Towards Homeostatic Architecture: simulation of the generative process of a termite mound construction

A thesis presented for the degree of
MSc in Adaptive Architecture & Computation

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Declaration

I, Olga Linardou, confirm that the work presented in this thesis is my own. Where information has been derived from other sources, I confirm that this has been indicated in the thesis.

Olga Linardou

Abstract

This report sets out to the theme of the generation of a 'living', homeostatic and self-organizing architectural structure. The main research question this project addresses is what innovative techniques of design, construction and materials could prospectively be developed and eventually applied to create and sustain human-made buildings which are mostly adaptive, self-controlled and self-functioning, without option to a vast supply of materials and peripheral services. The hypothesis is that through the implementation of the biological building behaviour of termites, in terms of collective construction mechanisms that are based on environmental stimuli, we could achieve a simulation of the generative process of their adaptive structures, capable to inform in many ways human construction. The essay explicates the development of the 3-dimensional, agent-based simulation of the termite collective construction and analyzes the results, which involve besides physical modelling of the evolved structures. It finally elucidates the potential of this emerging and adaptive architectural performance to be translated to human practice and thus enlighten new ecological engineering and design methodologies.

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Manos, because you were there to inspire this project and unconditionally uphold me until the end.

Table of Contents

List of Figures

1. Introduction

'Nature uses as little as possible of anything'
Johannes Kepler

The ecological and collective intelligence through which nature operates has stimulated a new approach to architectural design and construction (Steil, 1987). This multidisciplinary approach draws largely on existing synergies between biology and computer science. In particular, the study of self-evolving biological systems and organisms (Alexander, 2004; Ball, 1999; Heylighen, 2003; Hoftstadter, 1979) and the inherent interrelation of architecture to its natural environment have affected current architectural thinking by putting the emphasis on the generative process of the structure, rather than the end product itself.

1.1. Biology in architecture

Solid models of natural systems developed in biological sciences can be studied to inform architecture with the aim of transmitting in the design ground the vital underlying principles of living organisms (Alexander, 1964, 1977; Goodwin & Webster, 1996; Thomson, 1961). Key biological concepts such as adaptation, homeostasis, emergence and self organization may be translated in architectural practice, in order for the manmade artificial structure to be 'alive', that is, to achieve equilibrium with its natural environment. Lamarck's concept of adaptation ensures the fitness of a system by causing changes as a response to environmental pressures, but also allows for the fit system-organism to influence its environment in turn. Homeostasis (Bernard, 1957; Cannon, 1932) allows a living organism to maintain a stable state in equilibrium with the intrinsic and extrinsic environmental conditions through the efficient use of various adjustment means. Emergence refers to the way complex systems and patterns can arise out of a multiplicity of relatively simple interactions (Huxley & Huxley, 1947). Self-organization characterizes the properties of a system such as the continual adaptation to a changing environment and the strong aptitude to restore itself without centralized control or supervision. Self-organizing parts of the system or else autonomous agents carry out simple local rules without the insight that they perform a global task or that they participate in global organization (Camazine et al., 2001; Heylighen, 2003).

In architecture, we could consider a homeostatic and self-organizing structure as a structure which adapts dynamically to the changing environmental conditions; a living system, a 'breathing' organism in equilibrium with its ecological environment. The main research question this project addresses is what innovative techniques of design, construction and materials could prospectively be developed and eventually applied and sustain manmade architectural systems which are mostly adaptive, homeostatic and self-controlled, without option to a vast supply of materials and peripheral services.

1.2. A natural example of homeostatic architecture

A concrete paradigm of a self- organizing, adaptive natural system is a termite mound. A termite colony is a collective super-organism: a self-organizing system which consists of autonomous agents- termites, who act independently, without a co-ordinator, performing a set of simple local rules in their close environment, while they remain unaware of the global order which they produce. Their building activity relies only on topochemical stimuli (e.g. the sense of smell which informs the termite as to the topography of the places surrounding it, by means of chemical emanations of pheromones which are extracted both by the insects and the building material), and on social stimuli, such as the effect of formerly completed work, which triggers the implementation of additional work by the termites (see the concept of 'stigmergy', Forel, 1928; cited by Wilson, 1971, p252). The result of their collective construction mechanism is a homeostatic structure, created by sparing use of local materials that are utterly sustainable: energy regulating systems, embedded in the mound, accomplish its adaptiveness to the environmental changes. Function is integrated in the complex forms of termite mounds, whose various types of structures indicate the adaptation to the different external conditions. Not only ventilation and thermoregulation mechanisms but also rapid mound restoration in case of threatening exogenous factors, such as extreme environmental states or attacks of living organisms, reveal the ability of these agents to dynamically achieve a constant equilibrium in their ecosystem: to create and live in a homeostatic structure. As Wilson (1971) aptly notes "the entire history of the termites can be viewed as a slow escape, by means of architectural innovation, from a dependence on rotting wood for shelter" (p135).

Figure 1: Examples of site-specific termite mounds

For the present project, the generative process of a termite mound will serve as a case study and a basis of simulation of a self-organizing system, which builds by means of collective construction a homeostatic structure. This thesis points to previous biological and computational studies of termites building behaviour. Grassé (1959, 1984) and Bruinsma (1979) provided the first biological accounts of the termite behaviour, while Deneubourg (1977) made the first attempt to model the termites' collective construction in 1- and 2-dimensional worlds. Bonabeau et al. (1997) developed further the previous model, by incorporating more realistic factors in the paradigm's physics. However, it was Theralauz and Bonabeau (1995) that made the first attempt at modelling the process of collective construction in an agent-based manner, in the case of a wasp nest, but still with many weaknesses. Ladley and Bullock (2004) reimplimented the Bonabeau et al. (1997) model. Ladley (2004) developed next a 3D agent-based model, where through the use of local information in the type of simple rules, complex lifelike structures could emerge. However, none of the aforementioned approaches (see Chapter 2) managed to bind together the emerging, self-organizing termite structure with the concepts of homeostasis and adaptation, and their application to human construction and architecture.

1.3. Aims and objectives of the thesis

The aim of this thesis is twofold. It will firstly address the dynamics and factors which motivate the complex adaptive architectures and ecological functions of the termite mounds. Consequently, it will examine the extent to which the generative processes that underline these adaptive architectures and ecological functions can be implemented to human construction and thus enlighten new engineering and architectural design methodologies.

The main objective is first to simulate the collective construction of termites mound in a three-dimensional model, in order to acquire the underlying rules and collective mechanisms which regulate their homeostatic self-organizing structure. Subsequently, the objective is to study on rapid prototypes the generated termite mounds' types, and assess the potential impact on human construction methods, with respect to issues of sustainability, sparing application of materials and small consumption of energy. The hypothesis of the present thesis is that through studying and implementing the given biological data –in relation to the collective construction mechanisms- of termites, we will achieve a simulation of the generative process capable to inform architectural design and construction.

The present thesis studies natural life by attempting to capture the behavioural core of the essential components of a living system, and generating a simulation of analogous artificial components with similar behavioral repertories in a computational setting. At present, computational models (e.g. Cellular Automata) have proved to be a rich framework for investigating complex systems and phenomena. If coordinated correctly, the aggregate of artificial elements should demonstrate matching dynamic performance to the natural system. This bottom-up modelling method can be implemented at any stage of the hierarchy of living schemes in the natural world (the concept of Artificial Life, see Langton, 1997). Nevertheless, we are not concerned in creating precise replications or making exact forecasts about real-world systems. The natural world operates as a departure point for reflecting about adaptive, self-organizing systems and investigating termite-like behaviours (Rescnick, 1997).

The collective construction of a termite mound is going to be simulated through algorithmic applications on the platform of Processing programming language. Processing enables visual designers to work directly with code for responsive parametric sketching and prototyping. The user is at the same time the data tester, the transmitter and processor (Reas, Fry & Maeda, 2007). While software created for architecture presumes a definite range of design intentions, more generic software which serves computer science tasks allows for the exploration of self-organizing phenomena. On the other hand, the integration of different fields introduces translation difficulties across various parameters, material logics and architectural practices, while some of them are being tested through the rapid prototyping method on the termite mound paradigm.

1.4. Structure of the thesis

Chapter 2 reviews the relevant literature in biology and computer science and reports critically on former approaches to the simulation of termite collective construction. Chapter 3 explains the methodology adopted for the purposes of this project and presents the results. The main methodology consists of a 3-dimensional agent-based model- algorithm that has been implemented in Processing, in order to simulate the termite mound construction. The results demonstrate the simulation and rapid prototyping outputs. Chapter 4 provides a critical evaluation of the results, discusses their importance for current approaches in architectural practice and explicates the potential of improvement through further experimentation. Chapter 5 concludes with a summary of the project by highlighting the main research results and suggesting the next steps for the future expansion of the model.

