HUMAN CROWD SIMULATION AS AN EVALUATION TOOL FOR GENERATIVE TEMPORARY SITE ORGANIZATION

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ABSTRACT

HUMAN CROWD SIMULATION AS AN EVALUATION TOOL
FOR GENERATIVE TEMPORARY SITE ORGANIZATION

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The advents in computational technologies enabled designers to produce data derived generic models in order to deal with complex design problems. One of the significant data regarding context of a project is the user experiencing the building and the site. Although crowd simulation algorithms have been used as accurate models in movie and game industry, when the computational cost concerned for complex architectural problems, these tools are not suggested to be used within/throughout in design process. Within the scope of this thesis a new model that integrates crowd behavior algorithm into the site generation model is developed based on Agent Based Modelling and Cellular Automata algorithms by introducing non-uniform cells into the field. In addition, the implemented tool is verified via two case studies: Lange Voorhout and METU Science and Technology Museum.

Keywords: Crowd Simulation, Agent Based Modelling, Cellular Automata, Quad-tree, Generative Model

ÖZ

ÜRETKEN ALAN ORGANİZASYONLARI İÇİN BİR DEĞERLENDİRME ARACI OLARAK İNSAN TOPLULUĞU SİMÜLASYONU

Kruşa, Müge
Yüksek Lisans, Mimarlıkta Sayısal Tasarım ve Üretim Teknolojileri
Tez Yöneticisi : Doç. Dr. Arzu Gönenç Sorguç

Eylül 2013, 50 Sayfa

Gelişen sayısal teknoloji ile tasarımcılara kompleks tasarım problemleri için veri tabanlı jenerik modeler üretme imkanı verilmiştir. Yapıyı ve alanı deneyimleyen kullanıcılar, projenin bağlamındaki bu önemli verilerden biridir. Topluluk simülasyon algoritmaları film ve oyun endüstrilerinde hassas modeller olarak kullanılmasına rağmen, karmaşık mimari problemler için sayısal yük düşünüldüğünde, bu araçların tasarım sürecinde veya tasarımın içerisinde yer alması tavsiye edilmemektedir. Bu tez kapsamında, topluluk davranışları algoritmasını (crowd behavior algorithm), alan üretim modelinde (site organization model) kullanan yeni bir model sunulmuştur. Bu model, "Agent Based Modelling" ve "Cellular Automata algoritmalarını temel alarak ve alan üzerinde düzensiz (non-uniform) gridler önermiştir. Ayrıca, üretilen araç, Lange Voorhout ve ODTÜ Bilim ve Teknoloji Müzesi Alanı olarak iki örnek alanda test edilmiştir.

Anahtar Kelimeler: Topluluk Simülasyonu, Agent Based Modelling, Cellular Automata, Quad-tree, Üretken Model

To my advisor, my family and my friends

TABLE OF CONTENTS

LIST OF FIGURES

FIGURES

CHAPTER 1

INTRODUCTION

"Generative Design is a morphogenetic process using algorithms structured as not-linear systems for endless unique and un-repeatable results performed by an idea-code, as in Nature" (Soddu, 2011).

Generative Design becomes already an essential part of the architectural practice enabling to explore complex design problems never experienced before. The advance in computational technologies and the sophisticated algorithms allow designers to develop models embracing various complexities of design problems. Hence today computational design is not only a medium of design inquiry but also it is a medium of evaluating the potentials of the design. Hence the data to be incorporated in such computational models becomes very crucial affecting the quality and precision of the design process and the product i.e. artifice. Analysis is not only seen as verification of design, but also acknowledged as an integrated part of the generative process to produce data for computational models and this approach can be summarized as *"Form follows data", data follows analysis.*

The most significant data to be incorporated in architectural design is the user experiencing the building or the site. As a part of this experience, movement within the building or in the site becomes an important input to be considered in the generative design process. Hence, Human Motion Analysis, which analyze the context and simulate the behavior of the people in the site,is one of the significant data that should be an integral part of the design process from the very beginning.

In this thesis, author presented a new pre-design tool which is based on a model developed for a site generation under the impact of crowd. Considering both the developer and the user are defined as designers from the very first beginning, aim of the tool is stated as producing generative and adaptive space organization with respect to crowd simulation model. The initial model is developed for the case of Lange Voorhout (The Hague) in the scope of a Graduation Project at TU Delft as a part of the joint program of "METU-TU Delft Computational Design and Fabrication Technologies in Architecture". The assigned site of the project is defined as a "Living Environment" which describes the site as it can change itself in time with respect to the behavior of the crowd experiencing buildings and events, and vice versa. Initial approach to the model is occurred with respect to changing nature of the site. Hence, human motion analysis is integrated into model as generation data. Then, in the scope of this thesis proposed model is extended to develop a generic pre-design analysis tool for the design of new site generations having similar requirements with Lange Voorhout. Proposed model aims at providing organization schemas, which reflects the relation between crowd behavior and site organization.

While the Model is developed in this context, generative approaches such as Shape Grammar, Space Syntax, and Cellular Automata which are common for site organization have been examined. For human motion analysis, crowd simulation models which are based on Agent Based Modelling have been studied. As a result of these two research , Crowd Simulation and Cellular Automata algorithms have been considered together to produce an integrated model regarding context and specific precision. In the algorithm of the model, Cellular Automata and Agent Based Modelling has been implemented together with customizations.

This thesis aims to describe the proposed model in five chapters. The second chapter includes definitions, and related examples of Cellular Automata (CA) and Agent Based Modelling (ABM). The third chapter gives detailed information about the structure, algorithm, initial assumptions, parameters and possible outcomes of the proposed model, and author's customization of CA and ABM algorithms. In the fourth chapter, implementation of the proposed tool into computational medium is described in detail. In addition, advantages and limitations of both implemented model and computational medium are discussed. The fifth chapter is focused on two case studies that the tool is applied on in order to verify proposed model: Lange Voorhout, and METU Science and Technology Museum Area. Finally, in the last chapter, a brief summary of the study with contributions, limitations and recommendations for future work is stated.

CHAPTER 2

GENERATIVE SITE ORGANIZATION SYSTEMS AND CROWD SIMULATION METHODS AS AN EVALUATION TOOL FOR DESIGN

2.1. Introduction

The model of open air temporary organization problem has been of concern and a new tool is developed based on two well-known algorithms Cellular Automata (CA) and Agent Based Models (ABM) are versatile and commonly used algorithms among designer, game developers, and mathematicians, but in this thesis CA and ABM has been revisited in the context of open air temporary organization and the related literature is presented in this chapter.

The use of generative design tools in various fields have becomes a common practice, allowing designers to explore design problems with their constraints, parameters to obtain plausible solutions in a defined domain regarding theory and practice. Urban design as a broad discipline tackling with different levels of complexities in different scales can benefit from such tools. Several studies, implementations and projects can be seen in practice.

Open space organization has always been the concern of designers, citizens and rulers since the very first settlements and people have started to experience, organize and alter their environment. Although the idea of urban planning exists even in the first settlements, "urban planning" was evolved into "urban design" with the first Urban Design Conference held in Harvard Graduate School of Design by Josep Lluis Sert in 1956 (Mumfor, 2008). Then the foundation of Urban Design Department at Harvard University acted as a trigger to accelerate the development of the field. The very first products of the urban design movement were published as a critique on modern urbanism such as "The Death and Life of Great American Cities" by Jane Jacobs (Jacobs, 1961). As a continuation of this approach, urban complexity theory is proposed by Christopher Alexander, Michael Batty and Bill Hiller. Complexity theory claims that urban spaces should be considered as multilayered structures which require data processing dealing with all layers.

As a pioneer of this theory, Christopher Alexander (Alexander, Ishikawa, & Silverstein, 1977) (Alexander C. , The Timeless Way of Building, 1979) has introduced the terms; pattern language and urban pattern and proposed a model based on city complexity, in 1987 (Alexander, Neis, & Ingrid, A New Theory of Urban Design, 1987). In this model in order to deal with complexity, possible rules have been proposed and applied in the case of San Francisco. However due to the insufficient technology in late 80s, it took a decade for the first examples, which deals with multilayered systems of urban organization, generation and emergence has appeared as suggested by Alexander.

Rapidly developing technologies also support Agent Based Modelling (ABM) and make it possible to be put in practice. Initially, ABM was proposed by Reynolds (Reynolds C. W., 1987) in order to simulate bird flocks. The significance of this model for generative urban design is not only its potential to simulate human crowds, but also its capability to support the integration of urban design with generative algorithms. Therefore this movement not only integrated with models derived from different fields such as Shape Grammar and Cellular Automata, but also created its own analysis method such as space syntax as shown in Figure1.

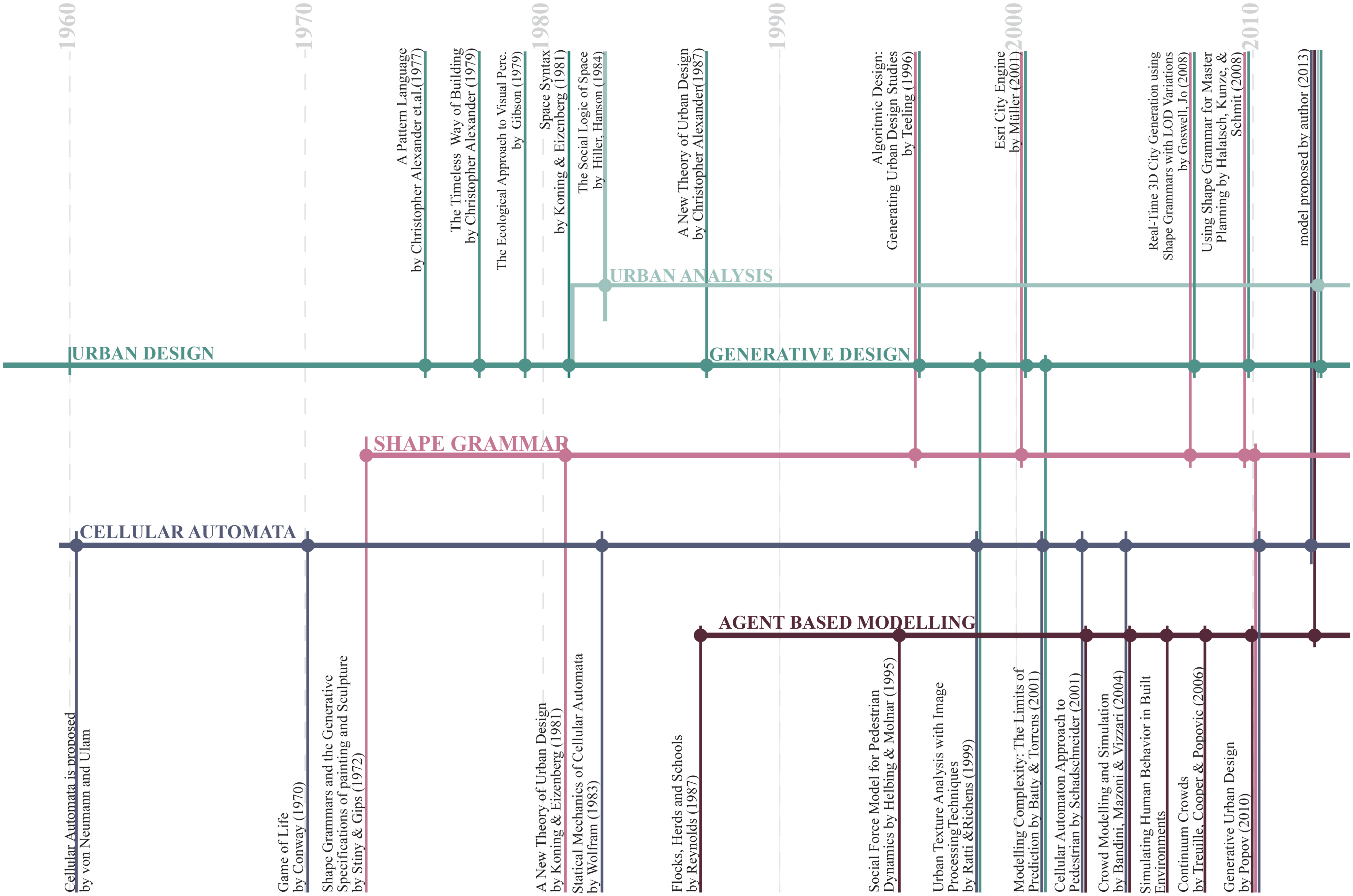

Figure 1 : Timeline of Urban Generative Approach

2.2. Cellular Automata as a Site Organization Algorithm

The possibility of dealing with the complex urban patterns as a composition of relatively simpler sub-spaces interacting with each other and the environment makes Cellular Automata (CA) popular among architects and urban designers to explore complex growth and generation patterns.

2.2.1. CA Algorithm

Although the mathematical model of CA was originally proposed by John von Neumann and Stanislaw Ulam (A.H.Taub, 1963), as a matter of fact, some traditional settlements in Africa such as Borobudur temple, Prambanan Central Java, Sukuh Temple Mendut Temple and Cangkuang Temple in Indonesia have shown the basic features of CA (Situngkir, 2010). That recalls to mind that even before the algorithms of Neumann and Ulam, mathematical model of CA has emerged as a natural reflection of design approach.

CA algorithm was initially proposed as a kinematic model of self-reproduction observed in living organisms John von Neumann and Stanislaw Ulam (A.H.Taub, 1963). Then the model was simplified by abstracting the reproduction patterns in 2-dimensional Euclidian space which is modeled as composed of identical infinite square cells. Then, rules, based on neighborhood definition of 4 cells, were defined for cells determining the behavior of each and every individual cell.

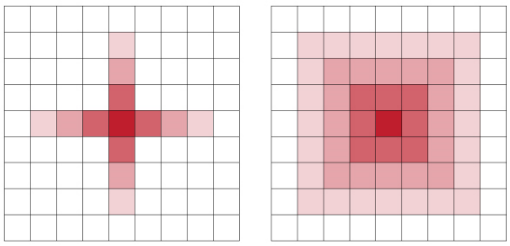

Figure 2 : (Left) Von Neumann definition for neighborhood, (Right) Moore's definition for neighborhood (drawn by author)

Later, Moore proposed a new neighborhood concept which defines neighborhood by eight cells around the initial cell of interest (Moore, 1962). The model having 9 neighborhoods was proved to be more accurate than the model proposed by von Neumann et.al.

In 1970, John Conway's new game called "Life" which is known as "Game of Life" was introduced and attracted attention into CA. It was developed as a simulation game that resembles life itself with genetic rules and classification of cells as survivals, deaths, and births and it has been constructed based on Moore's neighborhood definition. The most popular and stable algorithm of the game is Glider's Gun which is briefly illustrated in Figure 3.

