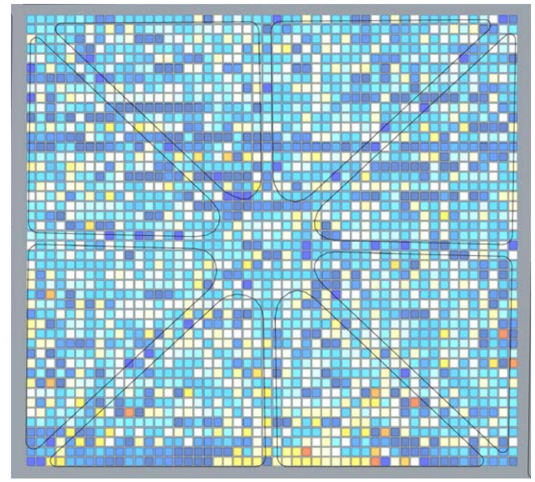
Results & Findings

Heatmap after n iterations

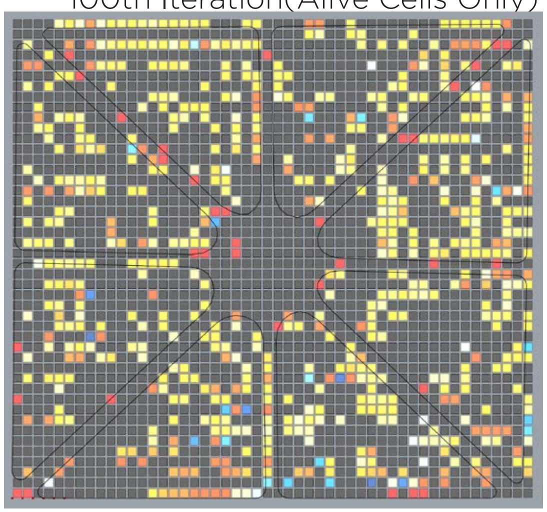
35th Iteration



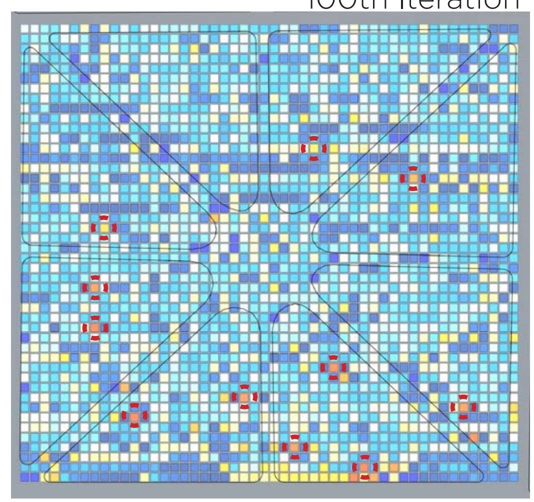
70th Iteration



100th Iteration(Alive Cells Only)



100th Iteration



1. Heat map showing freqency of cells over n Iterations

Cells with highest alive cell occurence

A hundred iterations are executed to specify the final result. The analysed area is 135m per 122m. The 2.5m size square cells are set in the cells grid. It gives 2300 cells which are to be analyzed. A total of 230,000 iterations are analyzed to give an interpretable result. First based on the output from the Ladybug analysis, The cells is registered with dead (black) and life (white) cells only. The red cells are alive cells that are within the pathway and will be tested for the probability condition. The red cell are not taken into consideration and were identified for visual purposes only.

Three general behaviours

Region A,B,C and F in the 35th iteration show a rapid popupation from the initial state . Intensive alive cell is observed at this region. This occurs when the cells are within a close proximity to the dead cells in the pathway, the alive cells were observed to flock together. However this behaviour did not continue in the 70th iteration, were the cells had moved and were more randomly distributed and sparsed except for region C which slightly had more alive cells within the proximity to the pathway at the 100th iteration. The concept of overpopulation and loneliness was observed in the behaviour of the cells. as they tend to favour a more evenly dispersed spread accrosss the site than concregate to one region.