2. Literature review

Scientific research about the termite building behaviour and its remarkable results has been conducted for the last 40 years. The first researchers studied the social insects' performance in a biological basis, by observing the actual structures and the real termite activities. More recently, the advent of swarm intelligence (Funes & Pollock, 1997) approaches in Artificial Intelligence paved the way for the study of the collective behaviour of decentralized self-organising systems and allowed the investigation of termites by biologists and computer scientists. Since the 90's, it became evident that the simulation of the social insects' behaviour in computational models was not only a viable approach for the understanding of their collective construction, but also for its generalisation in other decentralized self-organising systems and practices.

2.1. Biological Models

Grassé (1959, 1984), Stuart (1967) and Bruinsma (1979) were the first biologists who provided the foundations for this field of research, by revealing important information about the termites behaviour. Grassé (1959) studied the formation of the various types of structural elements that are present in termite nests. Grassé (1984) also underlined the social stimuli which motivate the termite building activity. He explained insects' behaviour in terms of 'stigmergy', the process by which a trace left in the environment by one termite stimulates the subsequent action by another. This approach represented the first step towards an understanding of the mechanisms that operate in the insect colony. In his two-step account, Grassé explained that first, there is the phase of 'unco-ordination', during which the termites explore the given setting, and start depositing soil pellets anywhere in the ground. As soon as the deposited material reaches a 'critical density' (when several soil pellets are fixed together), the termites become more attracted to the initial structure, than to single pellets. Subsequently the phase of 'coordination' starts: the insects transform the incipient structures into pillars and combine them, when within a critical distance, to form arches.

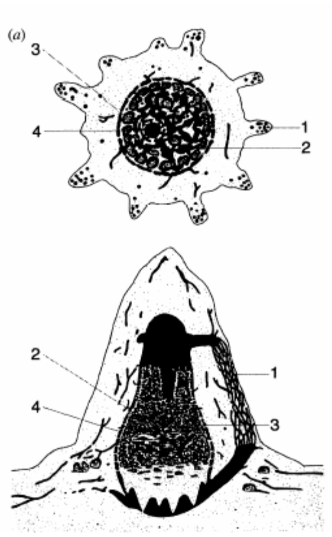

Figure 2: Cross-section of a Macrotermes mound (Lüscher 1961): (1) walls containing ventilation ducts, (2) brood chambers, (3) base , (4) royal chamber

Stuart (1967, 1972) further explained that the termites' motivation to construct is a response to a 'low level excitatory' stimulus (e.g. temperature, air flow, odour, light, etc.) that differs from the normal nest environment. The subsequent building activity gradually eliminates the contributory stimulus, and when a stable state is reached, building performance stops. On this account, Stuart concluded that the immediate function of building is an homeostatic one, because building activity is triggered by changes to the state of the system, and this activity ceases when the state is stabilized.

Bruinsma (1977) analysed the building behaviour of the termite Macrotermes subhyalinus by focusing on the function of pheromones (i.e. chemicals with the property of triggering natural behavioural responses on members of the same species). The termites' skills that give rise to a variety of structural elements in the mound are their ability to employ pheromones in a versatile way for orientation and their efficient processing of tactile sensations provided by physical objects. Bruinsma distinguished three different types of pheromones: the 'building' pheromone which is extracted from the queen termite, the 'cement' pheromone which emanates from the built material, and the 'trail' pheromone that emits from the walking termites. The queen's pheromone provides distance orientation to the termites, while their directional orientation is mediated by trail- and cement pheromones. For Bruinsma, the overall building activity is mediated by several negative feedback mechanisms that allow termites -like most other social insects- to control the environment within their mound by dynamically sustaining several stable states, based on behavioural and physiological regulation (the concept of 'social homeostasis', Emerson, 1954).

More recent biological accounts, such as the one provided by Turner (1994, 2000a, 2000b, 2001, 2005) have focused on the creation and embedded homeostatic functions in termite mounds, such as thermoregulation, air flow and gas exchange. He observed the architecture and morphogenesis in the actual mounds of different kinds of termites. Despite the indispensable value of the biological accounts on termite building construction, these models are limited by the very fact that they remain at best accurate observations of *what* the termites are doing. A more comprehensive understanding of *how* the termites accomplish their monumental structures requires the modelling the generative process that underline their collective construction.

2.2. Models of Collective Construction

The first attempt to model the termites' collective construction has been conducted by Deneubourg (1977) who tried to explain the creation of pillars within a termite mound (see also Deneubourg et al., 1989, 1990, 1992). Deneubourg (1977) claimed that the pillar formation was the result of a positive feedback circle, based on the interactions among the termites, the 'active' building material and the cement pheromone which was being extracted from the latter. Consequently he simulated those three factors by a sequence of differential equations and presented their performance over space and time in 1D and 2D worlds. The strong points of Deneubourg's model were twofold. First, he retained a minimalism at the parameters in relation to the effect of the pillars formation and second, and most importantly, that there was not a single termite-leader or coordinator who was responsible for the nest's collective construction. Instead, the construction was the collective effect of a self-organizing system. Nevertheless, there were several weaknesses in his model, such as the unrealistic spatially and temporally input of new termites in the world, the unnatural effect of the cement pheromone's diffusion and also the fact that the already deposited building material had no influence on the termite movement.

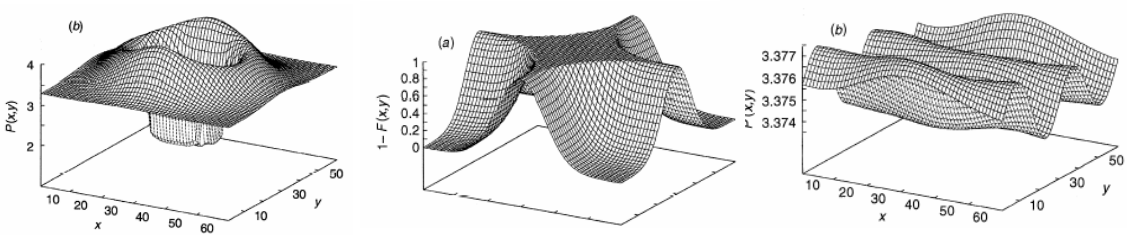

Figure 3: Formation of royal chamber and trails (from Bonabeau et al., 1998)

Bonabeau and colleagues extended the focus on the modelling of building behaviour of insects (1994, 1997, 1999, and 2000). Bonabeau et al. (1997) further developed Deneubourg's model, by incorporating factors like the queen pheromone template, the impact of wind, and an artificially enforced flow of termites across the 2D world. As a result, a royal chamber and walkways were constructed on the basis of very simple rules, whereas the effect of environmental factors was obvious on the creating performance. Nonetheless, the limitations of Deneubourg model remained unanswered in Bonabeau's proposal: the building material had still no influence on the movement of termites and the diffusion of the pheromones was again unrealistic. Furthermore, the two dimensional world did not allowed for enclosed volumes to be shaped. Subsequently, there was no evidence of completion of either the chambers' or the passageways' volume.

However, it was Theralauz and Bonabeau (1995) who made the first attempt at modelling the process of collective construction in the case of a wasp nest by employing an agent-based approach,. The model simulated the behavior of individual stigmergic wasps in a 3D world. At each time-step the wasp's movement was determined by a set of local rules, that where quite realistic, such as the constraint of the already existing material. The wasps had neither the sense of communication, nor the idea of the complex global structure which would emerge by their performance. The strengths of this model were several and important. It brought together an agent-based approach in a 3-dimensional world that allowed complex lifelike structures to emerge through the use of local information in the form of simple rules. Yet, some weak points still remained such as the unrealistic form of the building material, its unlimited distribution and the imprecise way of communication among wasps.

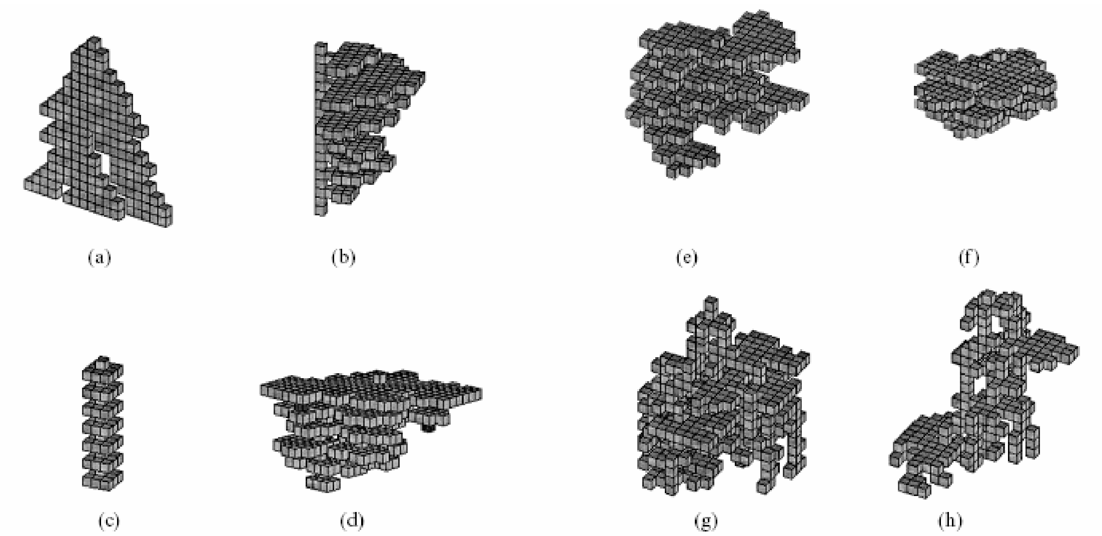

Figure 4: Collective building by social insects (from Theralauz & Bonabeau, 1995)