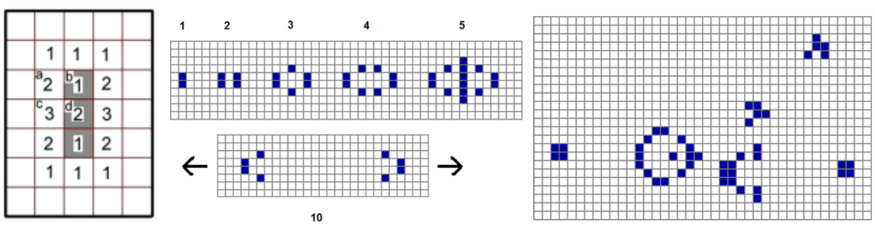

Figure 3 : Neighborhood definition by Conwey and some of the rules of Glider's gun and one moment of the model (Bays, 2010)

Later on, this theory was elaborated and detailed with many publications by Stephen Wolfram by adapting CA into many other disciplines in order to explore natural phenomena such as evolution of spiral galaxies, kinetic aspects of phase transitions, and non-linear chemical systems and algorithms to design kinetic structures (Wolfram, Statical Mechanics of Cellular Automata, 1983). The implementation of CA in different fields such as simulations in material science (Raabe, 2002) (Zheng, Raabe, & Li, 2012), in ecological modelling (Hogeweg, 1988), and in computer science (Dennunzioa, Formenti, & Provillardb, 2012) is still an ongoing study. Moreover, three dimensional models are created using CA algorithm such as Pseuda 3-dimensional algorithm by Stephen Wolfram (Figure 4) (Wolfram, A New Kind of Science, 2002).

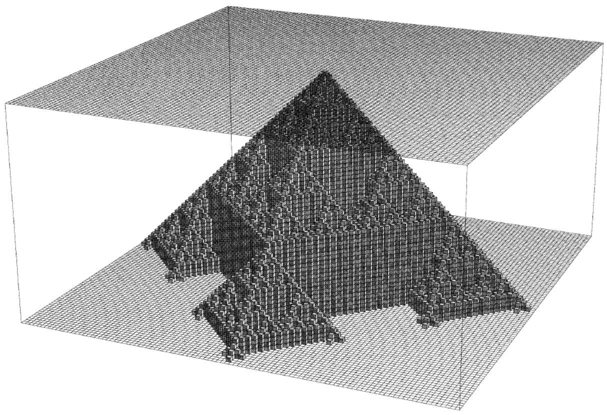

Figure 4 : Pseuda 3-dimensional algorithm by Wolfram) (Wolfram, A New Kind of Science, 2002).

2.2.2. Cellular Automata and Space Organization

CA has been used as an analysis and simulation tool in science since 1980s, whereas adapting CA to architectural design (mostly urban design) started to occur in late 1990s. The first implementation of CA in Architecture and Urban Design can be seen in Gallion's statement:

> *"An urban area can also be defined as a composite of cells, neighborhoods, or communities where people work together for the common good" (Eisner, Gallion and Eisner 1993)*

CA in dealing with high population density and long-distance spatial interactions in special organizations were mostly considered as a low performance approach due to the difficulties in computational technologies in the late 90s (White 1998). However the rapid developments of computational technologies and pioneering projects makes CA very popular and in 2011 it has already been accepted as an effective modelling approach in the research of urban systems (Kim and Batty 2011).

As one of the pioneering projects, Dynamic Urban Evolutionary Modeling (DUEM) is proposed by Xie in 1996 (Xie, 1996). With this model, the author integrated cellular space, model space, and geographic space and levels running within these spaces, and as a result, simulated urban growth (Figure 5) on cellular based approach with respect to growth field, neighborhood, and regions (Figure 6). With this integration and complex model, the author proposed a new tool modelling complex systems, and human and social systems.

FIG. 6. The External Constraint Regions: "Natural Areas." The natural areas are derived from the Map of Perodical Dispersion of Constructions by adopting the GIS Technique of "surface smoothing."

Figure 5 : Simulation of growth according to algorithm (Xie, 1996).

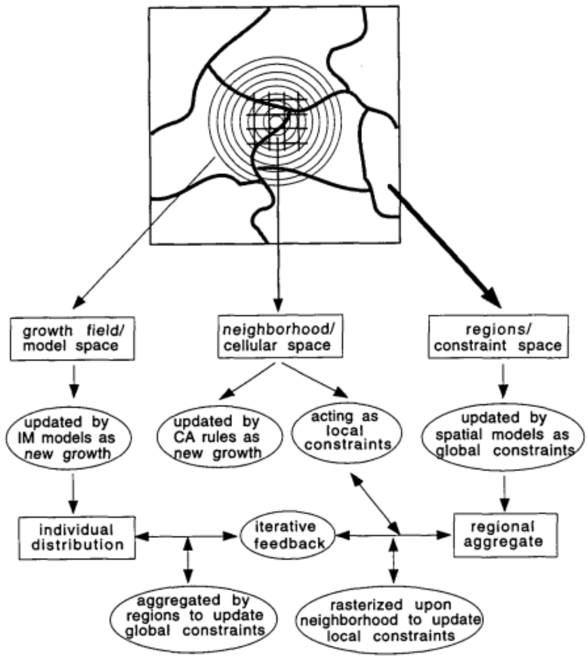

Figure 6 : Relation flowchart of growth field, neighborhood and regions (Xie, 1996).

CA was started to be used as an analysis and simulation tool for urban planning in the 1990s. At the same time it was adapted as a supporting algorithm in order to analyze specific features of the site. For instance, in 1999, in the research of Carlo Ratti and Paul Richens (Ratti & Richens, 1999) CA has been integrated to an urban analysis tool based on Image Processing and used to simulate the diffusion of pollutants in an urban context as it can be seen in Figure 7. It has been stated by Ratti and Richens that Cellular Automaton approach is prominent tool to work with image processing tools when pixels are seen as cells. Also the author claims that dividing the model environment into subspaces reduced the computational cost of the algorithm and enables the model to have further processes.

Figure 7 : Urban ground map showing built and unbuilt areas (left) and urban Digital Elevation Model – DEM (right) for a selected case-study in central London (Ratti & Richens, 1999)

As one of the pioneers of the complexity theory; Batty and Torrens (Batty & Torrens, 2001) introduced a new model to generate possible growth patterns for urban areas with the Cellular Automaton approach. In this research they defined seven rules including initial cell decision, cell tendency about center of location and roads for accessibility and death of aged cells (Figure 8). Regarding these rules, the proposed model became capable of simulating emergence and growth of urban settlements.

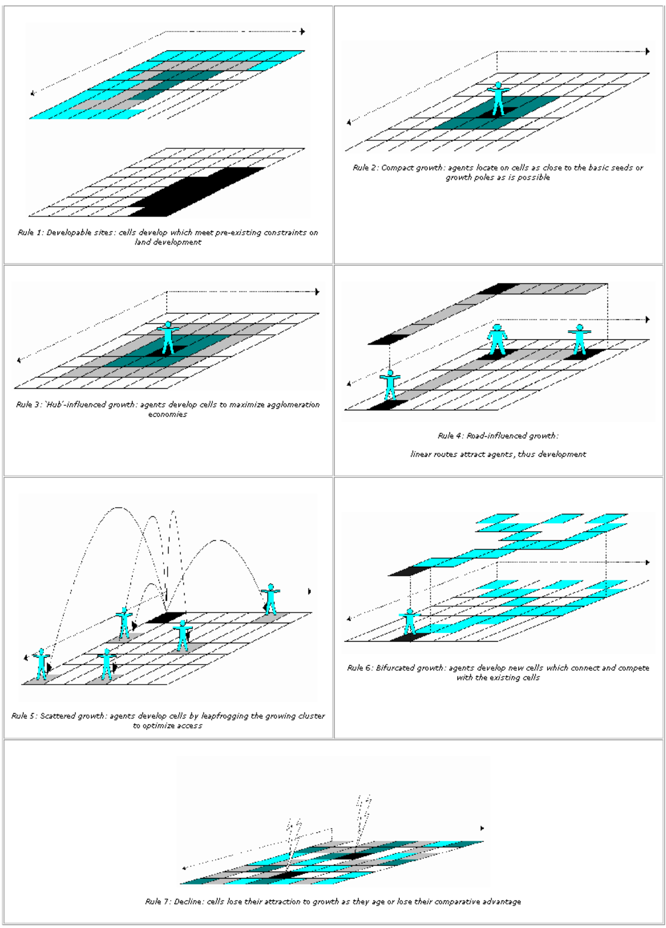

Figure 8 : Seven rules used by agents in Batty and Torrens's CA Model (Batty & Torrens, 2001)

2.3. Agent Based Modelling

As one of the models used in analysis and generative algorithms, Agent Based Modelling (ABM) was introduced in 1987 as a simulation model and was developed by mathematicians, and engineers, and also adapted into several fields in time. ABM was first introduced by Reynold while working on bird flocks, in order to simulate a reliable and efficient crowd behavior model by claiming that it is necessary to have a behavioral and perception model of the individuals (Reynolds C. W., 1987). Rules defined by Reynolds are separation, alignment and cohesion (Figure 9).

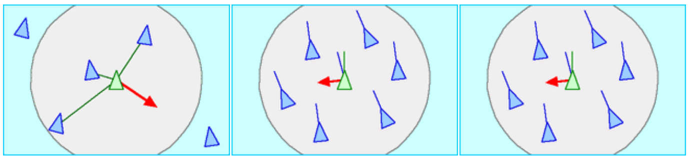

Figure 9 : Swarm Behavior rules based on Boids algorithm: Seperation, Allignment, and Cohesion (Reynolds C. , 2000).

Although it seems that the theory behind this methodology is quite reliable and appropriate for crowd simulation, technology behind it should be powerful to run this algorithm in real-time. For this reason significant examples on this field has been seen in movie and game industry and examples in architectural spaces are relatively rare due to the limitations of computational power employed in design (Reynolds C. , 2000).

2.3.1. Agent Based Modelling and Space Organization

Besides adapting ABM into different fields, it has been developed by others in the following years and new models have been proposed. As one of these models, Social Force Model, has been proposed by Dirk Helbing and Peter Molnar to simulate Crowd Simulation in 1995 and developed by them and colleagues. They claim that the "social forces" that define the pedestrian motions, emerged from both personal environment and internal motivations in order to perform their movements (Figure 10) (Helbing & Molnar, 1995).

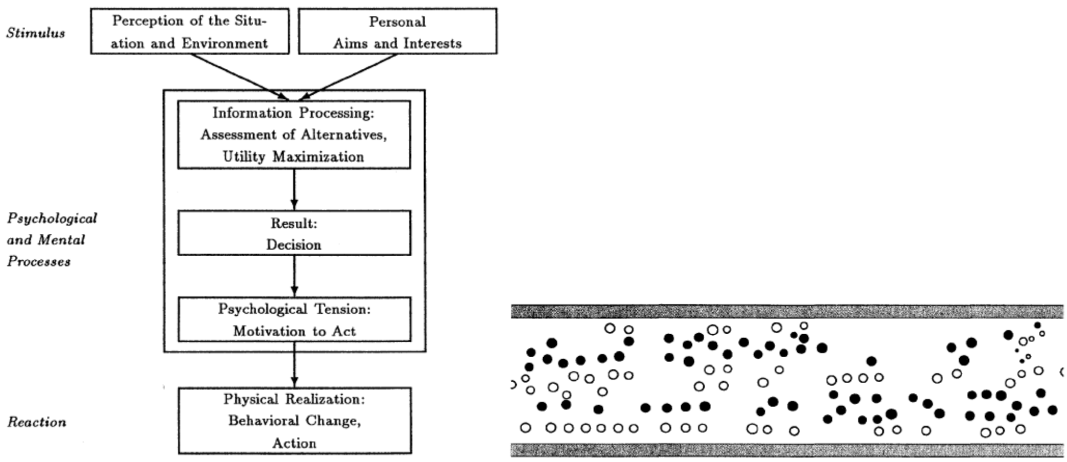

Figure 10 : Schematic representation of process and one example on critical pedestrian density (Helbing & Molnar, 1995).

In their further study, Helbing and et.al extended their algorithm into a model named "active walker" that simulates pedestrian trail system on a site in order to predict optimal path for urban planning. In this model inputs are listed as human motion, orientation and the environment occurred during the movement. Resultant paths are simulated in Figure 11.

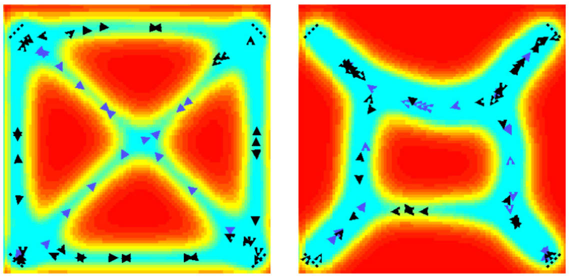

Figure 11 : Walking directions of pedestrians

In addition to being a space generation and analysis tool, CA has been used as a crowd simulation tool which having discrete cells with one or zero agents and moving them through neighbor cells towards the goal, as can be seen in Schadschneider's research on Pedestrian Dynamics (Figure) (Schadschneider, 2001). Model has been developed based on ABM algorithm applying on Cellular Automaton Euclidian grid system.

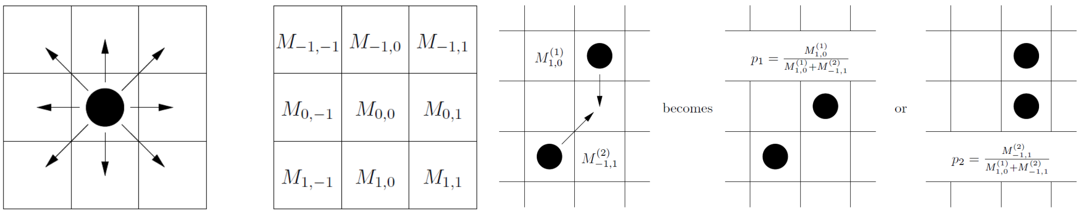

Figure: A particle, its possible transitions and the associated matrix of preference and Solving conflicts according to the relative probabilities) (Schadschneider, 2001)

As an extended research of Schadschneider, Bandini et. al proposed a crowd simulation model based on Multi Agent System (MAS) with respect to Situated Cellular Automata (Bandini, Manzoni, & Vizzari, 2004). This research has been focused on agents' perception, deliberation and action. In this method, after bidimensional model (Figure 12) is created as the first step, agents' behavior has been placed in the environment according to local environment and possible actions.

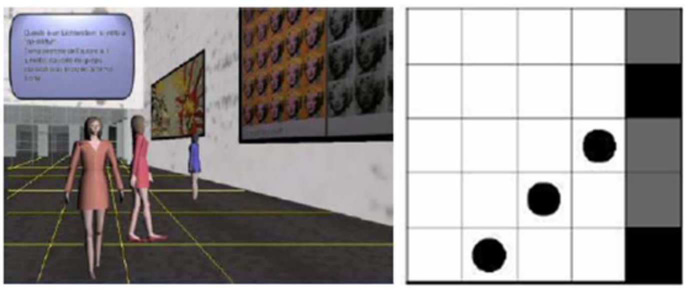

Figure 12 : Bidimensional abstraction of a 3Denvironment (Bandini, Manzoni, & Vizzari, 2004)

In 2005, Wei Yan, and Yehuda Kalay (Yan & Kalay, 2005) has proposed a new model based on a behavioral analysis of human crowd on a built area. Algorithm that was developed based on tracking the people in different sites (Figure 13) gives possibility to simulate the experience of the agents (Figure 14) so it will create a tool for designers to test their proposals before it is actually built.