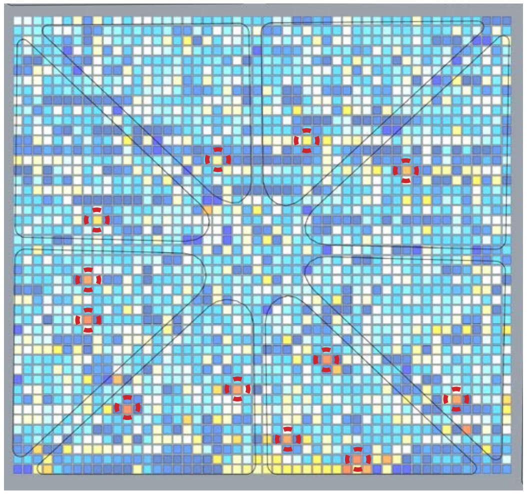
Region D,E,H and I in the 35th iteration showed little concenteration of life cells, there was no spontaneous generation of life and the cells were observed to move far away from the pathway in search of sustained life. This behaviour continued in the 70th and 100th iteration respectively as cells were relatively dispersed around the region with no core concenteration and bond with neighbours. This is analysed as the behaviour of cells in stasis, they manage to survive to the next iteration but do not gain any predominantly large numbers of alive cells within its region

At the 100th iteration, intensive life cell activity was observed within the boundary regions of C and F, this also maintained a close proximity with the pathway. It is observed that cells that congregate close to the pathway have a tendency of having intensive life activity. Other regions maintained a strongly dispersed cell behaviour with some regions becoming extinct.

In the heatmap which shows the life frequency analysis, the cell condition state are summed up for the first 100 iterations, The colours that tend towards red have the higher frequency count during the iteration process.

Further Development Pedestrian Simulation

CA Results to Pedestrian Simulation using PedSim Plugin



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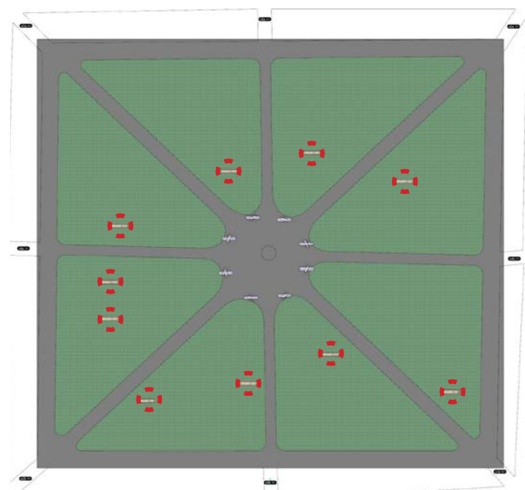
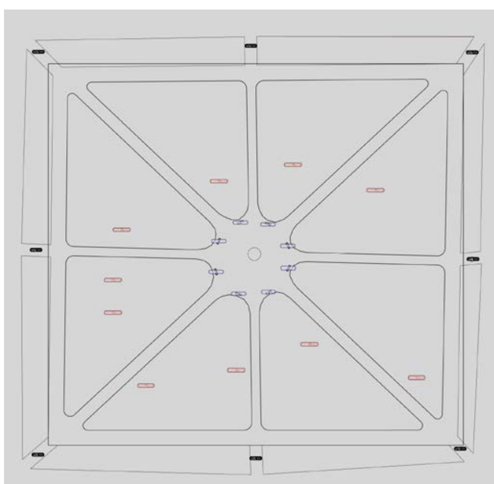


Cells with highest alive cell occurence become new points of interest for shade trees.



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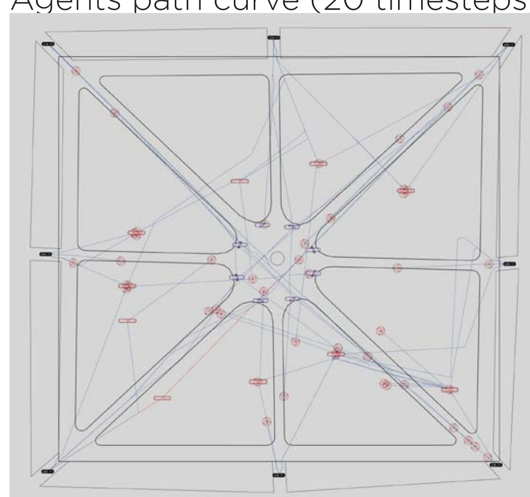
Agents path curve (20 timesteps)



Agent simulation Curve Path of Pedestrian movement with new points of interest as