Ladley and Bullock (2004, 2005) revisited the Bonabeau et al. (1997) model by combining the performance of active material (i.e. recently deposited) and inactive material (i.e. material that has ceased to emanate cement pheromone) in the process of pillars' formation. This extension of Bonabeau's 2D model was only appropriate to capture the primary tendencies of the termites' building behaviour and not to illustrate their long-term construction performance. Consequently, Ladley (2004) developed a 3D agent-based model to improve on the weaknesses of the previous representations and to respond in a more realistic way to the termites' behaviour of collective construction. The form of the building material and the three types' of pheromone diffusion which were directing the agents' building decisions formed a hemispherical dome which has been considered as a type of the royal chamber, and walkways of a termites' mound. However, the end structures were not integrated and seemed quite abstract and 'artificial', in terms of building material deposition and generated shapes. Additional weaknesses included the unrealistic attempt of wind simulation, which had been modelled as a one-directional pheromone flow.

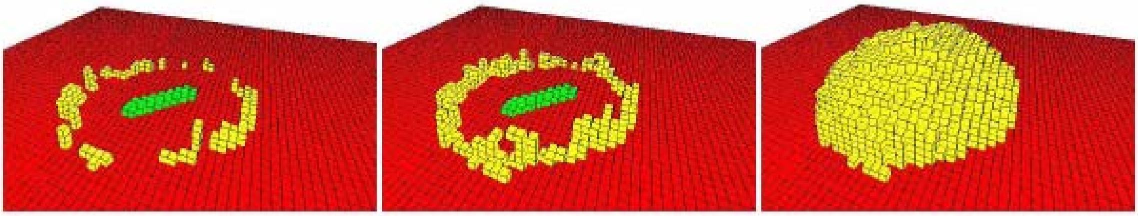

Figure 5: Formation of royal chamber (from Ladley,2004)

Nonetheless, there is not yet a line which binds together the emerging, self-organizing termite structure with the notions of homeostasis and adaptation, and their application to architectural design and construction.

This thesis intends to embed the objective biological factors which arouse the complex adaptive architectures and homeostatic functions of the termite mounds, in a simulation of this natural phenomenon of termite collective construction. Subsequently, the purpose is to explore the extent to which our understanding of the generative processes that underpin the homeostatic architecture of termite mound construction can be implemented to the design and construction of manmade structures and inform new engineering and architectural design methodologies.

3. Methodology and Results

3.1. Methodology

The hypothesis of the present thesis is that through studying and implementing the given biological data –in relation to the collective construction mechanisms- of termites, we will achieve a simulation of the generative process capable to inform architectural design and construction.

Methodological framework

The present thesis investigates the collective construction mechanisms of termites on the basis of their use of biological information by simulating the generative process involved in the construction of their mounds. The implementation of this simulation required a methodology that is appropriate for the study of self-organizing systems (Camazine et al., 2001). Accordingly, our methodological approach consists of (i) the observation of the behaviour of the system under investigation, (ii) the development of an hypothetical model that governs this behaviour, (iii) the experimental testing of the model through simulation and (iv) the evaluation of the results to assess the extent to which the simulated model agrees with the actual system's performance.

The understanding of the behaviour of the system derived from the extensive biological studies on termites as reviewed in Chapter 2. In particular, we attempted to capture the behavioural essence of the critical parts of a termite colony super-organism. The different types of pheromones and their sources (the queen, the built material and the termite movement's trail), physics (such as pheromones' diffusion), the concept of stigmergy, the realistic termite input in the world and the termite movement constraints have been simulated by algorithmic applications. Thus, different simulations were implemented by changing the type and form of interactions that exist among the variables of our complex system. In this way, the type of global behaviour can be varied such that the system as a whole can be globally goal-seeking, while only local information is passed around by its parts- the autonomous agents and their environment. Consequently, we hypothesized that if coordinated correctly, the collective of artificial elements should demonstrate analogous dynamic performance to the natural system of a termite colony. These elements were used as independent variables implemented in a code written on the platform of *Processing* programming language. The code was used to simulate construction behaviours produced by the manipulation of the independent variables.

Agent-based model

The basis of the code was a computational 3-dimensional Cellular Automata-like machine, as CA is a decentralized computational model and its principal characteristics (e.g. parallelism and local interactions) are analogous to the real termite behaviour mechanisms. The model was agent-based. The termites were considered as autonomous agents, like in natural life: they are units that interact with their environment but act independently from all other agents. There is not a leader who coordinates their activity, nor does an agent have awareness of the global, orderly plan that arises through his performance. The simulation model was built in a 'bottom-up' way. The behaviour of the individual agents-termites was programmed to replicate their real natural performance. We thought that a bottom up approach would produce a more accurate model, as it would be based on the behaviour of the system's subunits.

Thus, the simulations aimed at generating a performance of collective behaviour which as a whole would resemble to the actual system. If this happened, the termites-agents would be responsible for the patterns observed; otherwise it would be evident that vital factors of the system were missing from the model. Finally, for the purposes of this thesis, what is important is not the precise replication of real-world systems. The natural world operates as a departure point for reflecting about adaptive, self-organizing systems and investigating termite-like behaviours (Rescnick, 1997), and to this end, the emphasis is on the performance of the generative process itself within a self-organising system.

Piloting simulations

At the very beginning, StarLogo (www.education.mit.edu/starlogo/) provided a playful environment where basic swarm behaviour of turtles, ants and other collective parts were simulated in a 2-D interface (see Figure 6).

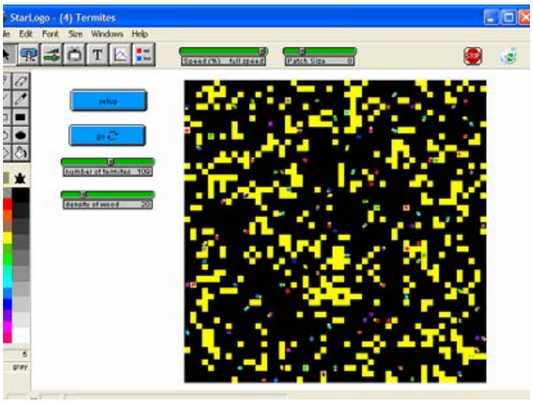

Figure 6: Experimenting in StarLogo environment

This piloting simulation in StarLogo was then followed by a more "generated" and controlled simulation in a code written in *Processing* programming language. In the beginning the simulation attempts were performed in a 2-dimensional model-world. The result was not a simulation of the actual construction of a termite mound, but instead it was a display of a termite-like behaviour (see Figure 7). There were randomly distributed soil pellets- represented by black squares- all over the ground, and as time passed, random piles were formed around a queen-point. The white locations indicated the empty space. The few algorithms involved simple rules that affected the termite movement, in arrays where the possible next pellet-deposition locations were stored. The termite picked each time a soil pellet and transferred it to an empty location, in order to form more dense piles.

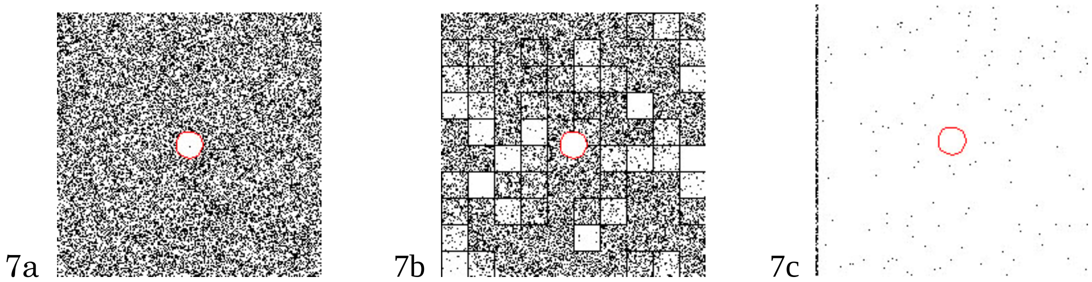

Figure 7: Initial experimentation in Processing: figure 7a shows the random distribution of soil chips, figure 7b shows the grid that turns into random piles, figure 7c shows the soil chips- termites distribution only from the left world side.

Experimenting on an agent-based 3-D model

The final agent-based 3-dimensional model was a simulation of the termites self-organizing building behaviour that aimed to demonstrate their collective construction performance. Interactions which occurred amongst the agents and the local environmental parameters contributed to the generation of a global organization pattern. The final model is based on Turner's initial code.