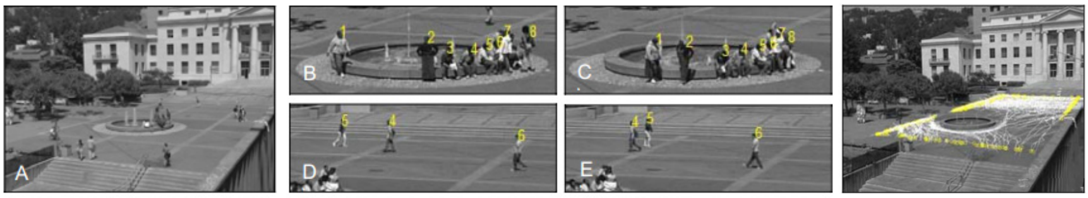

Figure 13 : Analysis based on tracking people and motion paths derived by tracking (Yan & Kalay, 2005)

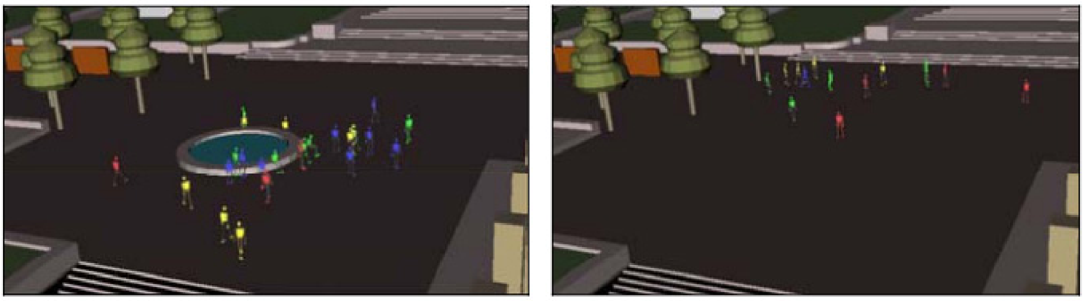

Figure 14 : Simulated users on site with different features (Yan & Kalay, 2005)

In another example, research of Treuille et al. has produced a continuum algorithm including multi-agent system having one common goal and as a result having realistically moved agents in an area. It has been stated that while it is possible to have an agent based system having each individual decisions and as a result to have real crowds, it has a huge computation cost. Thus algorithm that is proposed was a large crowd motion synthesis model with respect to global path planning and local collision avoidance (Figure 15) (Treuille, Cooper, & Popovic, 2006).

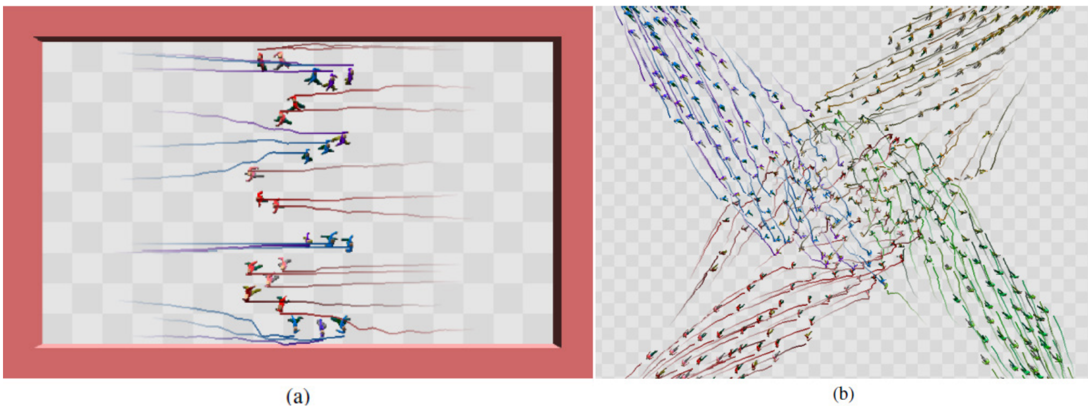

Figure 15 : (a) Two groups pass, naturally forming lanes. (b) A vortex forms as four groups cross (Treuille, Cooper, & Popovic, 2006).

ABM has been used with generative algorithms and helps to provide an interdisciplinary tool which works more efficiently in terms of computational time. One of these type of models has been developed by Popov (Popov, 2010) with the name of "Generative Urban Design with Cellular Automata and Agent Based Modelling". Proposed hybrid model including these algorithms, is applicable on unplanned settlements to generate possible design variation (Figure 16). However, according to the author, due to the limitation of CA's grid nature, model has symbolic and abstract outputs.

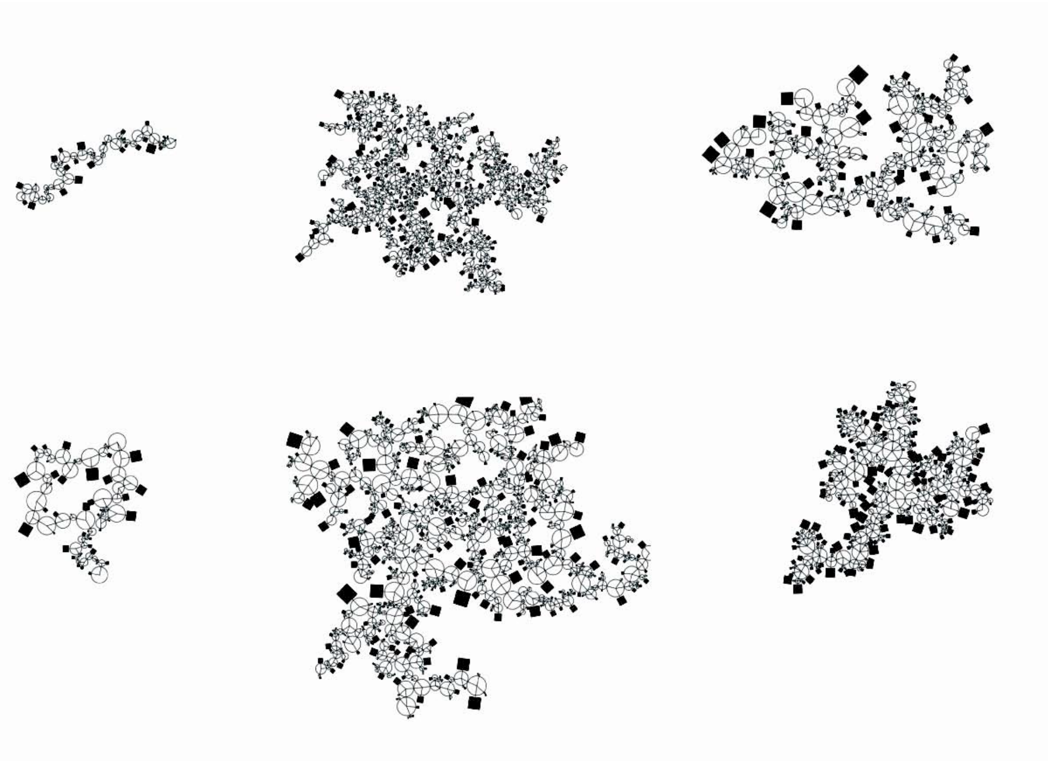

Figure 16 : Various Spatial Morphologies created by Popol's algorithm (Popov, 2010)

Consequently, previous studies on generative space organization, analysis and simulation algorithms reveal that although genetic algorithms have great possibility on analyze, and simulate emergence and growth of space organizations, for an extended research on generative design of site organization, models consisting of these algorithms become essential. Hence, in this thesis, a hybrid model is proposed for generic site organization modelling the site and the crowd movement together feeling and evolving each other based on Cellular Automata and Agent Based Modelling is presented.

CHAPTER 3

NEW PROPOSAL FOR CROWD SIMULATION AS AN EVALUATION TOOL FOR SPACE ORGANIZATION

3.1. Introduction

> *"In nature it is only the genetically coded information of form which evolves, but selection is based on the expression of this coded information in the outward form of an organism. The codes are manufacturing instructions, but their precise expression is environmentally dependent. Our architectural model, considered as a form of artificial life, also contains coded manufacturing instructions which are environmentally dependent, but as in the real world model it is only the codescript which evolves."* (Frazer, 1995)

As mentioned previously, in this study, a computational model was initially developed for a graduation project in TU Delft, aiming at designing a temporary settlement for exhibitions, and sales in Lange Voorhout in Den Haag. The computational model has been further elaborated to support the design of any open air temporary space including dynamic human movement patterns with respect to urban magnets (attraction points, events, and buildings), obstacles and basic swarm rules.

Previous studies on site generations show that in order to provide conventional model for designers, methods have been integrated not only from the field of architecture but also from different fields such as biology, computer science and mathematics.

The algorithm used in the model combines crowd simulation for a given site taking into account of the site conditions as constraints or objectives, and Cellular Automata (CA) to generate the possible organization schemas. The conventional CA algorithm has been modified within the scope of the present study, by using non-uniform grids generated by quadtree division algorithm. Quad tree algorithm which can be used for image processing, non-uniform meshes includes a tree with nodes having four children and each children has possibility to have subdivision. These subdivisions is based on one principle which is "split squares until each square contains ≤ 1 point (Buchin, 2013).

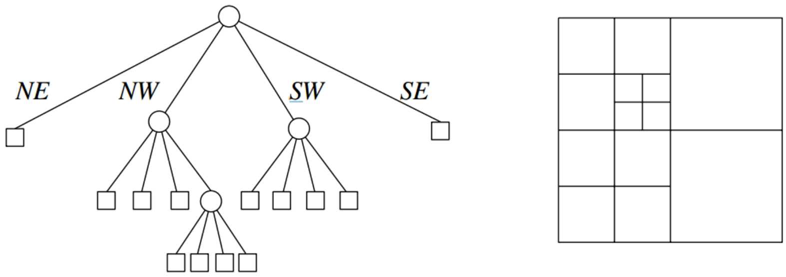

Figure 17 : General structure and basic visualization of quadtree algorithm (Buchin, 2013)

The non-uniform grid system generated as a consequence of the movement paths allows the model to respond to temporal changes that may occur in movement patterns or changes in the site conditions and thereby resulting in new organizational schemas.

3.2. The Model

The model presented in this study, is based on basic principles underlined in the Cellular Automaton algorithm with non-uniform quadtree cells and Crowd Simulation modelling the possible human movement patterns.

The general structure of the algorithm is shown in Figure 18.

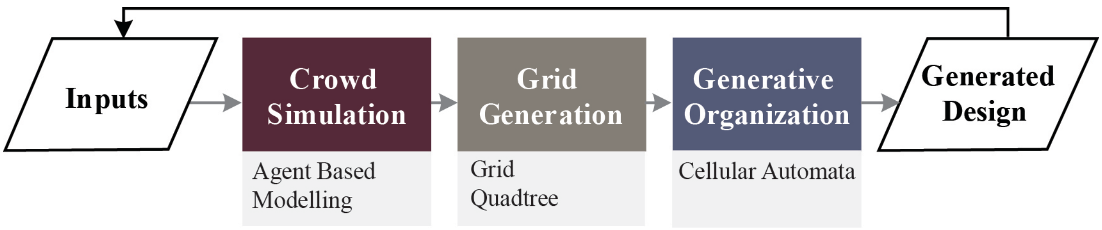

Figure 18 : Basic Structure of the Algorithm

In the development of the present model, it is aimed to provide a fast and a simple computational tool with low computational cost enabling designers to explore various configurations of the temporal organizations in early design phases. The model has been developed based on the following assumptions.

First, the site should be well defined and boundaries should be known. And in the model, this boundary condition is achieved by introducing polylines to the site. The site is presumed as two dimensional and any topographical change has been ignored. Secondly, it is assumed that each site has at least one direction for pedestrian movement. These directions may already exist within the site or can be defined by the designer. Pedestrian movement is assumed to be in an axial direction and is defined in the model as curve(s). Third assumption is based on modelling and behavior of the people. People experiencing the site are defined as agents with reference to swarm behavior, and they are simplified as points in the model. Assumptions regarding possible population of agents, their initial distribution on the site, and their density are determined by the designer in the model. These assumptions are provided as inputs to the model via numerical data. It is also presumed that the majority of the people within the site will naturally follow the major movement direction(s). Hence, natural directions of agents are assumed to be dependent on major movement axis. The rest of the crowd will diverge from majority as being attracted by crowd-pulling components such as entrance of buildings and event locations. Crowd pulling components are defined with points in the proposed model. Also, swarm behavior aspects like obstacle and collision avoidance for agents are included in the algorithm.

Moreover, the CA algorithm has been extended to include crowd movement and thus its adaptability has been improved considerably. In this course, instead of using conventional grid system, the site has been divided into nonstandard grids produced by quad tree algorithm and movement paths. The algorithm to simulate crowd movement within the site is based on swarm behavior which is originally developed to simulate behavioral patterns of bird flocks, ant colonies and such.

3.3. Crowd Simulation Algorithm

Crowd movement analysis and simulation have been subject of research for various fields such as urban analysis, computer science, psychology, transportation and game industry. The analysis methods and the resulting models may have different levels of precisions regarding the fields' requirements. In the context of present study, since it is aimed to have low computational cost and a fast simulation tool, crowd simulation algorithm is simplified as follows:

- The simulation of the crowd movement patterns within the site should include the effects of the attractive and avoidance zones, obstacles, collision on agents' movement in order to redefine the possible movement path,
- Movement paths are derived according to given conditions in the site and any change in the given conditions can be incorporated by the model.

➢ In the analysis, designer should define:

- The attractive buildings, their zones and impact area
- Movement axis, pedestrian road or any flow axis which has access from its surrounding for people.
- Obstacles such as, trees, pavilions, buildings

➢ Besides, it is also aimed to provide a compatible interface allowing data exchange between different CAD programs in order to provide flexibility and compatibility for the model.

3.2.1. Simulating the Crowd

As it is stated above, the crowd movement pattern is modelled by using swarm algorithms proposed by Reynolds. However, since the model aims to be low computational cost model, certain behavioral aspects like psychological and social behaviors are excluded within the context of present study. The algorithm aims to be a predesign tool which will help designer to support his design decisions and explore site conditions providing precise enough but low computational cost tool.

In order to construct crowd behavior model for a part of a space design tool, following emergence and swarm behavior aspects has been analyzed, reinterpreted and remodeled.

Populating Agents and Defining the Initial Movement Vectors

It has been assumed that since each site has at least one movement direction, which has been defined by designed vehicular or pedestrian road or observable in-between spaces, agents have been populated with respect to this movement axis/axes. Model has been constructed firstly by populating various number of agents along the axis in specific range. Each site has various properties and need. Hence number, range and density of population decision has been made by user/designer.

Since it is assumed that the agents are following the predefined paths on a given site, the movement has been guaranteed by the following mathematical relations. Each path has been represented by a curve and tangent of the curves determine the directional vectors followed by agents.

Then, considering the opposite direction movement, half of the agents have been chosen randomly and their movement directions are reversed. The main movement vector regardless of the attractors and obstacles, defines the regular movement of the agents (Figure 19). For each iteration, tangent vector is recalculated for each agent so that agents to adapt to possible changes in the curvature of the major axis.