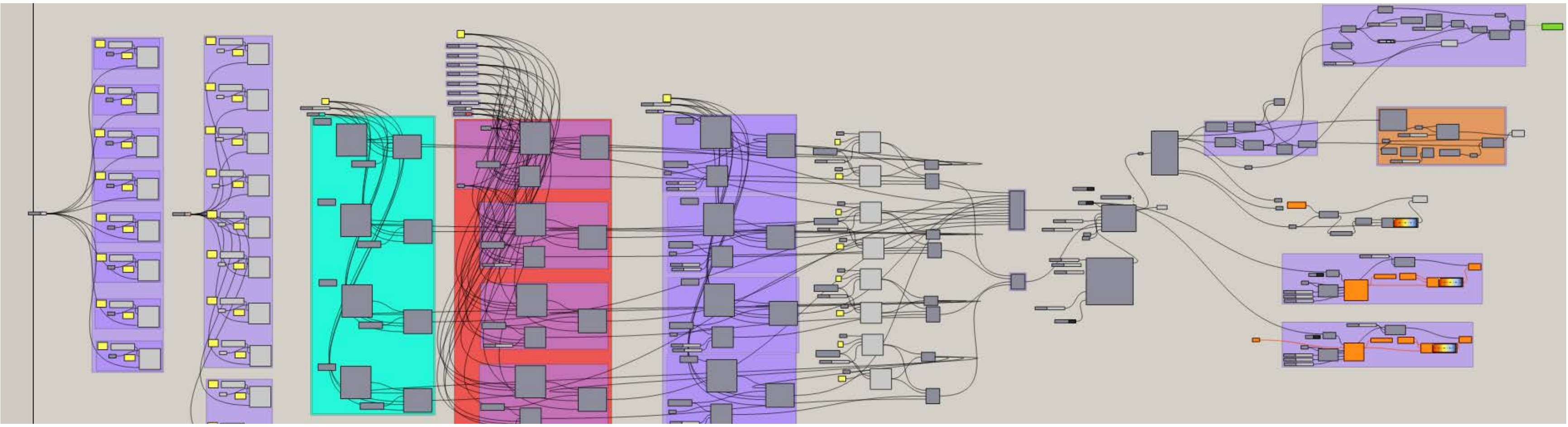
CA Results to Pedestrian Simulation using agent-based PedSim Plugin

As a result of the limitation of CA in visualizing natural movement of sytem due to its limitations to cells within a grid, PedSim, an agent based system is explored further to interprete the results of the CA algorithm, hence two generative systems are used in this study The Cellular Automata (CA) and Agent Based Modelling. One important step was to create person templates to delfine interest for each user group or person.Based on observation from a site visit, the general behaviour of pedestrians using the park were classified into 3.

1.) Pedestrians walking through the pathways to arive at the other side of the cityare given a blue colour

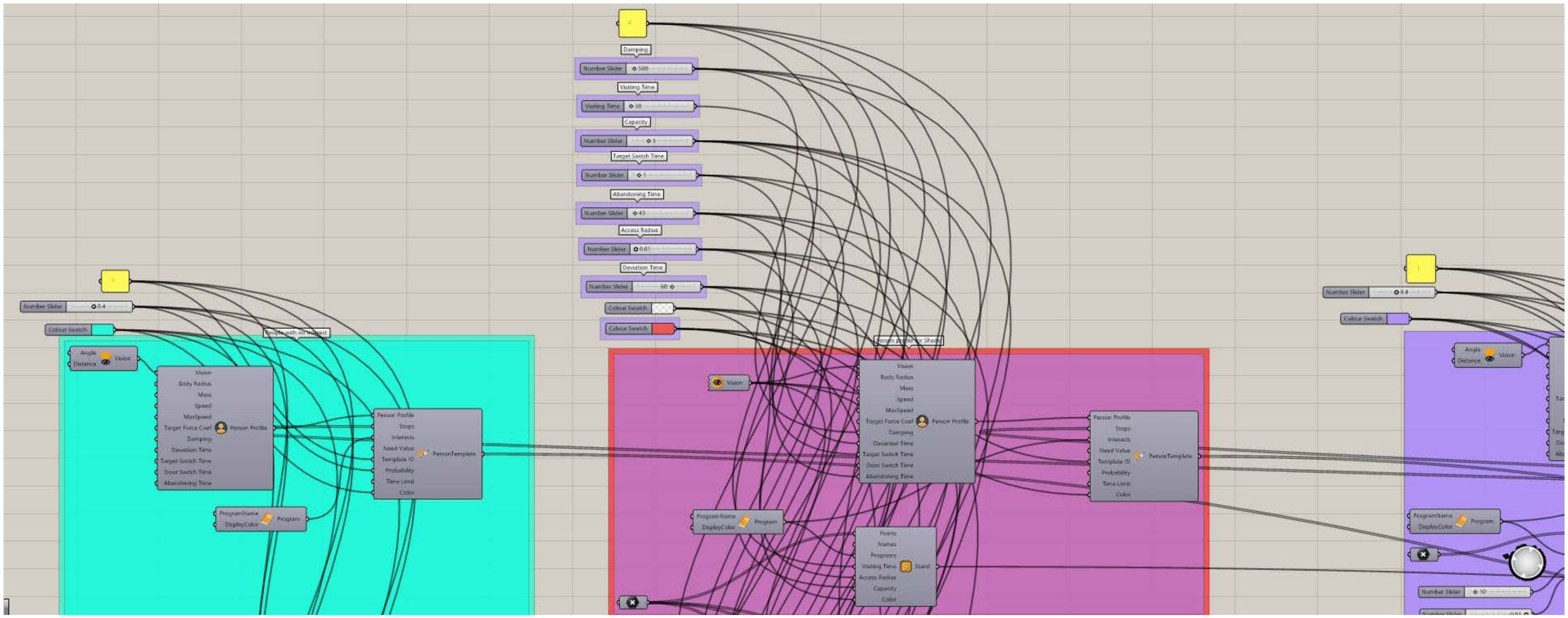
2.) Pedestrians, coming to sit down for a short time on the bench to enjoy the views of the park. This pedestrians willl wait a little at the benches and proceed to the exit, They are given a purple colour.