Algorithm for the self-organizing collective construction process:

In the Main:

a. let the queen's pheromone approach equilibrium
b. create the empty world
c. upgrade the world (generation of mound)
d. disperse pheromones

In Class Cell:

a. create the pheromone lattice which sorts current and next pheromones values, allowing a CA-like synchronous update for dispersion

In Class Location:

a. sort world locations
b. record the filled locations' adjacencies
c. define the accessible building locations

In Class Termite:

a. define termite movement in the world
b. define final building location

The model was built in a 'bottom-up' way, as aforementioned. The addition of features to the program was gradual in order to check that they function correctly. The world involved a 3-dimensional cubic grid (80x80x80) of units-cells or locations. The ground was empty and open. Each unit of building material was represented by one filled cell. There was not an actual appearance of termite-like objects in the world. The 'termites' corresponded to the building material that was being laid down. The simulation limited the termites to one kind of performance, combining building and moving activities, ignoring other activities performed by termites in nature, such as nursing and foraging.

Filling the world and moving around it: rules and constraints

In order for the simulation to be realistic, there were several movement and building material constraints. The building material which filled the cells could be placed down only when specific conditions were met. All of them are scripted in code's Class Location:

(a) The first constraint is that the termite must end up inside the world.

```
//Create an array of accessible locations
Loc [] locs;
//Create tables of value and position in array
Pair [] sorttable;
Reset_accessible_locations
Exclude_starting_location
//Test locations: must be inside the world
Position x >= 0 && Pos.x < world_width &&
Pos.y >= 0 &&Pos.y < world_depth &&
Pos.z >= 0 && Pos.z < world_height
```

(b) The second constraint is that the next to-be-filled location had to be unoccupied by building material. This condition prevented the termites from moving through already built structures.

```
//test the array of filled_locations
```

(c) The third constraint was that one of the new location's neighbouring cells must have been occupied by building material or belong to the ground

```
//test the binary string of positions_adjacencies
```

(d) The fourth constraint obliged the termite to attach to surfaces and stopped it from wandering around the world. Accordingly, it had to share at least a face with another piece of deposited material

```
.       Test the binary strings of positions and positions_adjacencies
        if ((posAdjacencies & testPosAdjacencies) != 0) {
            accessible = true;
```

Moreover, the building material that was laid down blocked the termites' movement, the pheromone diffusion and the possibility that any more material was going to be placed there.

Pheromones' diffusion

At each time step, every termite was allowed to act and the three types of pheromones were allowed to diffuse.

```
In Class Cell
//Create two arrays of pheromones_levels/ the pheromone has two values: the current
and the next: CA-like synchronous update for dispertion
float [][] pheromone_level;
pheromone_level = new float [PH_TYPE_COUNT][2]; //count the three types of
                        pheromone and both their current and next step levels
```

These pheromone types could occupy any cell of the 3-d world lattice: every location in the world represented the pheromone level at that location. More importantly, the amount of each type of pheromone at every location changed over time due to evaporation, diffusion, and already deposited building material.

The pheromone sources were of two types. First, there was the queen's or cement pheromone (queen_pheromone) with fixed output. This type was expected to maintain a constant template throughout the simulation. Then there was the building material's (earth_pheromone) and termite's trail (trail_pheromone) pheromones, which were being regulated over time by the world's physics (diffusion and built material).

The pheromones' diffusion was based on the established method of finite volume (Rübenkönig, 1992) Thus, the mechanisms of the artificial physics operated through local updates of the cells states, and the pheromones distribution was quite realistic because the deposited material had to be taken into account. For instance, if the cell, to which a particular volume of pheromone was being transferred, contained a block of building material, the pheromone was returned to its source location and dispersed amongst the unoccupied cells.

```
In Main
//Pheromones disperse at each time step
//Sort in array the adjacent locations and their pheromone levels
float [] pher_level = new float [PH_TYPE_COUNT];
…
pher_level[ph_type] = grid[i][j][k].pheromone_level[ph_type][current];
   pher_total += pher_level[ph_type];
// Half the pheromone stays where it is
…
grid[i][j][k].pheromone_level[ph_type][next] += pher_level[ph_type] / 2.0;.
// first count the filled squares
// ignore the central cell
 (a != i | | b != j | | c != k)
  // concentrate on the pheromone within the world
 if (a >= 0 && a < world_width  && b >= 0 && b < world_depth && c < world_height)
…
Distribute_remaining_pheromone_among the unfilled cells
```

The insects' movement in the model was basically random and influenced by the pheromones' quantities. A given world location- cell was filled in the model when a termite entered a location in which the concentration of queen or earth or trail pheromone was within a certain value.

Below there are some lines (written in pseudocode) which played an important role in the simulation, as they utterly affected the termite movement and consequently the deposition of building material. By slightly tuning the following bits, significant changes appeared on the construction patterns.

```
In Class Filled Location
//look for higher/lower levels of pheromone for the next step
Set up a table of location pheromone value
Sort  location's position in array
Find_somewhere_to_build
//sort the locations and their pheromone levels
Begin from the queen and move towards building_material
Sort
Begin from the building_material and towards the queen
Sort
Begin from the queen and the building_material and towards where last_deposited_
material
```

```
Sort

In Class Termite
// this function keeps the termite stepping until the pheromone drops off
Find_Drop_Location
Check_queen_pheromone_level_at_build_site
Build_when_in_distance_from_queen
Check_pheromones_level_at_build_site
Do_not_built_on_trail
```

Constrains in the simulation process itself

Physical constraints on the movement of termites and the pheromones diffusion did not disorder the construction process. Nevertheless, they have made the completion of the structure more challenging as some locations became more difficult to reach and the termites were blocked and finally lost. In some cases, constraints on diffusion have probably caused far too high levels of pheromone to allow any building activity to occur.

Another actual constrain in the simulation, was the long term running time. As a result, most of versions needed many days in order for the structure to be generated. Moreover, it was only when the structure raised, that we could evaluate and hypothesize possible modifications that could improve the code, and run it over again.

3.2.Results

Overview of the general behaviour of the system

The general behaviour of the system represents a quite realistic simulation of the termites' behaviour as described by previous biological and computational models (Bruinsma, 1979; Grassé 1959, 1984; Stuart, 1967, 1972; Turner 2000a, b, 2002). In particular, the code managed to simulate successfully the agent-based approach within a 3-dimensional representation on the basis of local information only. As a result, the collective construction performed by actual termites was simulated successfully (see Figure 8).

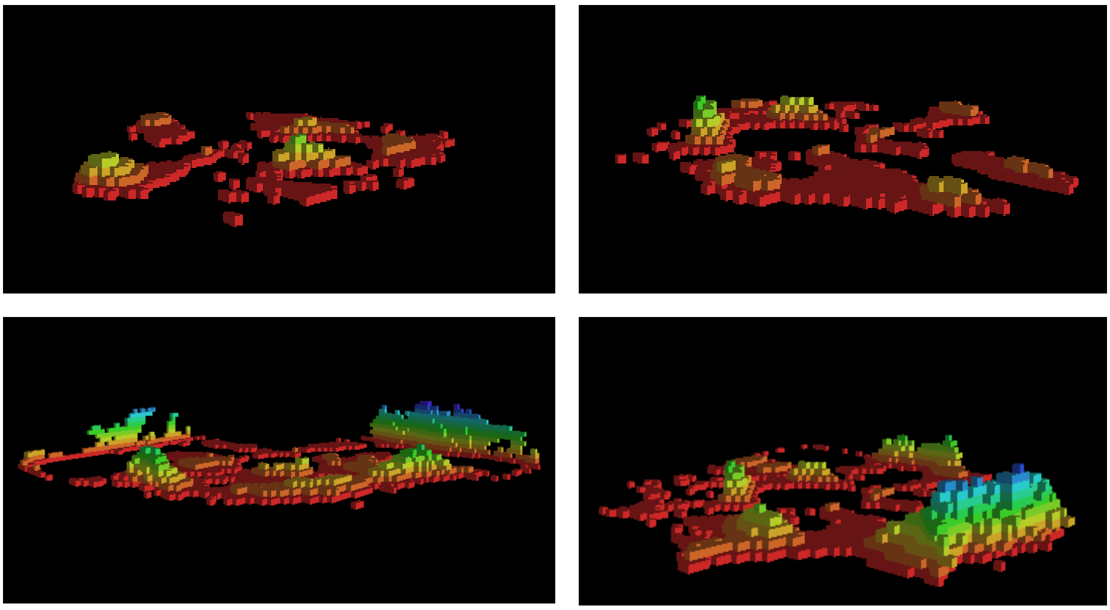

Figure 8: Initial stages of the simultaneous and collective construction at different locations in the 3D world across 4 different simulation runs

The modelling of termite movement constraints was successful. Termites were limited to move on the surface of any material in the world, not through already built material and were not allowed to build on trails. As a result, the output of the simulations represent biologically and physically plausible constructions. The realistic modelling of pheromone diffusion, based on finite volume methods, resulted in a physically plausible model of diffusion as the pheromones could not disperse through the building material. The modelling of building constraints prevented the creation of many unrealistic assemblies of filled cells. However, at the same time it made it possible for the agents to build large vertical structures or thin high towers.