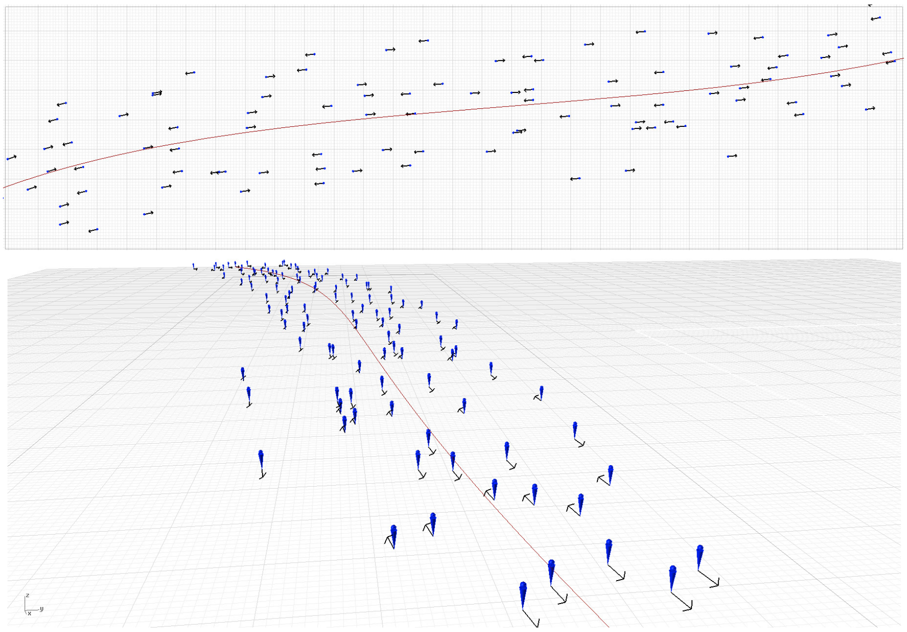

Figure 19 : Top and Perspective view of Agents and movement vectors with respect to an axis on the site

Influence of the Attractors (Magnets of the Site)

When the behavior of the people on the site is analyzed, it is seen that giving attention to an attractive point could cause agents to diverge from path defined by major axis which is unlikely to occur in animal swarms. Thus, in addition to having an axial movement, project has included attraction points, their zones and influence of these points are initially defined by the designer and employed as input to the algorithm. (Figure 20).

The algorithm that evaluates this data is as follows:

- A ratio of the agents pass through the site following the main axis without any distraction by the attractors. These agents are denoted as "rebels" in the algorithm and this ratio is pre-defined by the user as a numerical data depending on the function or intended use of the site.
- In each iteration, agents are checked if they are in an attracted area or not. If they are, then they move through that attractor point with respect to their previous axial movement. It is assumed that agents change their directions smoothly while attracted to point of interest as illustrated (Figure 21). This movement is shown by $\overrightarrow{V_{directional}}$ Equation 1 where V_{total} is resulting movement vector of the agent, $d_{toattractor}$ is distance between agent and the attractor, $\overrightarrow{V_{axial}}$ is axial vector depends on major axis, n is user defined numeric value defining the smoothness of divergence, and $\overrightarrow{V_{directional}}$ is directional unit vector from agent to attraction point.

$$\overrightarrow{V_{total}} = (d_{toattractor}) * \left(\overrightarrow{V_{axial}}/n\right) + \overrightarrow{V_{directional}} \qquad \textit{Equation 1}$$

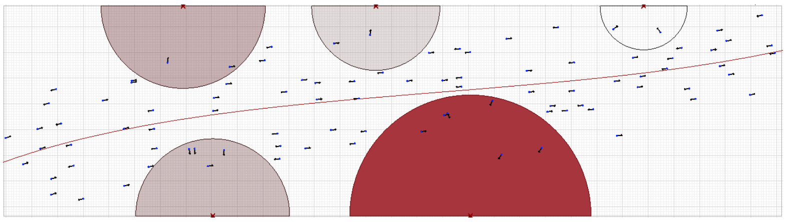

Figure 20 : Determination of attraction zones and agents influenced by these zones (drawn by author)

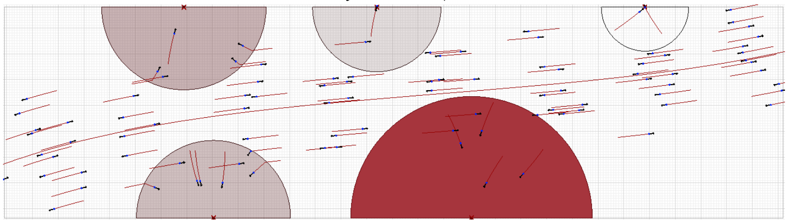

Figure 21 : movement paths and vectors of agents according to movement axis and attraction zones (drawn by author)

Avoiding Obstacles:

In many cases the site to be designed includes obstacles like trees, statues, small buildings, pavilions interfering the movement of agents. Hence the collision with such obstacles should be avoided and yet some of these obstacles can be the point of interests, which agents would like to visit resulting in a change of the path, they follow which are important in order to reveal the influence of obstacles on the movement.

Obstacle avoidance module developed within the model is based on the rules given below:
Obstacles located on the site have been redefined as circles inside the model. Direction of the agent is changed in the circumstance of encountering with an obstacle. This change in the

direction of agents is calculated based on calculating the tangent vectors between the agent and the obstacle. Direction vector of the agent is replaced with the tangent vector, which has smaller angle with the initial target vector, until the agent leaves the obstacle zone. If an agent enters obstacle zone target vector and tangent vectors are calculated and compared at each iteration. Influence of the obstacles on movement path is shown in Figure 22.

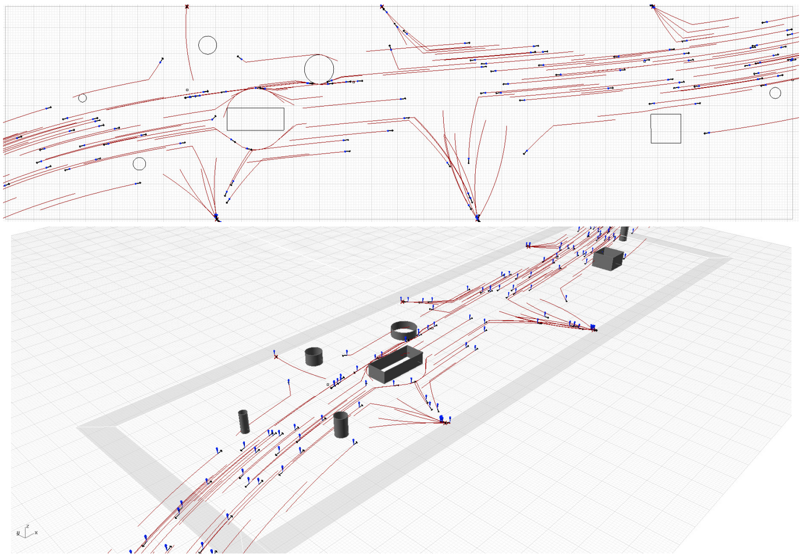

Figure 22 : Influence of the obstacles on movement vectors (top and perspective view) (drawn by author)

Avoiding Collision:
Since collision avoidance among agents is a significant issue for real time crowd simulation especially in game industry and visualization, algorithms developed in those fields have complex structure to deal with collision. On the other hand, in this proposal, a simplistic approach is followed to avoid agents' collision throughout their movement and can be defined as: "If two agents' movement zone intersect with each other, they will both change their direction with an angle defined by user."

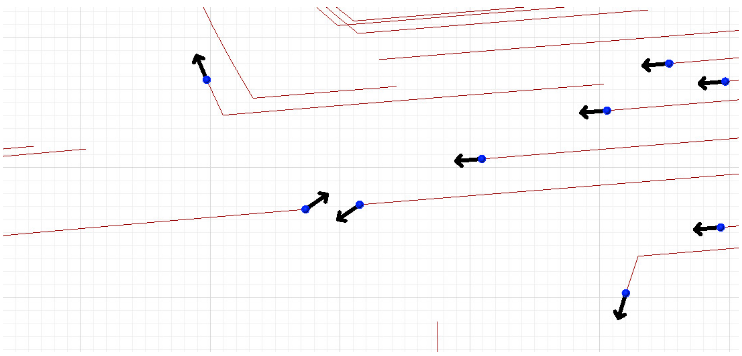

Figure 23 : Vector display in the case of collision (drawn by author)

Whereas agents avoid collusion, there is a possibility to crash into an obstacle area. Hence changing direction has requires a second test for obstacle avoidance. If there is a collision into an obstacle, then model forces agent to move on the edge of the obstacle.
Therefore, crowd can be simulated on site and movement paths has been derived by populating agents on design area, defining major movement axis, and determining user defined values

regarding agents' behavior, obstacles and collision avoidance, for user defined number of iterations.

3.2.2. Data Derived from Simulation

Crowd Simulation for generative model has been applied in order to produce movement paths on the project site. These paths has been generated to retrieve the following information;

- Used and unused locations according to access of agents
- Influence of site geometry, events and obstacles on movement
- Usage statistics of attraction points

Number of iterations that the algorithm makes is determined by the user since the amount of data according to the size of the space, number of attraction points on the site cannot be generalized and designer intuition becomes significant. Besides, number of agents, their density, randomization factor on the site, range of the agents according to the main axis have also been decisions that can be altered by user.
As a next step, these movement paths (curves) derived from crowd simulation have been interpreted as an input for a self-organizing algorithm to compute a new site organization. The model is constructed to be adaptable to various situations including changes in time. For this reason, cellular approach to site organization is adopted for the next step of the model.

3.4. Quadtree and Cellular Automata

Cellular Automaton model is embraced with swarm behavior and non-uniform grid based on quad-tree algorithm to develop generated site organization for multipurpose open-air settlement regarding adaptability. Quad-tree is preferred to divide initial regular cells into sub-cells with respect to movement paths of the agents in order to create diversity for form generation.

Conventional cellular automaton algorithm dividing a given area into regular cells is used to explore relations of the neighboring cells and the resulting site generation. However, the use of uniform grids reveals a limitation on exploring the full potentials of the usage and the flexibility on control of the model. Therefore, in this study quad-tree algorithm, which is based on iterative divisions within the cells with respect to movement paths is integrated in order to provide precision by producing smaller cells on active areas and this approach provides finer control on these areas and creates variation on different scales. Merging these algorithms enables the designer to generate an adaptive site organization and also the initial uniform cell division makes the model adaptable to the later changes on the site.

The model operates consistently with respect to the variables defined by the user and the role of the user is inevitable and the site must be carefully defined regarding the inputs of the model. After the inputs are provided to the model, user/designer may explore various spaces by simply changing and tuning the input variables to achieve the various outcomes of the solution. One of the important variables in the construction of the site is the selection of initial grid system. The proposed model is constructed for a square grid system, yet in extreme cases other grid systems can be employed with necessary modifications to the model.

3.4.1. Movement Paths to Trigger Quad Tree Division

The initial square grid is adapted according to agents' movement paths on the site. During this process, retrieved movement paths and user defined initial grid have been placed and their relations are calculated based on quad-tree algorithm.

For proposed model, quad tree algorithm has been adapted with one simple rule which is "If a cell intersects with a movement path (curve), then divide cell into n (4 as the default value) equal pieces" Then the algorithm applies this function until either " the number of iteration defined by user" is reached, or "the area of the smallest cell is equal to or smaller than the predefined area" condition is satisfied. Both of these termination criteria should be decided by the user considering structural and spatial features. One of the possible configurations is shown in Figure 24.

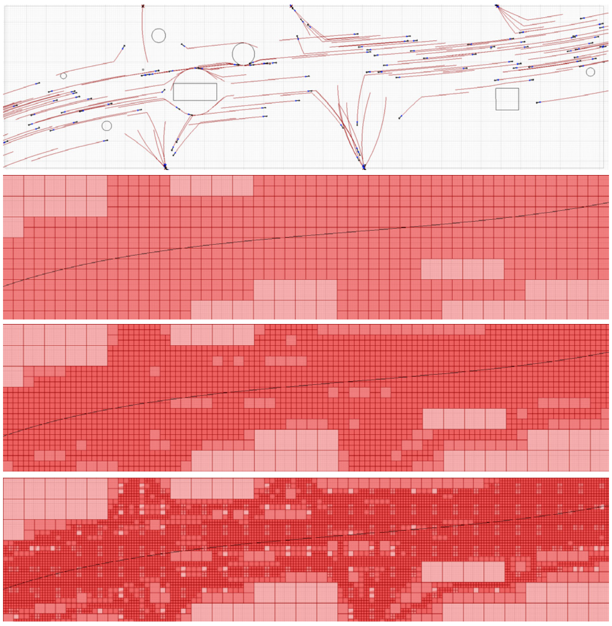

Figure 24 : Quad tree division on site (generated by the algorithm developed by the author)

3.4.2. Defining Clusters based on CA

With the use of the proposed model, cells with different size, location, and neighboring relationships are generated by Cellular Automaton Approach based on crowd simulation and quadtree division. Cells are classified as *active cells*, *passive cells* and *virtual cells (dead cells)* according to the functions assigned and relation with their neighbors. One example of classifying cells, is stated in Figure 25.

To sum up, model is constructed with the basis of providing input variables as site boundary and major movement axis for site construction, assumptions regarding number of agent, their initial location and behavioral rules for crowd simulation, and grid size, number of iterations and classification rules for generative design by user. This model outputs curves denoting crowd movement paths, and cells with classifications defining function of the area. The consequent hybrid model outputs not only generate a site organization but also provide an analysis of the existing site.

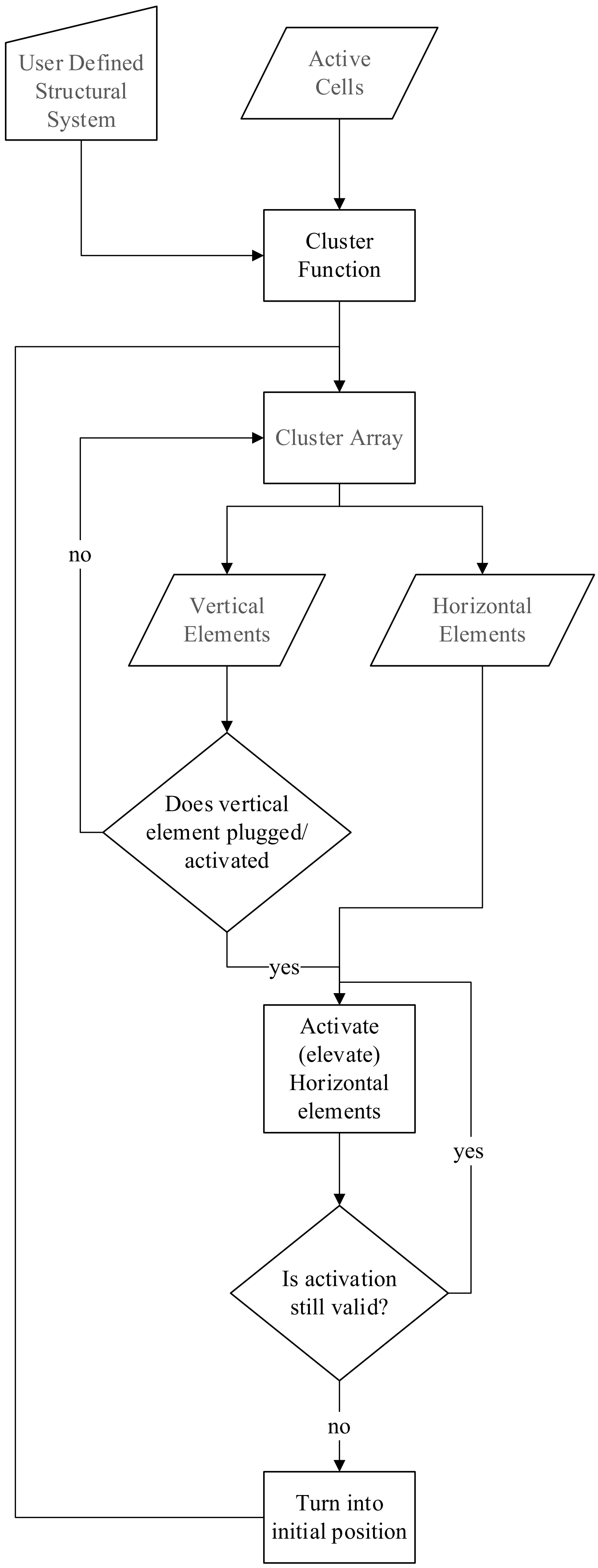

Figure 25 : Concept Diagram of Structural System

CHAPTER 4

MODEL DEVELOPMENT AND VERIFICATION

In this chapter, the previously proposed model is implemented into a generative tool regarding Cellular Automaton Approach based on crowd simulation algorithm. As discussed before, the model had been developed for a project in Lange Voorhout in the scope of Graduation Project in TU Delft. Hence, verifications of cases with similar inputs and expectations have been tested during process and model developed accordingly.