3.) The third are pedestrians interested in relaxing under the shade and would like to remain for a time duration(x) beofore making their exit. This pedestrain will try to find the nearest shade from them and will divert to another shade within good distance if peope are occupying the shade and the waiting time is longer than tthe time to his exit. These type of pedestrians are represented in red colour.



Grasshopper Simulation Setup in PedSim Plugin

Simulation Links



Person Template and Agent Behaviour Parameters

Link to Grasshopper Script and Simulation.

Link to Data Sets and Scripts : https://drive.google.com/file/d/1GcFtn_RUFodQT6EacXI-BjWXt4KS2NdE/view?usp=share_link

Link to Simulations : https://drive.google.com/file/d/14CsG9pGi_rYjvbi3zXaMq00EX5OJv8pj/view?usp=share_link

Conclusion

The project does not attempt to present a final solution, rather is an experimental attempt to interpret and describe the already explored context of Cellular Automata and Agent Based Modelling(ABM) in a small scale urban settign. This algorithm is developed as a means to predict optimal locations for new amenities in a small scale urban setting. In this project it has been used to predict the placement of shade trees but the methodology can be applied to different types of amenities in a public space. Further developments could be to make the system more Intelligent, the cells could have an intelligence that monitors and records its state history over its past iterations on a global scale and makes predictions with this embedded intelligence . Other rules and grid configurations(i.e Hexagonal Grids, Triangular Grids) for implementing new interest would also be interesting to explore and compare the results. This would clearly demonstrate the most attractive place in the region and would serve as a catalyst for further growth of the study. The project presents an approach to prediction of the optimal locations for shade trees in a park with a generative, self-organizing tool such as Cellular Automata.

References

Christiane M. Herr Dipl.-Ing. (*Arch), March.(2002) Generative Architectural Design and Complexity Theory*. Generative Art Conference 2002

Borong Lin_, Xiaofeng Li, Yingxin Zhu, Youguo.(2008) Qin. *Numerical simulation studies of the different vegetation patterns' effects on outdoor pedestrian thermal comfort*. Journal of Wind Engineering and Industrial Aerodynamics 96 (2008) 1707–1718

Christiane M. Herr, Ryan C. Ford.(2015) *Cellular automata in architectural design: From generic systems to specific design tools*. An International Research Journal Design & Engineering, Construction Technology, Maintenance & Management.

Paul Rendell. (2017) *Turing machine universality of the Game of Life*. Springer International Publishing, Switzerland

Nikolay Popov.(2010) *Generative urban design with Cellular Automata and Agent Based Modelling*. 44th Annual Conference of the Architectural Science Association, ANZAScA 2010, Unitec Institute of Technology.

Paweł Unger, Luís Romão. *Shape Grammars and Cellular Automata Based Tool for Prediction of Human's Behaviour in Cities.* Gdańsk University of Technology, Poland University of Lisbon, Portugal.

d.o.o, Yu Media Group. "Weather Atlas | Weather Forecast and Climate Information for Cities All over the Globe." *Weather Atlas*, www.weather-atlas.com.