The overall behaviour of the system suggests that the evolved structures- such as the queen's chamber and the termite mound- observed in the simulations, can be biological and physically plausible representations of the generative process of termite collective construction.

Queen's chamber

An imperceptible 'queen'- pheromone source was in put the centre of the world in contact with the ground. Throughout the simulation the queen's pheromone source remained almost stationary, between a certain minute range. The simulation was initially run for a few time steps without the presence of termites to allow the queen pheromone template to become stable. Subsequently, the queen pheromone template guided the generative process. As the template was stabilized, the termites started to appear and occupied world cells which were in contact with the world's (empty) ground. From this time onwards the simulation proceeded as it has been explained in the experiment's section. Previous models (Deneubourg, 1977; Bonabeau et al., 1997; Ladley, 2004) had predicted that a single source of queen pheromone would trigger termites to raise a hollow chamber around the source. This forecast was confirmed by the agent-based simulation (see Figure 9).

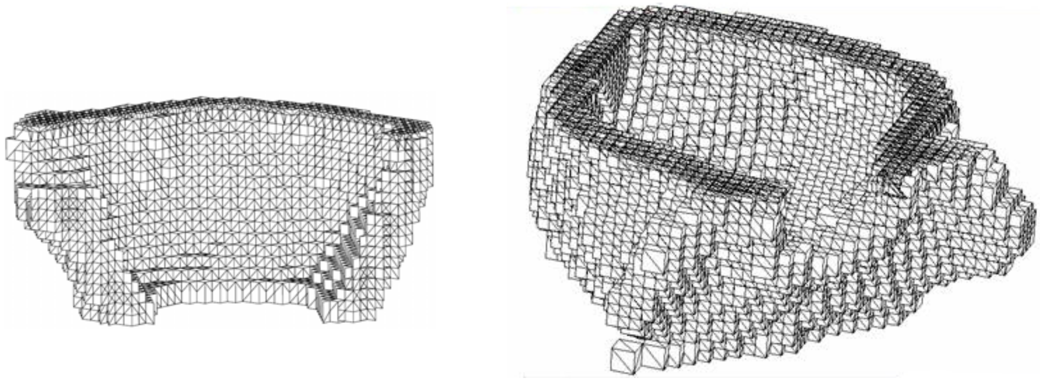

Figure 9: The stages of the created chamber over the pheromone source and the hollow unoccupied interior. The image on the left shows a section of the chamber while the image on the right is the isometric view. These drawings were generated by the transformation of the initial Processing code into DXF points. Consequently the DXF points were imported in AutoCad and processed to produce the views.

Primarily pillars were generated (Figure 10a), then they were connected by low walls (Figure 10b), and consequently pillars and walls grew until the chamber was formed (Figure 10c). The simulation generated royal chambers across different (in relation to the generative rules) run versions (Figure 11).

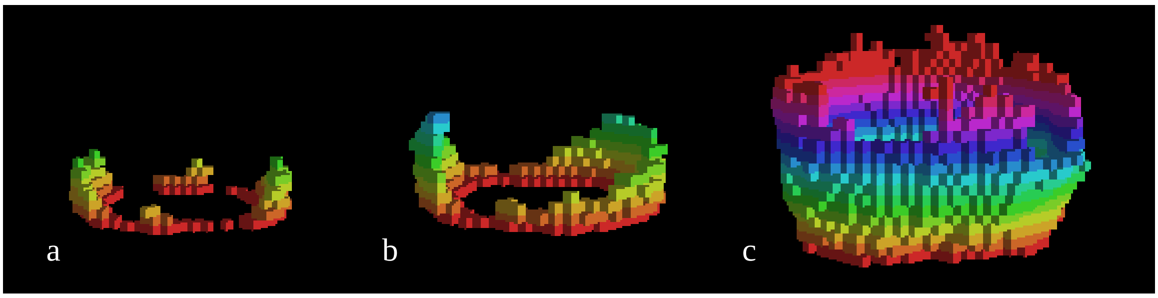

Figure 10: Pillars and walls formation

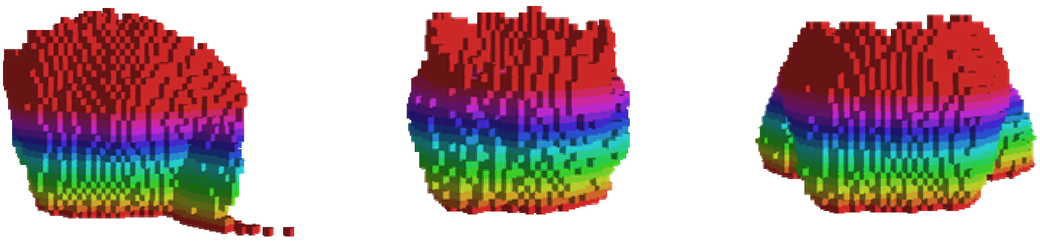

Figure 11: Exemplars of generated royal chambers.

In the initial stages of construction there may have been several entrances to the queen chamber (Figure 12a). As construction continued, many of the entrances were blocked, but with the influence of the trail pheromone one entrance always remained clear (Figure 12b, c).

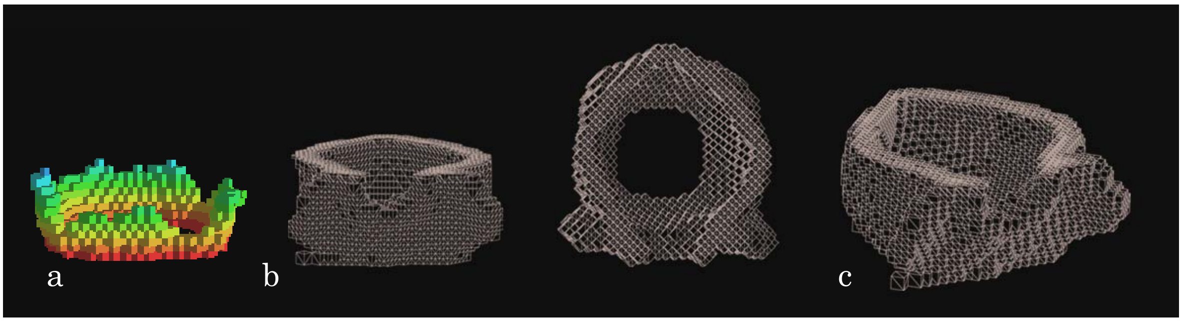

Figure 12: Entrances to royal chamber

The trail pheromone attracted termites towards an entrance resulting in the formation of a positive feedback cycle. This result represents one biologically plausible explanation of the formation of an entrance, at least within the context of the implemented simulation.

Termites Mound

Through some tuning and adjustments on the algorithm, the external shell of the whole termite mound started to be generated (Figure 13).

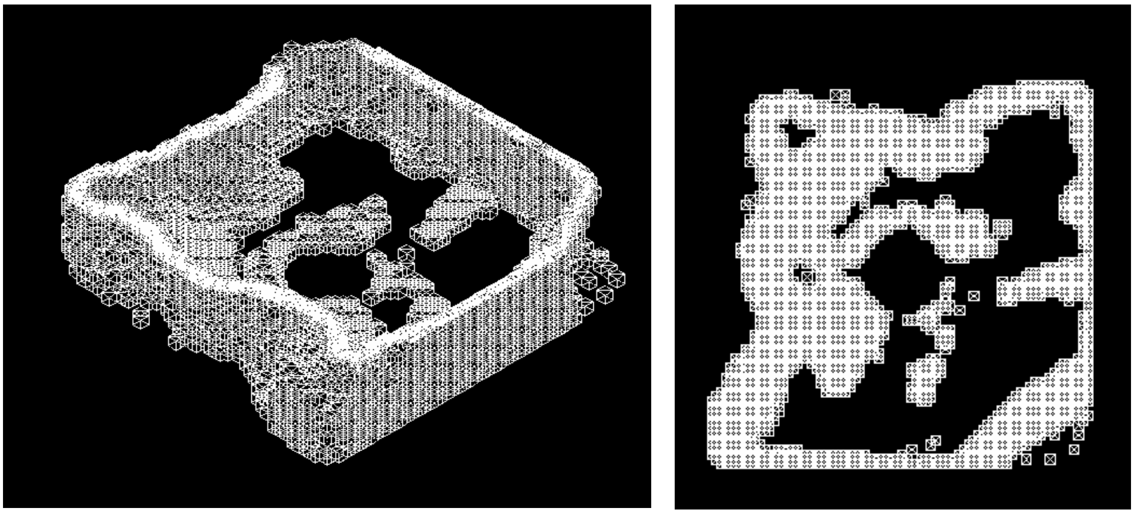

Figure 13: The mound isometric view (left) and the top view of the mound (right)

The invisible stationary queen pheromone source was placed again at the centre of the world in contact with the ground. The simulation run again for some initial steps without the appearance of termites to allow for a stable queen pheromone template. Then the queen pheromone template guided the generative process and the world locations –firstly those in contact with the ground-started to be filled with building material. From this time onward the simulation proceeded as it has been explained in the Methodology.