4.1. Objectives of the Model

A new modular, iterative and adaptive model is developed to analyze the site and generate a cellular automaton space. Since model has been created as a predesign analysis and generative tool, it is capable of not only serving as design process itself, but also as a part of the process. The objectives of the model are:

- Model should provide valid information about functionality of the area by simulating movement paths and rearranging space according to these paths,
- It should be easy to use and develop for designers with fast feedback
- Inputs of the model defined by the user should be simple containing basic information that can be reached by the user.
- And also outputs of the model should be able to retrieved and be readable for further design stages and should be in a format that can be imported into common design software

Proposed model has been designed as a user dependent system. Since the human factor is seen crucial for planning and design projects, for all the stages, user involvement is accepted as a control and a decision mechanism. Both simulation and generation part of the model is dependent on the user's judgment, view and aesthetic concern. Hence it gives possibility to change inputs after revealing consequences of each part regarding parametric design issues. Control loop is defined in Figure 26.

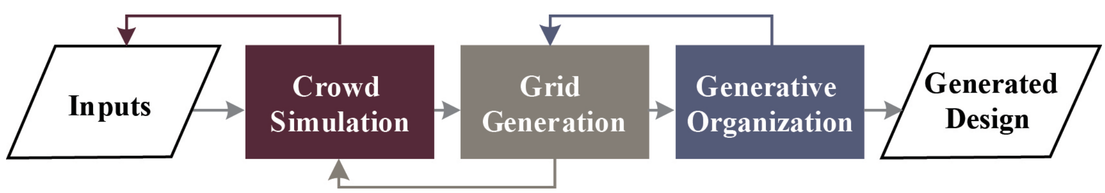

Figure 26 : Use of the program

In the development of the algorithm, the interface generating the forms should be easy and compatible with many other CAD tools, therefore Rhinoceros 3D is chosen together with Grasshopper (GH) which is a comprehensive plug-in for Rhinoceros on parametric modelling. GH is based on linear mathematical functions and it is not possible to achieve iterative operations. In order to achieve iterations in the model, Hoopsnake, which is an add-on component developed for GH, has been included in the model.

Diagrammatic representation of the algorithm is illustrated in Figure 27.

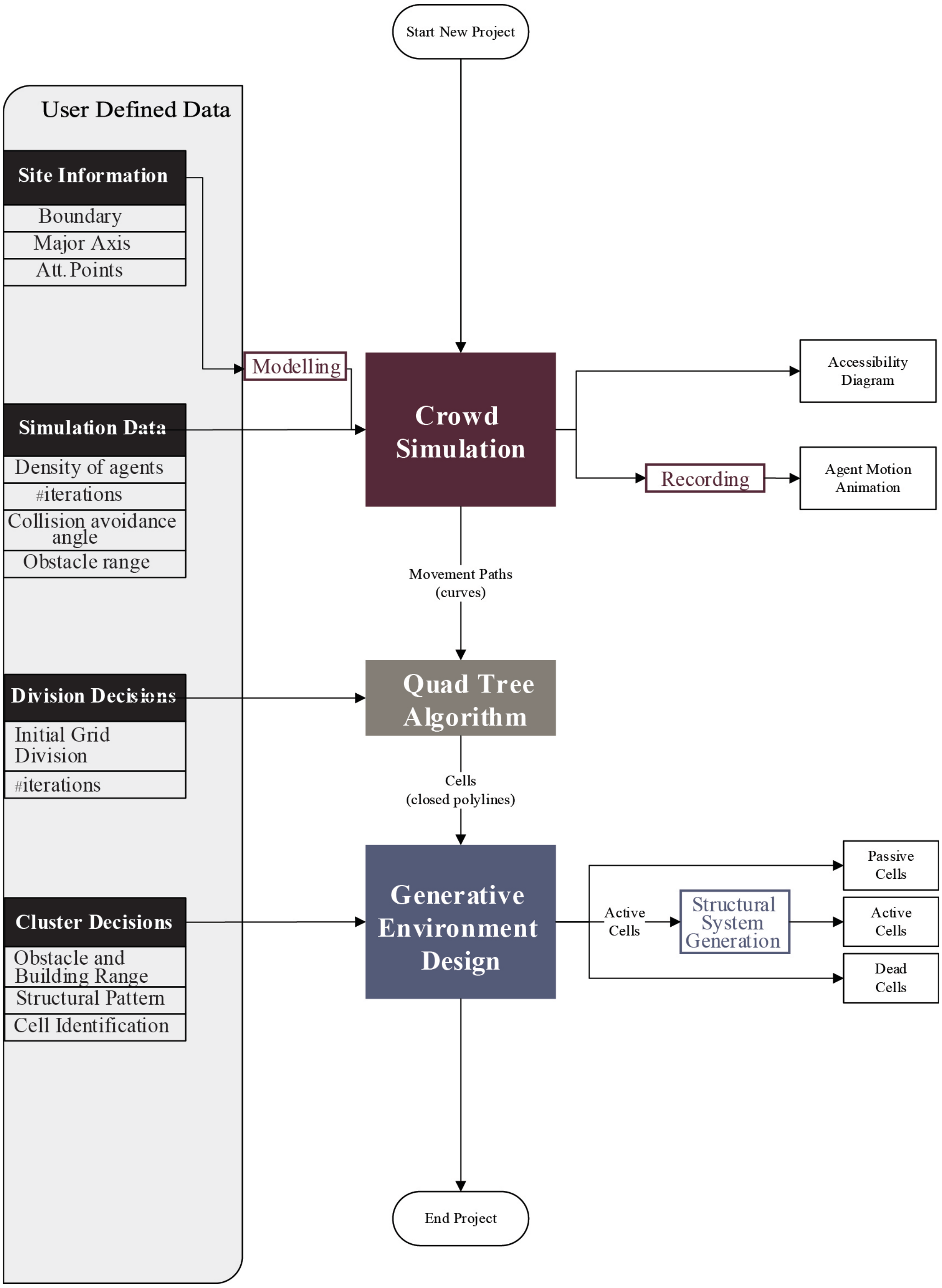

Figure 27 : Conceptual Diagram of the Algorithm

4.2. Adaptation of Model into the Medium of Grasshopper

Model is constructed consisting of two parts; crowd simulation and cellular automaton generation. Although both parts are designed to work together, they have been assembled in two different files in the program to reduce the computational time. As crowd simulation generates agents on design site, and simulates their behavior and draw their paths; generative part of the model uses those paths as trigger of cell division and group those cells with respect to environmental and neighboring features as well as their sizes.

4.2.1. Part 1: Crowd Simulation

Initially, crowd simulation in model is achieved by swarm behavior rules as explained in the previous chapter. As crowd simulation algorithm in the model includes modules for various tests and functions, these are created as groups in the program and created a *open box* model, which reveals the steps of the process and enables them to be altered, to run the analysis. As a result of the simulation, agent movement animation and consequent paths are revealed. The visualization of these results is customizable by user with respect to their preferences. Then, Hoopsnake add-on has been added to obtain iterative function into the modules that have been put together in one model. Input-Output relation in the algorithm is shown in Figure 28.

Although model has been created as white box model and gives possibility to alter the structure, inputs have been grouped as user defined inputs to avoid accidental alteration of the structure of the models. These inputs are named as “designer decisions” and can be described as follows: In order to simulate the site conditions, site boundary and axis should be defined as curves. Agents are identified as points and placed in an area between two offset curves from the major axis. The offset distance from main axis to both sides to define the area, which the agents will be populated on, is required to be input as integers. Number of agents and their initial locations are calculated from division of the area regarding u and v value of this area. Agents are dislocated from formal grid alignment with randomization value defined by user. Another decision regarding the agents is their speed during each iteration and this data is retrieved via numerical input that user can modify.

After initial decisions about site and agents, further inputs are required regarding attraction points and their range, obstacles’ footprints in order to simulate their influence on the simulation. For the case of collisions among, agents and with obstacles, rotation angle and range of obstacles have been defined as numerical input.

After providing all inputs mentioned above, number of iteration is provided by the user to execute the operation of the model. It is possible in the algorithm to change the inputs and have various results rapidly. And visualization of these results are able to be changed via “Visualization” module which determines the color and shape of agents and movement paths, color, length and thickness of vector displays and color of attraction zones.

4.2.2. Part 2: Generative Design

As it has been stated in previous chapter, quad tree division of the system is provided with resulting movement paths of crowd simulation. Mathematical function of the algorithm is simple so it is modelled in Grasshopper as it is showed in figures below and iteration has been achieved with Hoopsnake.

Initial grid cell division is created according to initial user defined grid cell size and site boundary. Although initial cell is proposed to be regular square grid, model makes it possible to work with any polygon grid that user defines. After the initial grid is defined and constructed, Quad tree algorithm is generated with iteration of division module regarding the step size that user defines. Since model includes both parent cells and their children that are generated from division of those, parent cells had been excluded in quad-tree module. Where after cell divisions are derived; obstacle, closure and neighbor tests has been applied. Even though all cells are generated at first, cells within or around the obstacle boundary are classified according to their location regarding obstacles. As it has been stated previously, model includes various assumptions made by user that can also be called *design decisions*. Thereafter, the module is constructed based on user decisions. In this course, cells have been classified according to these decisions regarding the limit of imminence to building line and interaction with each other to form a structural unit.

Consequently, model, which has been described in detail, consists of two parts running sets of algorithms. First part of the model is named “Crowd Simulation” and it simulates behavior of the crowd and produce paths of the movement based on swarm behavior, and the second part is named “Generative Design” that includes grid cell generation based on quad-tree algorithm and construct relations between cells with their boundary and site conditions, obstacles and other components. Although, these parts has been constructed consecutively to reveal an efficient model for site organization based on crowd simulation as it has been shown in Figure 29, *white box* nature of model enables separation into parts and they can be used as modules for various study purposes.

As the development of this model is motivated by the generative site organization model for Lange Voorhout in the first place, this case study and an additional case study of Museum Area in METU is being inspected to clarify both the use and the potential outputs of the model. Although these two cases differentiate regarding their historical and locational aspects, both satisfies initial assumptions and requires human motion analysis for new site generation.