By keeping the pheromones diffusion method stable, and modifying the algorithms that controlled the termite movement among the different pheromone sources, which in turn affected the insects' choices to fill world locations, a primitive representation of the complex termite mound was generated.

Primarily pillars arose then they were connected by low walls (Figure 14), and subsequently pillars and walls grew until the mound was formed (Figure 15). The mound interior was generally hollow at this stage, but there is evidence of the formation of low structures that can be considered as the predecessors of some intricate inner constructions, such as tunnels and chambers (Figure 16).

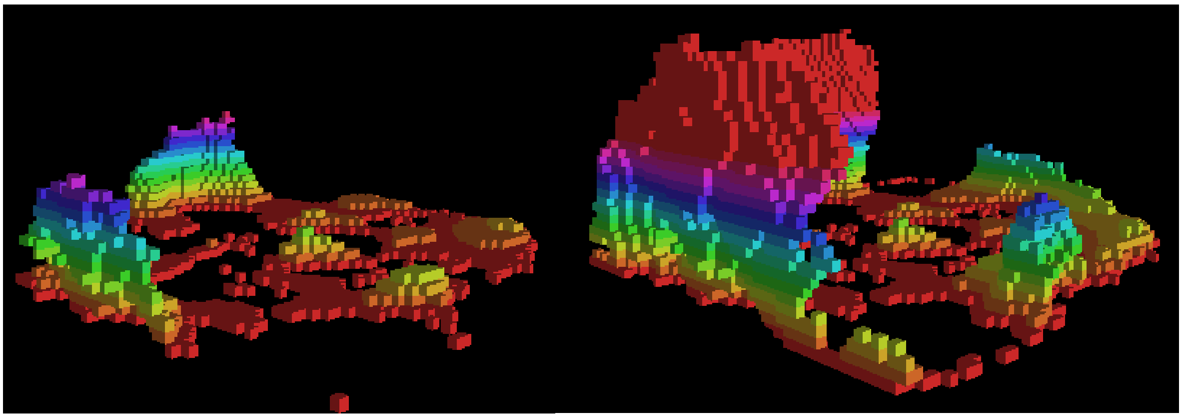

Figure 14: Generation of mound pillars and walls

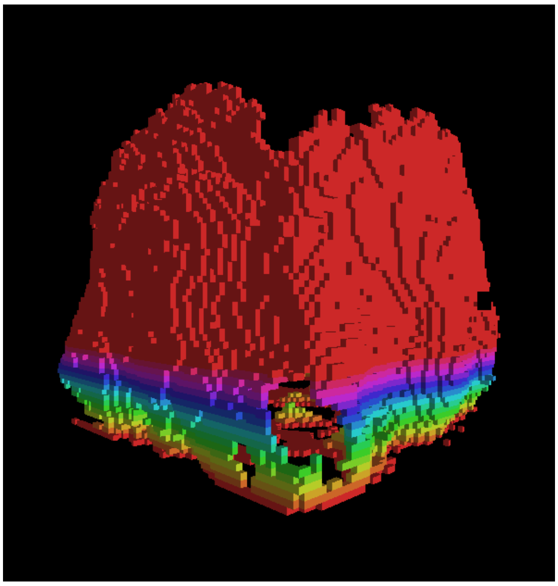

Figure 15: Towards Mound Completion

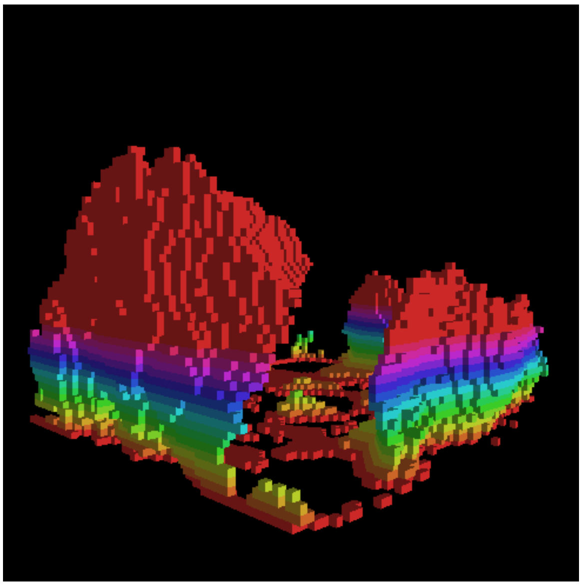

Figure 16: Internal structures

As before, the appearance of the base of the queen chamber, in the centre of the mound is evident (see Figure 13). In the primary stages of construction there were again several entrances to the termite mound (see Figure 16). As construction continued, many of the entrances were blocked. However, it is possibly due to the effect of the trail pheromone that one entrance remained clear (see Figure 15). We can also observe some holes on some of the mound walls. Overall the simulation succeeded in generating a basis of a termite mound-like structure (see Figure 17).

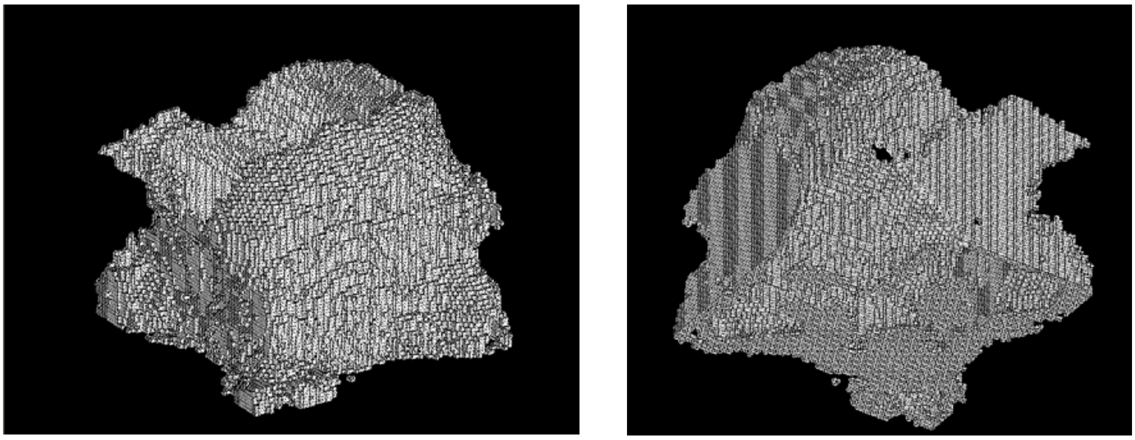

Figure 17: Isometric and bottom isometric views of the mound.

Both the simulations of the queen's chamber and the mound (Figures 18, 19) show that the generated computer models succeeded in creating 3D structures that shared the basic properties of termite mounds on the basis of generative processes.

Figure 18: Top views of mound and royal chamber

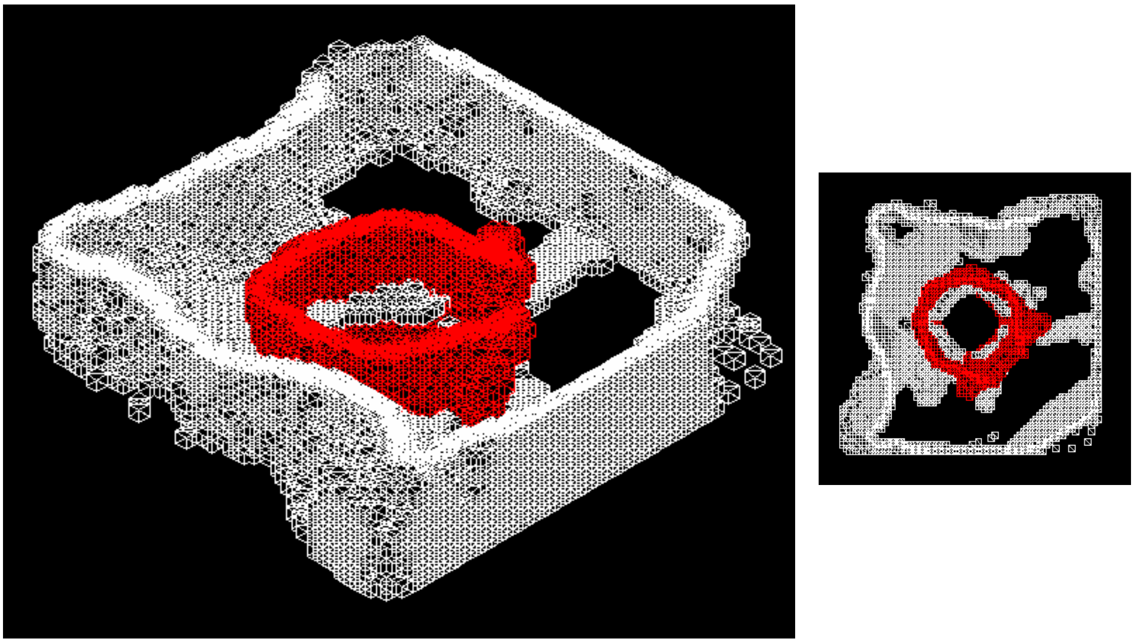

Figure 19: Isometric and top views showing how the royal chamber is embedded in the termite mound

The process of experimentation that involved tuning of the parameters of the algorithm is illustrated in Figures 20 and 21. Figure 20 shows the stages of generation of the royal chamber and the termite mound across different time-steps. Figure 21 illustrates versions of royal chambers and termite mounds generated in several simulation runs caused by different pheromone levels. The numbers of filled world cells and lost termites are shown across time steps.