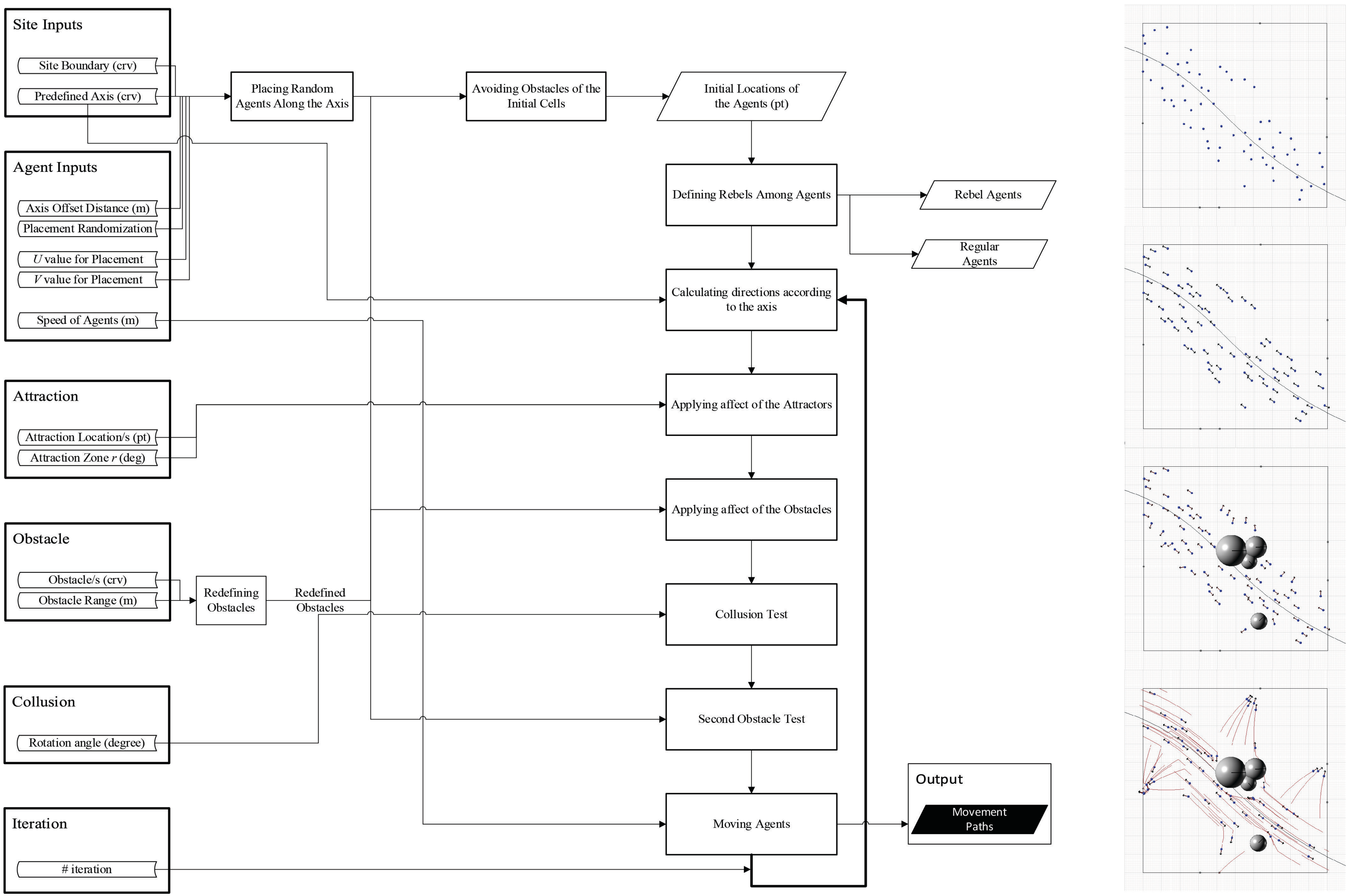

Figure 28 : Input-output relation of the Crowd Simulation Algorithm

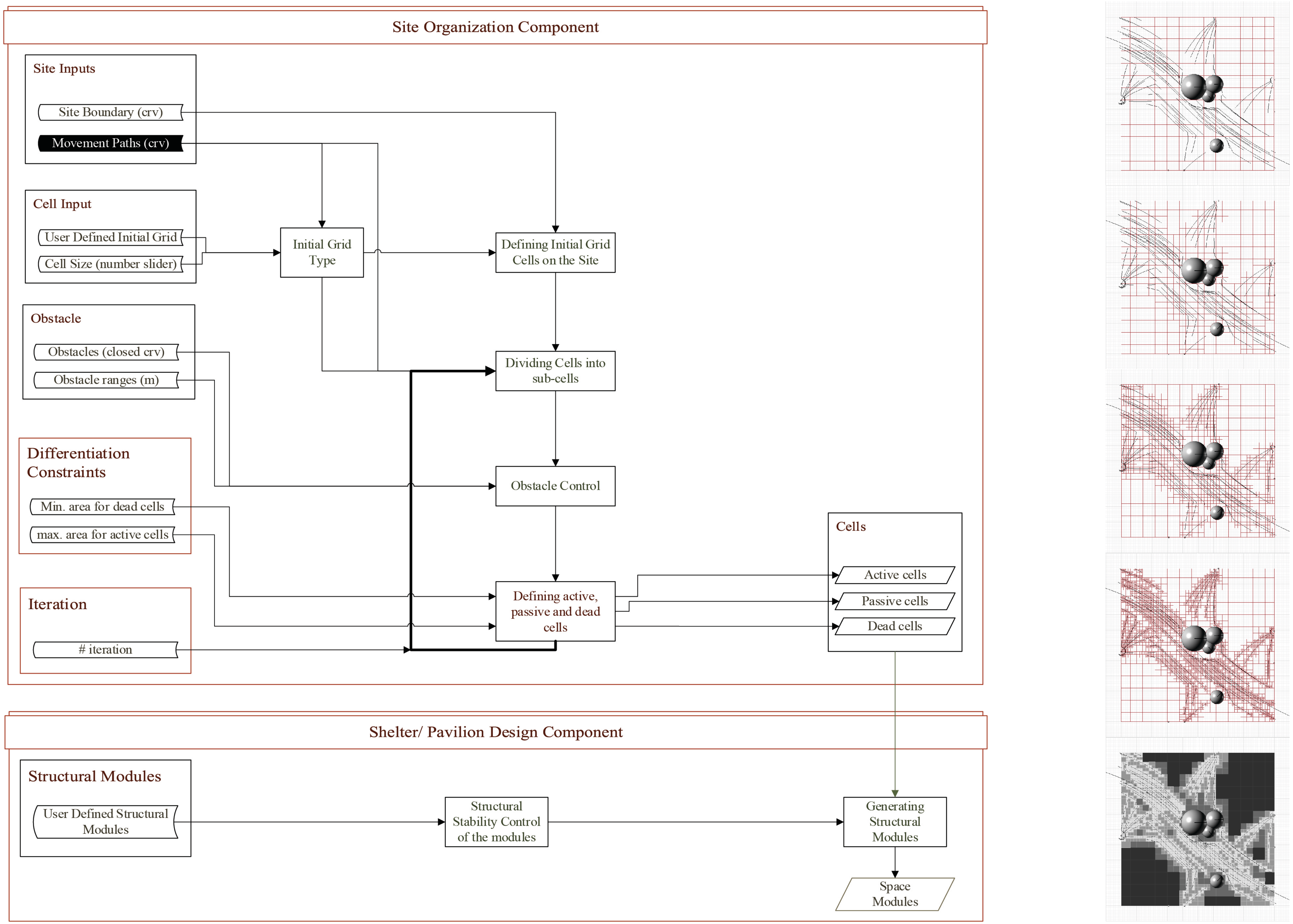

Figure 29 : Input-output relation of the Site Generation Algorithm

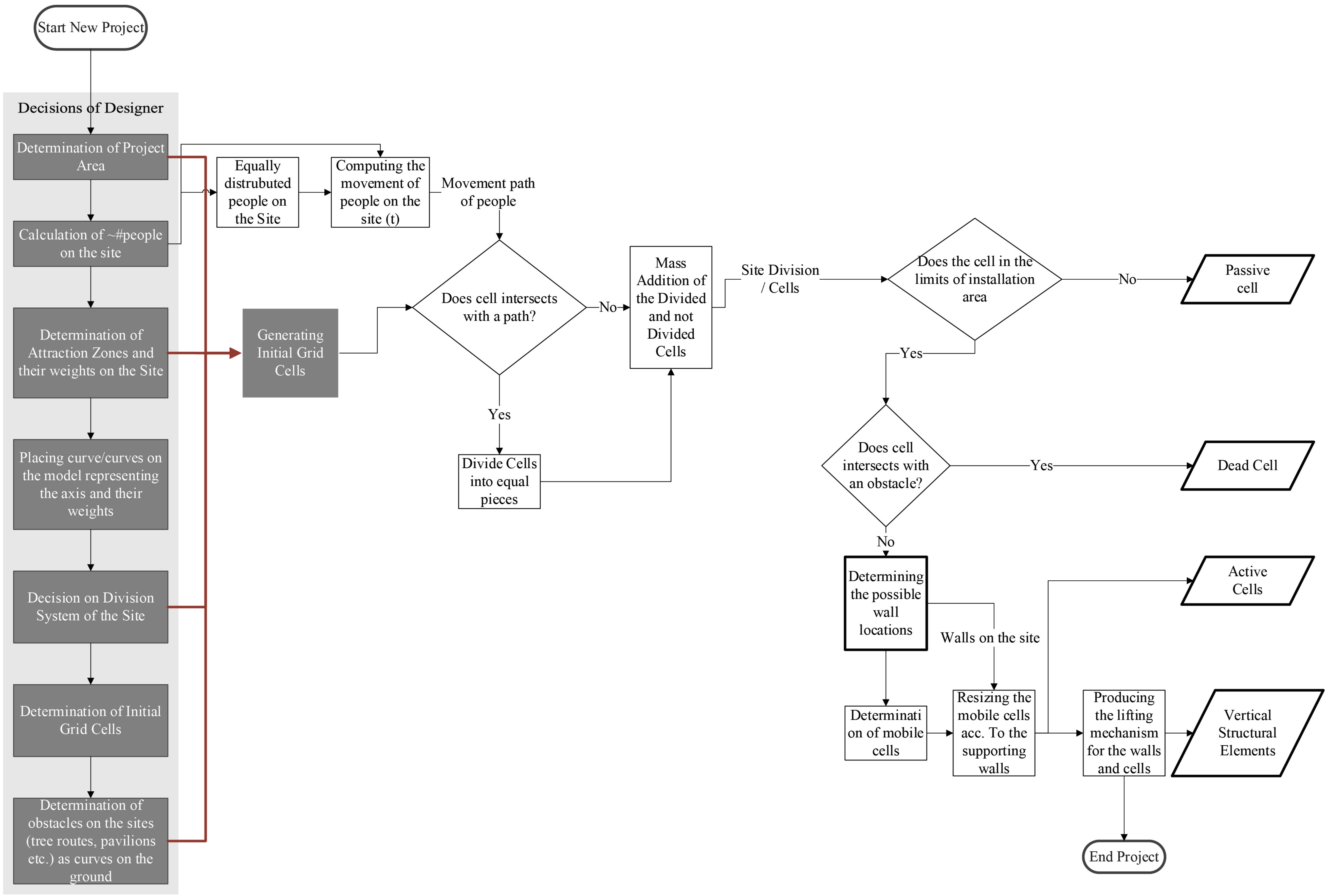

Figure 30 : Diagrammatic Representation of the whole Algorithm

CHAPTER 5

CASE STUDIES

5.1. Case I: Lange Voorhout

The generative tool described in the previous chapters is initially developed for a temporary open air organization including exhibitions and sales in Lange Voorhout which has unique characteristics like temporary and periodical events, significant buildings and historical trees. Main goal of the project was to develop a generative tool to provide a self-organizational schema based on human motion in the site. Hence computational model including crowd simulation and site generation algorithms is developed initially for this case. Crowd simulation algorithm based on swarm behavior has been included into the model to simulate people on the site as agents and provide input for site generation algorithm enabling to merge user defined data with CA to come up with an adaptable site organization. In the context of the project, the author suggest the temporary structures to be used in the site based on the schema generated by the tool. Author prefers to use structures composed of simple rectangular horizontal and vertical components to build up temporary shelters for the users.

Figure 31 : General view of the site (past and present)

5.1.1. Approach to The Site

Lange Voorhout makes feel the visitors that they are in a prestigious place staging all the royal events taking place and numerous buildings like Escher museum, Diligentia (Theatre), Pulcrhi (Studio) and restaurant such as Posthoorn surrounding the park. Therefore, any new design to be proposed for the site should consider the importance of the site for the public and should respect the natural beauty articulated by tall trees. (Figure 33) (Figure 32).

Figure 32 : Events of Lange Voorhout: Antique Market, Bookstore, Prinsjes Dag, Exhibition, Queens day, Haagse Uit

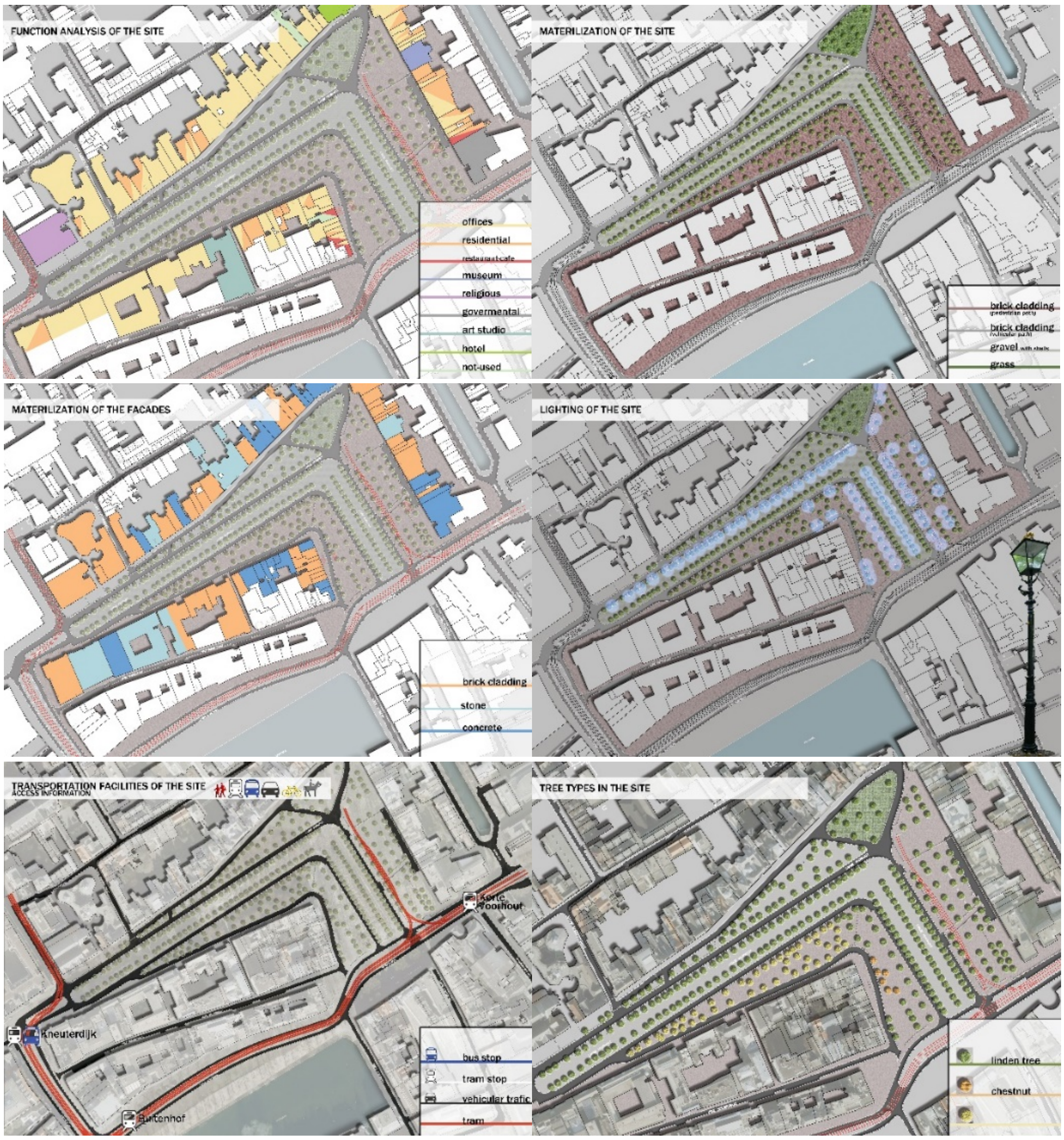

Figure 33 : Analysis on Lange Voorhout

It is seen that the old trees in the site have a great influence on visitors. These linden trees determine the main characteristics of the site thus designing new elements for this area should not compete with those trees but should be in harmony.

Site has various events in a year such as, Queens Day, Golden Couch, exhibitions, book market and parties. Also, Lange Voorhout has significant historical buildings, which require extension like Diligentia (theatre), Pulchri Studio, and Escher Museum which is a former palace (Figure 34).

Figure 34 : Historical buildings of the site

Despite of existing quality, historical background of the site is remarkable based upon 15th century. Timeline of the site transformation can be seen in Figure 35.

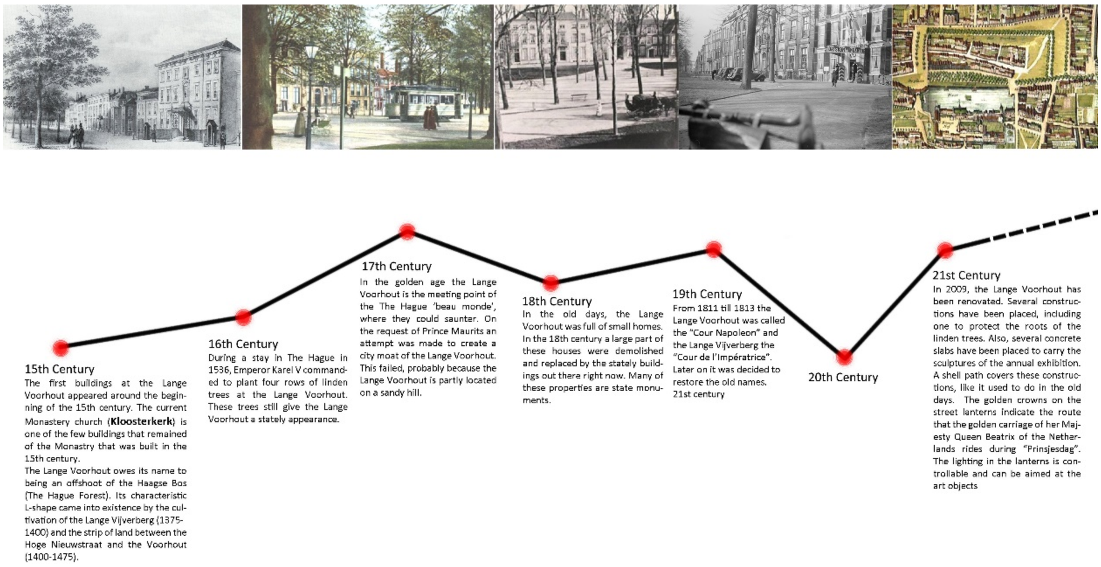

Figure 35 : Timeline of Lange Voorhout

Hence, Lange Voorhout is a living environment itself, despite of temporary solutions for changing needs, existing of an adaptable system become essential. The main issues of the site can be listed as static lighting elements which cannot adapt themselves to changing events, and shelters and pavilions (tents) that are constructed during festivals and exhibitions. Not to affect quality of the site, less complex forms should have been used as lighting elements and simple horizontal and vertical elements are considered to create spaces for events.

5.1.2. Defining the Inputs for Model

Initially site assumptions such as boundary, major movement axis, crowd-pulling points and obstacles, have been modelled for the case (Figure 36). Boundary of the national park has been presumed as site boundary, axis between the tree lines has been drawn as main axis, trees are defined as obstacles and Escher Museum, De Posthoorn (restaurant), and Diligentia Theatre, Pulcrhi Studio are classified as attractor points in the model.