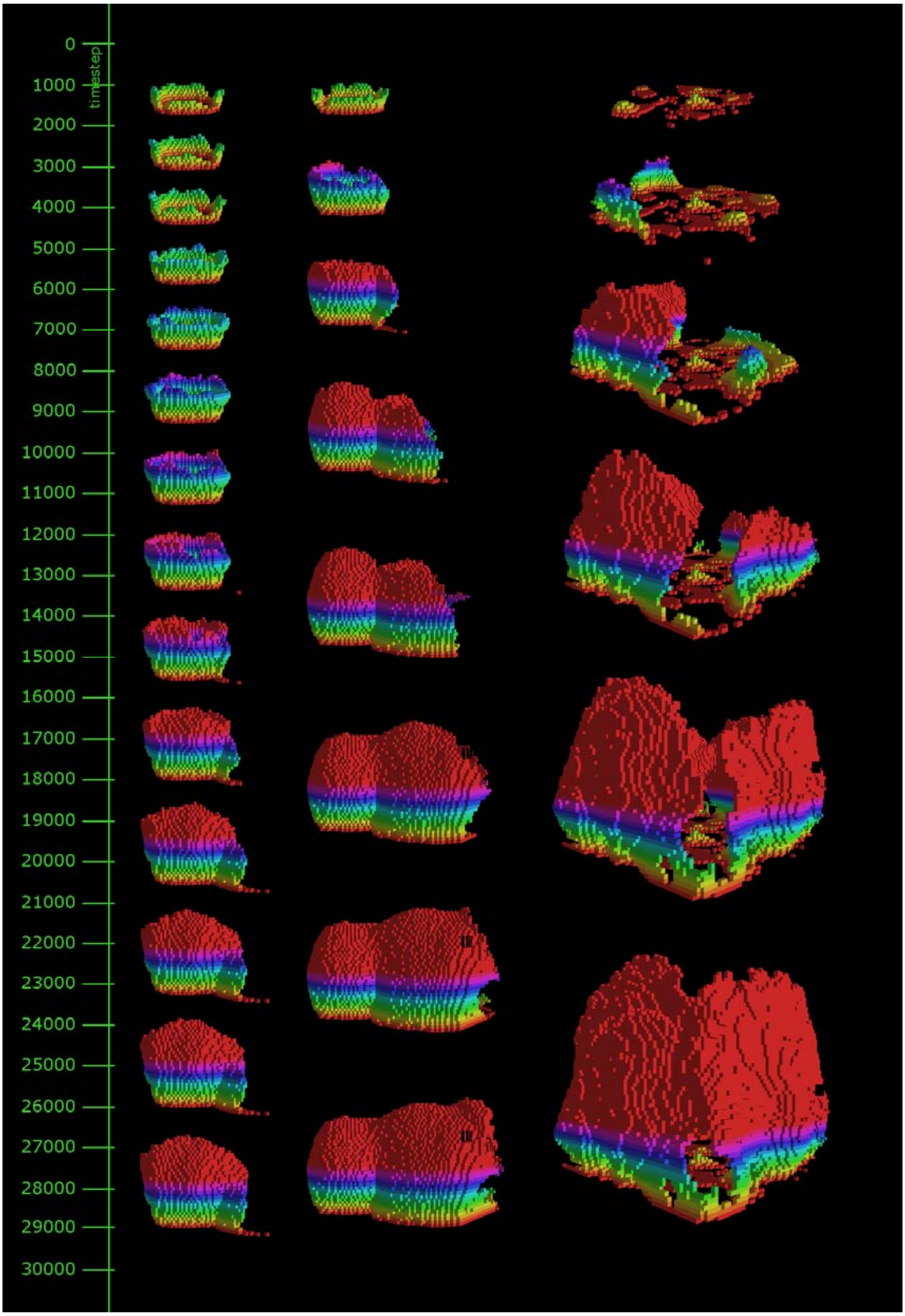

Figure 20: The stages of generation of the royal chamber and the termite mound across different time-steps.

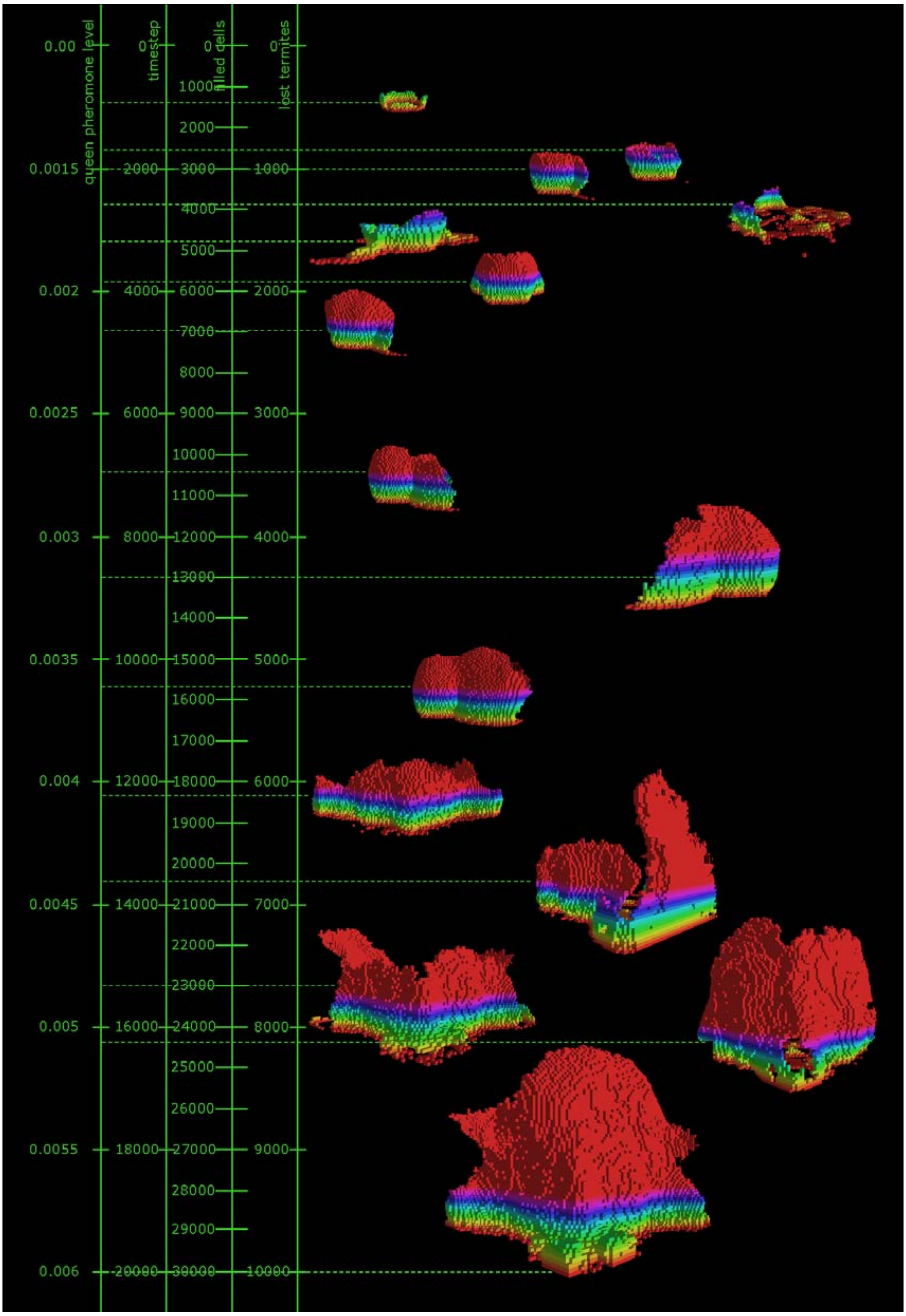

Figure 21: Versions of royal chambers and termite mounds generated in several simulation runs caused by different pheromone levels. The numbers of filled world cells and lost termites are shown across time steps.

Rapid Prototyping

Rapid manufacturing with the method of Solid Freeform Construction ha been used to translate the generated computer models of the queen's chamber and the termite mound into physical prototypes (Figure 23).