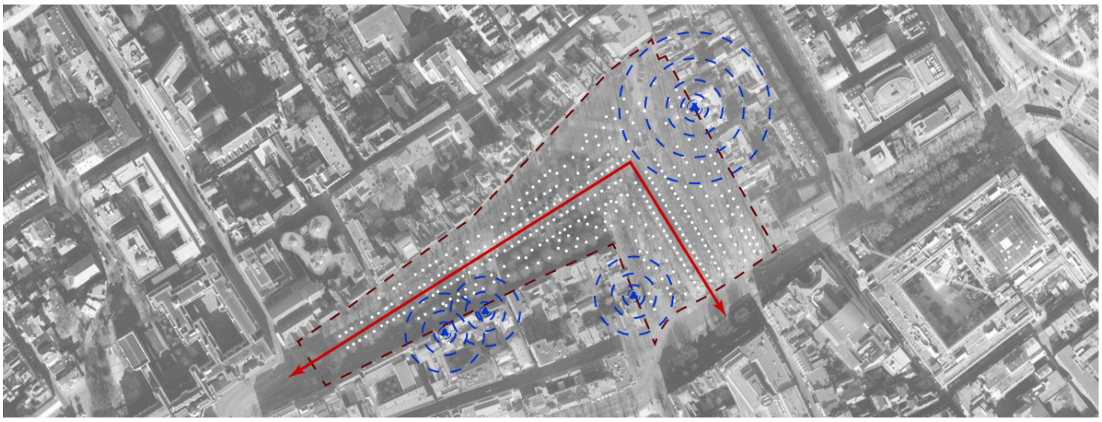

Figure 36 : Site Modelling

Moreover, user defined inputs regarding site conditions for crowd simulation algorithm has been determined as follows;

- Influence of the crowd-pulling points has been defined as attraction zones in the model and in this case these zones are defined with their radius based on author's observation on site. In the algorithm constructed for Lange Voorhout, radius of the attraction zones are 45 meters for the theatre, 30 meters for the studio, 100 meters for Escher, and 60 meters for the restaurant.
- Number of agents has been calculated based on area of the site as 134 for site.
- Since trees has been defined as obstacles in the algorithm, range of obstacles are determined by route physiology and 1.5 meter has been assumed in the algorithm for both crowd simulation and generation of the site organization.
- Since the site has a large area and low density of people, collision avoidance has been excluded for this project.
- As stated on the third chapter, in order to provide smooth direction change for agents attracted by crowd pulling constraints, user defined numerical value has been included. It has been defined as 40 for this case.
- 20 iterations of the algorithm succeeded to have sufficient data.

Furthermore, inputs for site generation has been stated below:

- Initial grid of the site has been determined as a custom grid by author with respect to existing tree rows. This non-uniform initial grid is created with linear cells around major axis in order to emphasize existing horizontality. This grid has been formed with numeric array of "0.25, 1, 2.5, 4.5, 7.5, 9.5, 8, 8, 8, 8…" for Lange Voorhout (Figure 37).

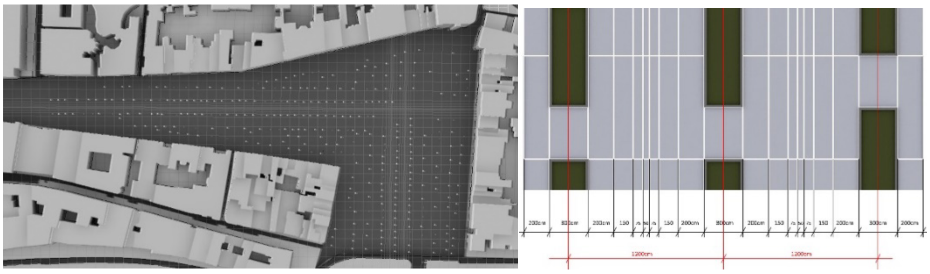

Figure 37 : (Left) Initial custom grid, (Right) close view of the custom grid

- Kinetic structural system of the installation is designed with modules including one vertical supporting element (walls) and 6 slabs that are carried by supports. System is illustrated as shown in Figure 38. More information about the mechanical system can be found in Appendixes.

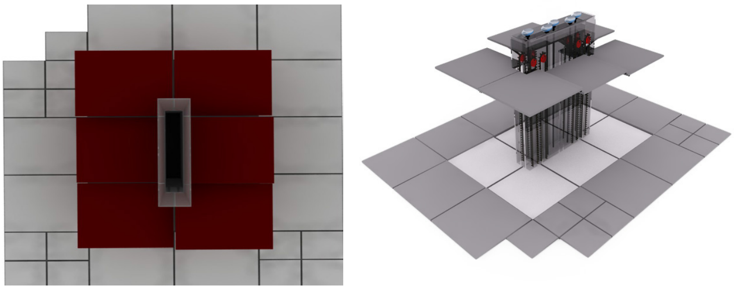

Figure 38 : Proposed Structural units

- Cells are named as slabs in this project regarding their potential to have kinetic components to for shelter and pavilion. Then, slabs are classified as axial slabs with custom size based on mentioned array and generic square slabs that can be divided based on quad tree algorithm. Ever after, generic slabs has been identified as kinetic which can be elevated, passive which will serve as pavement, and dead which will not be built on the site.

- As 8meter by 8meter square slabs has been identified as generic ones, generative algorithm is applied on these ones and 4 iteration of the algorithm produced 1 meter sized subslabs which is the termination criteria defined by author.

5.1.3. Outputs of the Model

As the first part of the model, crowd simulation algorithm has been applied, and resulting movement paths are retrieved based on assumptions and design decisions that have been proposed (Figure 39). As an outcome of this analysis/simulation, usage diagram of the site has been generated and also by modelling paths with curves in Rhinoceros, input of the generation system is occurred.

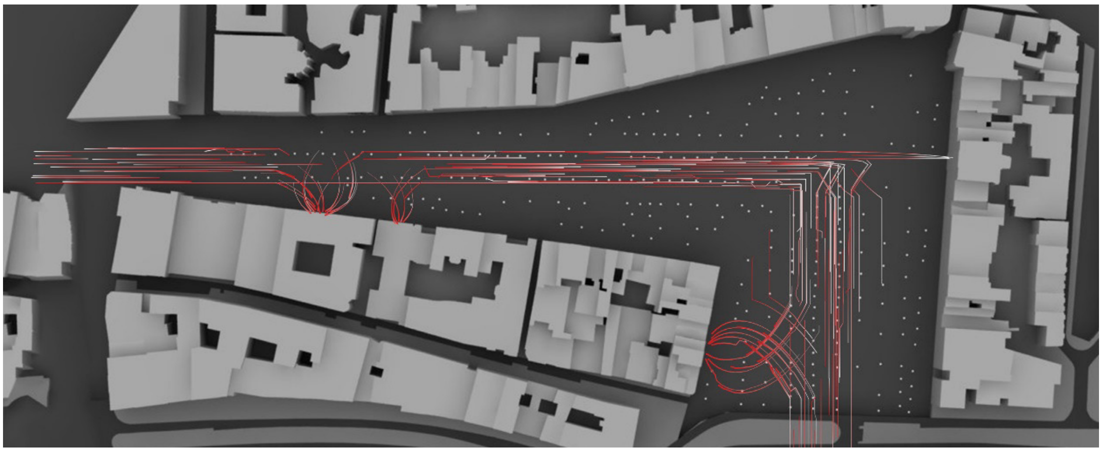

Figure 39 : Crowd Movement Paths of Lange Voorhout

Afterwards, second part of the model, which generates subslabs based on quadtree algorithm, has been applied into site with curves denoting movement paths (Figure 40). As outcome of this algorithm, slabs have been differentiated according to their sites. Hence slabs has also been classified according to their location, neighboring obstacles and potential to provide pavilion unit. In order to have those classification rules are constituted as below:

- Pavilion/shelter modules cannot be close to buildings more than 5 meters.
- Possible module locations will be located on site to maximize the number of modules.
- Presence of the slab should be restricted by a region which is 2 m neighborhood of trees which are imported into model as obstacles.

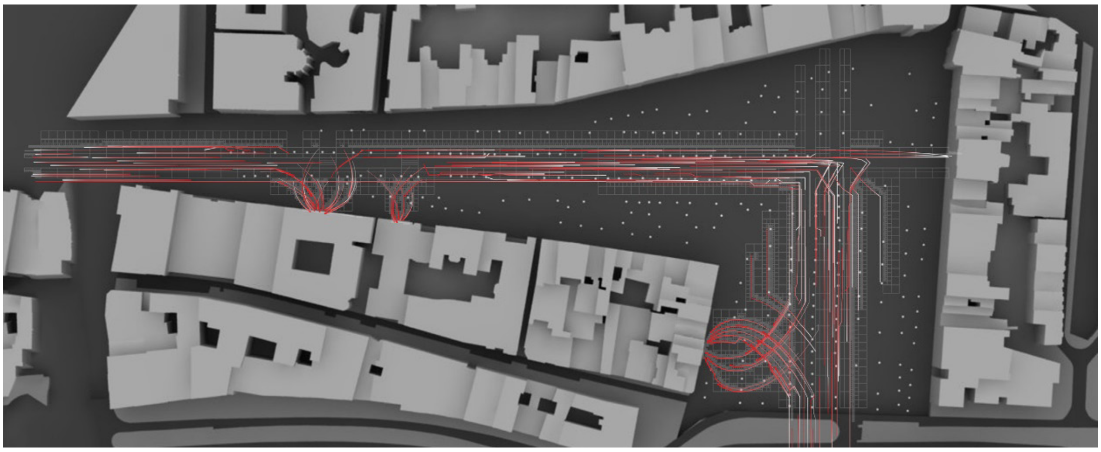

Figure 40 : Result of the secont part of the algorithm

Since generation of existing slabs and determining possible wall locations has been completed, model is able to be activated to see configurations during events. Activation occurs by placing walls into their location and elevating slabs connected to them in real world. On the other hand, in order to activate virtual model, attraction points have been applied on the area to define walls and resulting pavilions or shelters. As a benefit of modular system, various spaces are generated and there were unlimited options which will be considered in further projects. Some of them are illustrated in Figure 41.

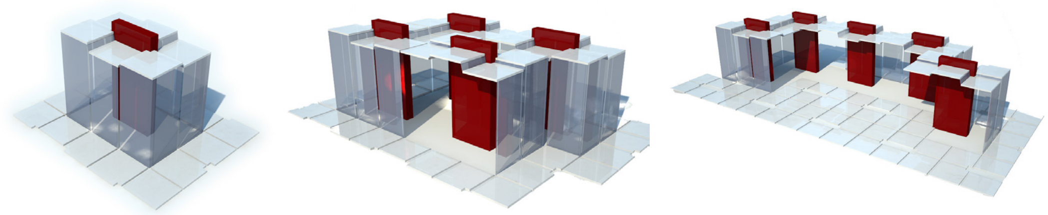

Figure 41 : Some of examples regarding modular system

Consequently, the proposed model has been modified for the unique case of Lange Voorhout in order to meet the requirements of the site. Altered model has been applied into the site as shelter for the exhibition, extension of buildings, the book market and the antique store, and the pavilion for exhibition of vulnerable pieces (Figure 42 and Figure 43). Existing solutions for the requirements of the site can be listed as tents for markets, glass portable boxes for protected exhibitions, modular panels for hanging exhibitions such as photographs and paintings, and portable umbrellas for extension of buildings. Instead of these solutions model has been proposed a system that is constructed underground and being able to be elevated via pluggable portable mechanical/structural walls. Regarding the crowd analysis, only the necessary part of the park has been constructed with respect to significant natural elements of the site and the rest has been left as it is. Although model has been constructed for existing functions on the site, it is possible to have more with combination of modular pieces and cells can be divided into subcells with respect to crowd analysis run for site in following years.

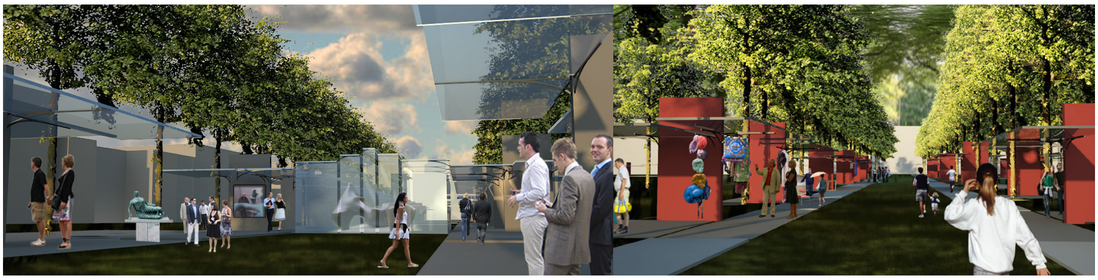

Figure 42 : Usage of axial slabs on the site

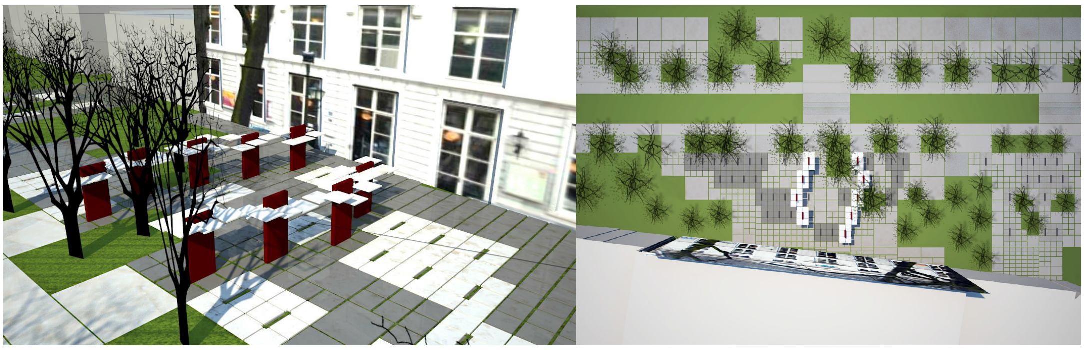

Figure 43 : Possible extension for the theatre

5.2. Case II: METU Science and Technology Museum

As a second case, the area of METU Science and Technology Museum, which is designed by Prof. Dr. Ayşen Savaş and located inside METU campus, is selected. In the area, museums were constructed not only to reflect the technological development of Turkey, but also to exhibit locomotives and aircrafts which are essential for the military culture (ODTÜ Toplum ve Bilim Merkezi, 2009). Considering the initial drawings of museum area, museum buildings are designed based on a grid located on the site. The model is employed on this initial grid for further exploring the potentials of the Museum Area to respond possible future extensions and respond to increasing number of visitors and artifacts to be exhibited. Museum area is still in development process so this is the main characteristic feature that differentiate the site from Lange Voorhout which has a dominant historical background. Potentials of the site are considered to be improved with a flexible system that not only responds to current needs of the area, but also is adaptable to the changes during the time. Hence the area has been identified as the project site and initial assumptions about the model is provided from the site and outputs are retrieved.

5.2.1. Producing the Inputs for the Model

Project site has been simplified and modelled (Figure 15) as follows:

- Boundary of the model has been identified regarding the forest area neighboring to the museum. Boundary condition in this case is flexible, since model is capable of discarding dead areas from the output.
- Major movement axis has been identified considering existing paths of the site. These paths have two entrances into the site so it is assumed that these points are the end points of the curve devoted for major movement axis.
- The Museum area includes four major buildings; a main hall also named "silo", a glass hall for reception and sales, a supplementary building called "hangar", and an audio visual hall. Entrance of these buildings and large exhibited objects such as aircrafts and a locomotive, are regarded as attraction points in the model and also the boundary of those are stated as obstacles which agents should avoid during crowd simulation.

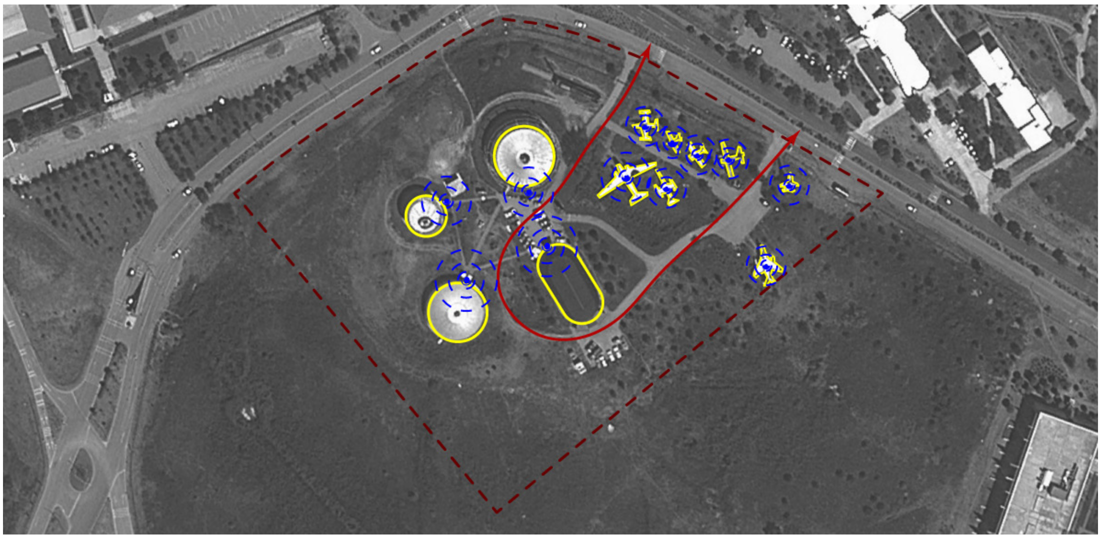

Figure 44 : Providing inputs for the model

Furthermore, user defined inputs regarding site conditions for crowd simulation algorithm has been determined as follows;

- Range of the attractor zones of crowd-pulling was points defined as 15 meters for buildings and 9 meters for exhibited aircrafts. This numbers has been specified by author with respect to site scale and observation on existing movement.
- Number of agents is assumed to be 50 based on area that museums located.
- Rotation angle in the case of collision of agents has been denoted as 30 degrees and during the design period it is found sufficient.
- Since limited agents has been modelled, 50 iterations of the crowd simulation algorithm have been applied to come up with sufficient movement paths for the next part of the model.

Moreover, design decisions considering site generation is stated below:

- Initial grid has been defined considering organization scheme of the museum buildings by changing angle of the grid. By observing dimensions of the buildings, 10 by 10 grid has been applied into the model.
- Cells produced by generative algorithm, has been classified as dead which will not be built, passive which will serve as pavement, and active which has potential to transform.
- Termination criteria of the algorithm is defined that “if smallest sub-cell become 1.25 to 1.25 square cells, then terminate”. So regarding initial cell division which is 10 by 10, number of iteration of the quad-tree algorithm become three for this case.

5.2.2. Outputs of the Model

Considering simplification of project site into model and user defined inputs stated above, crowd simulation algorithm has been run on the area and resulting curves representing movement paths are derived as shown in Figure 45.

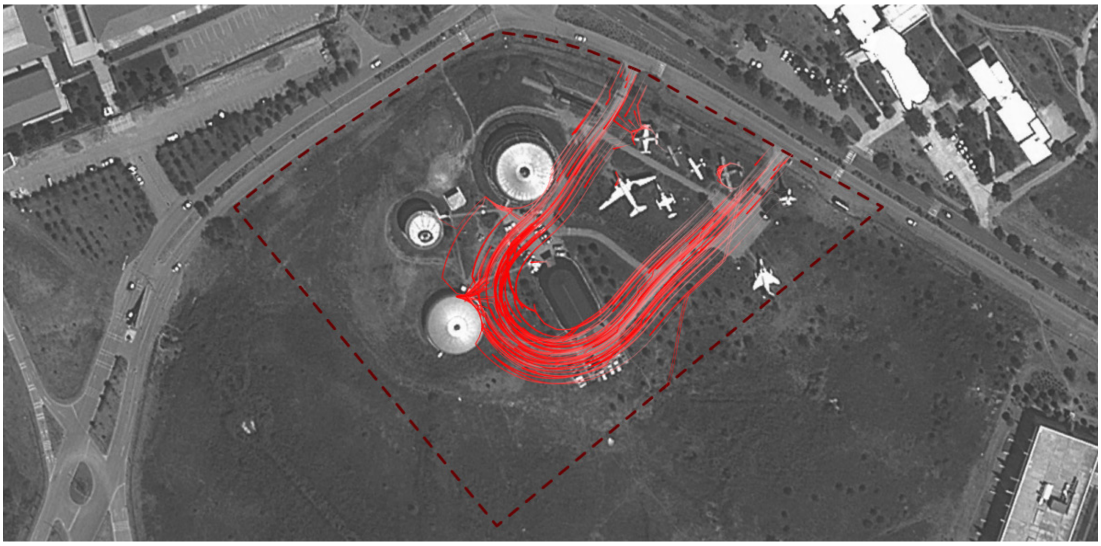

Figure 45 : Simulated agents on the site

Then, generic quad-tree algorithm is applied regarding movement paths derived from crowd simulation and assumptions of user. As a result of third iteration of quad-tree algorithm and obstacle control of the cells, and classification according to their sizes following site organization has been occurred (Figure 46).

Figure 46 : Generated site organization

For the case of METU Science and Technology Museum, model is applied in order to reveal possible organization schema for the site that leads pavement pattern and dynamic and static installations that can be implemented. It is observed that producing various scales of cells differentiates area according to their density and improves the control on dense areas of the site.

It is seen that the model developed for the case of Lange Voorhout is adaptable for sites that topography can be disregarded, however for the case of METU Museum Area, changes in the topography become an important data that should be considered on further studies.

On the other hand, crowd simulation algorithm shows that museum buildings are not on the same level to be reached by visitors and initial movement path should be reconsidered accordingly. Hence proposed crowd simulation algorithm within the model can be considered as predesign tool for designing the movement path for this case.

CHAPTER 6

CONCLUSION

In this thesis, the model which is initially developed for Lange Voorhout (in The Hague) is extended into a generic model integrating Agent Based Modelling and Cellular Automaton algorithms. This generic model is implemented for the case of Lange Voorhout which is the initial motivation of the model and METU Science and Technology Museum Area that can be considered as an important and developing area for METU Campus. It is shown that the proposed tool serves well to support the design of these two sites. Model contributes to the field with new integrated model which can be developed with further studies.

Proposed model is designed not only as an analysis tool, but also as a pre-design tool which integrates analysis into design from the very early stage of the design process and it improves design based on its performance by iteratively running the algorithms. The behavior of the people experiencing the site plays an important role in shaping the site organization, as well as the design of the site determining the behavior of the people. Therefore, the model proposed here including people's movement and site organization enable designers not only to test their validity of initial design decisions, but also provides data for further analysis and design of the site. Model is proposed as an integration of two well-known algorithms which have been applied on space organizations for decades. Both algorithms are accepted with their potentials and by improving their structure, the author has developed a tool that initially analyzes the behavior of the crowd on the design site and then generating a cellular automata for the site organization with various classifications of the cells. The Cellular Automaton approach is an acknowledged tool for space organization schemas with uniform grid divisions, introducing non-uniform quad-tree divisions regarding the movement paths provides variation on cell classification and neighborhood relations. Thus improves the algorithm itself.

Developing a tool in a medium, which designers are familiar with, allows designers not to be only end users, but also programmers which are capable of interacting with the model. Existing model is provided for the sites having well-defined boundaries, and major axis where temporary events take place. For such sites, the model is capable of generating a site organizations for various temporary functions such as exhibitions, sales, and ceremonies.

Model is tested on two cases namely Lange Voorhout and METU Museum Area, and the outputs like the movement of the people on site and custom grid based on this movement are found to be satisfactory to achieve the goal of the project. Adapted crowd simulation algorithm provides the usage data to form the site organization schema. Proposed organizational schema differentiates spaces according to their usage via custom grid system in the form of active and passive spaces depending on the functions, sizes and usage of the cells. This differentiation helps designers to organize the space in a much better and precise way. Resulting schema of the site organization has potentials to be further used by the designer to elaborate structural, organizational and functional elements of the site. Also, this variation enables designers to approach to the design of site from different perspectives and different scales, and provides finer control on dense areas. Current model achieves the expected level of precision and proved its validity, efficiency, and convenience for the predesign phase of the design process. Hence proposed research has a potential to serve as a base for further studies.

As the model initially designed for a specific site, several specific assumptions are made in relation with the given site. Then the model further developed in order to obtain more generative tool. The proposed model in this thesis can be further extended in order to be used in different contexts such as parks, university campuses. In this extension, definition of boundaries, number of people, number of axis, obstacle definitions and attraction influences will be broadened.

Agent Based Modelling algorithm employed in the given Model then it can be further extended to include more complex features of swarm behavior such as perception of agents during their movement, definition of initial target points for agents and agent groups for more accurate crowd simulation algorithm. The diagrams showing the usage of the site can be enhanced by including temporal changes in terms of time factor to develop hour-based data and analysis.

Quad-tree algorithm is capable to produce custom divisions for each kind of uniform grid systems such as hexagonal and triangle grid. However, developed model is capable of creating subdivisions only for square and rectangular grids only which are adequate for the cases that are proposed in this thesis. It is considered that further studies can offer flexible structure regarding grid types by providing various subdivision functions.

Further studies should also be carried to reduce limitations related with computational time. In the process of tool development, the computational cost of the model is higher than expected. For future studies, developing plug-in or component will be considered.

To sum up, model proposed in this thesis integrating Agent Based Modelling and Cellular Automaton approach proved its validity in organizing open space organizations and it is shown that the model has potentials for further elaborations.

BIBLIOGRAPHY

A.H.Taub (Ed.). (1963). *John Neumann: Collected Works.* Pergamon Press.

Alexander, C. (1979). *The Timeless Way of Building.* New York: Oxford University Press.

Alexander, C., Ishikawa, S., & Silverstein, M. (1977). *A Pattern Language: Towns, Buildings, Construction.* New York: Oxford University Press.

Alexander, C., Neis, H. A., & Ingrid, K. (1987). *A New Theory of Urban Design.* New York: Oxford University Press.

Bandini, S., Manzoni, S., & Vizzari, G. (2004). Crowd Modeling and Simulation: Towards 3D Visualization. In J. P. Van Leeuwen, & H. J. Timmermans (Eds.), *Recent Advances in Design and Decision Support Systems in Architecture* (pp. 161-176). Dordrecht: Kluwer Academic Publishers.

Batty, M., & Torrens, P. M. (2001). Modelling Complexity: The Limits of Prediction. *Cybergo: European Journal of Geography*, 7-11.

Bays, C. (2010). Introduction to Cellular Automata and Conway's Game of Life. In A. Adamatzky (Ed.), *Game of Life Cellular Automata* (pp. 1-6). London: Springer-Verlag London Limited 2010.

Buchin, K. (2013). *Geometric Algorithms (2IL55) – Winter 2013/2014 (Lecture Notes).* Retrieved from Eindhoven University of Technology: http://www.win.tue.nl/~kbuchin/teaching/2IL55/slides/09quadtrees.pdf

Dennunzioa, A., Formenti, E., & Provillardb, J. (2012). Local rule distributions, language complexity and non-uniform cellular automata. *Theoretical Computer Science*. doi:10.1016/j.tcs.2012.05.013

Frazer, J. (1995). *An Evolution Architecture.* London: John Frazer and the Architectural Association.

Helbing, D., & Molnar, P. (1995). Social force model for pedestrian dynamics. *PHYSICAL REVIEW E, 51*(5), 4282-4286.

Hogeweg, P. (1988). Cellular automata as a paradigm for ecological modeling. *Applied Mathematics and Computation, 27*(1), 81-100. doi:http://dx.doi.org/10.1016/0096-3003(88)90100-2

Jacobs, J. (1961). *The Death and Life of Great American Cities.* New York: Random House.

Moore, E. F. (1962). Machine Models of Self Reproduction. *Proceedings of Symposia in Applied Mathematics. XIV*, pp. 17-33. American Mathematical Society.

Mumfor, E. (2008). *Josep Lluis Sert: the Architect of Urban Design, 1953-1969.* Yale University Press.

ODTÜ Toplum ve Bilim Merkezi. (2009). Retrieved from Bilim ve Teknoloji Koleksiyonu Sergi Alani: http://www.tbm.metu.edu.tr/

Popov, N. (2010). Generative urban design with Cellular Automata and Agent Based Modelling. *On the edge: Cross-disciplinary and intra-disciplinary connections in architectural science. Proceedings of the 44th Annual Conference of the Australian and New Zealand Architectural Science Association, Auckland: the Association.*

Raabe, D. (2002). CELLULAR AUTOMATA IN MATERIALS SCIENCE WITH PARTICULAR REFERENCE TO RECRYSTALLIZATION SIMULATION. *Annual Review of Materials Research, 32*, 53-76. doi:10.1146/annurev.matsci.32.090601.152855

Ratti, C., & Richens, P. (1999). Urban Texture Analysis with Image Processing Techniques. *Computers in Building: Proceedings of the CAADfutures'99 Conference*, (pp. 49-64). Atlanta, Georgia.

Reynolds, C. (2000). *Reynolds Engineering and Design*. Retrieved 08 14, 2013, from http://www.red3d.com/cwr/boids/

Reynolds, C. W. (1987). Flocks, Herds, and Schools: A Distributed Behavioral Model, in Computer Graphics. *SIGGRAPH '87 Conference Proceedings*, (pp. 25-34).

Schadschneider. (2001). Cellular Automaton Approach to Pedestrian. *Pedestrian and Evacuation Dynamics*.

Situngkir, H. (2010, September). Exploring Ancient Architectural Designs with Cellular Automata. *BFI Working Paper Series*, pp. 1-9.

Soddu, C. (2011). *Papers on Generative Design*. Retrieved January 13, 2013, from http://www.argenia.it/papers.html

Treuille, A., Cooper, S., & Popovic, Z. (2006). Continuum Crowds. *ACM Transactions on Graphics , 25*(3).

Wolfram, S. (1983). Statical Mechanics of Cellular Automata. *Rewiews of Modern Physics*(55), 601-644.

Wolfram, S. (2002). *A New Kind of Science.* Champaign, IL,: Wolfram Media. Retrieved from http://www.wolframscience.com/

Xie, Y. (1996). A Generalized Model for Cellular Urban Dynamics. , 28:. *Geographical Analysis, 28*(4), 350–373.

Yan, W., & Kalay, Y. (2005). Simulating Human Behaviour in Built Environments. *Proceedings of the 11th International CAAD Futures Conference*, (pp. 301-310). Vienna.

Zheng, C., Raabe, D., & Li, D. (2012). Prediction of post-dynamic austenite-to-ferrite transformation and reverse transformation in a low-carbon steel by cellular automaton modeling. *Acta Materialia, 60*, 4768-4779.