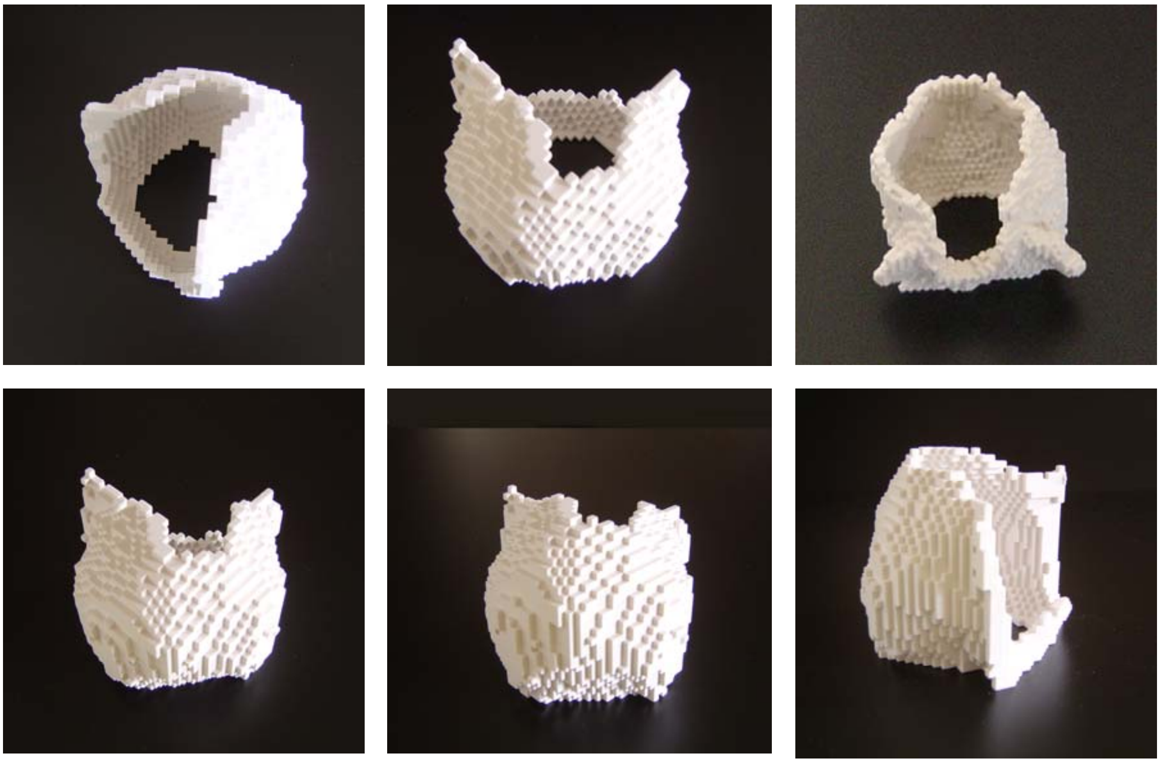

Figure 22: Physical prototypes of royal chambers generated through Solid Freeform Fabrication, after the transformation of Processing code to Stereolithography files.

In many respects, physical models exhibit a clarity and legibility that few kinds of visual representation can achieve. The advantage of the prototype lies within the interactive modality it supports and the subsequent critical response that this initiates. Although the option of digital representation provides a competitive alternative, the three-dimensional material nature of the physical prototype retains some important qualities for the critical observation of the architectural product (Callicott, 2001).

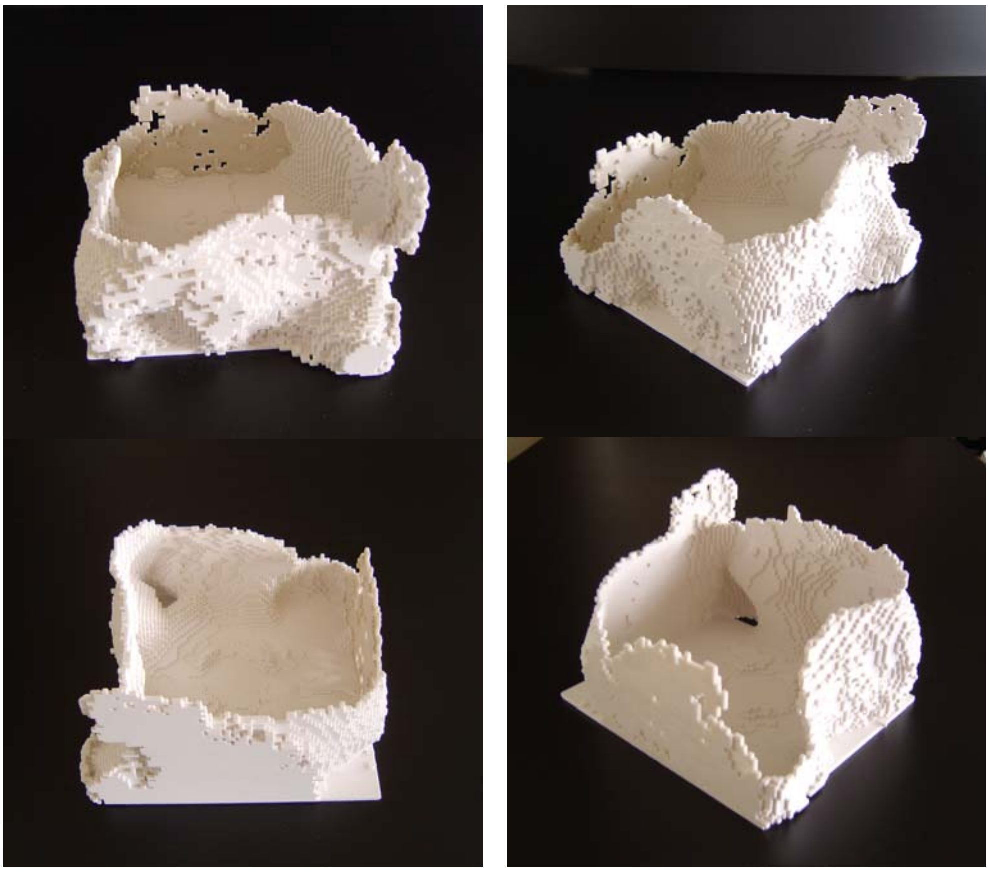

Figure 23: Physical prototype of termite mounds generated through Solid Freeform Fabrication, after the transformation of Processing code to Stereolithography files.

The actual termite structure models communicate their concept through their scale, volume and materiality. We can critically comment on their full shape and realize the enclosed volumes, which in case of completion of the termite mound, could serve as a physical testing of homeostasis and internal environmental conditions. However, physical modelling played an integral role in the completion of this thesis, as the project succeeded in *manufacturing performance*.

4. Discussion and Evaluation

The results of the project achieved moderately to respond to the main research question, which was to invent prospective innovative construction techniques, so as to sustain adaptive and homeostatic human-made structures. The starting hypothesis was that the implementation of collective construction termite mechanisms that are the based on the exploitation of environmental stimuli, would achieve a simulation of a generative process capable to inform in many ways human construction.

For the results to be meaningful, it was crucial that the behaviour of the simulated system corresponded well to the actual natural phenomenon of termite-mound construction as described in biological models (Bruinsma, 1979; Grassé, 1959, 1984; Stuart, 1967, 1972; Turner, 2000a, 2000b, 2001). To that end, the developed model managed to capture a close to the real termite colony system performance in terms of both its structure and the underlying physical parameters. The implemented code was a combination of agent-based approach, 3-dimensional representation and use of local information, analogous to the information found in a termite environment. The essential generative factors of the social insects' collective construction were simulated in a fairly pragmatic sense, as it has been analytically described at the results section. Consequently, the outcome involved the emergence of structures reasonably close to observed natural ones, such as the queen chamber and the external shell of the termite mound.

The most important factor, which has contributed to the formation of termite-like architectural structures, involves the realistic modelling of pheromone diffusion. The simulation of diffusion has been based on the established technique of the finite volume method. Thus, the mechanisms of the artificial physics operated through local updates of the cells-location states, and the pheromones distribution was biologically plausible because the deposited material was taken into account. For instance, if the location, at which a particular volume of pheromone was being transferred, contained a block of material, the pheromone was returned to its source location and dispersed amongst the unoccupied locations. Therefore the pheromones could not pass through already built structures, and that has contributed to an effective, realistic construction mechanism.

The realistic diffusion model was further complimented by (i) the sensible modelling of termite movement constraints (termites were limited to move on the surface of any material in the world, not through already built material and were not allowed to build on trails) and (ii) the pragmatic simulation of building constraints. Both types of constraints were the keys for the even, natural-like generative process, and resulted for the first time in the formation of the basis of a whole termite mound. It is precisely this combination of a realistic pheromones' diffusion model with the implemented movement and building constraints that represent the major advancement in comparison to previous models of termite construction.

Deneubourg's attempt (1977) to explain pillars formation, in 1 and 2-dimensional worlds, entailed several weaknesses, such as the impractical spatially and temporally input of new termites in the world, the unrealistic diffusion method of a *single* type of pheromone, and the null effect of deposited building material on the termites movement. Bonabeau et al. (1997) still do not have the answer to the limitations of the first model. Furthermore, the two dimensional world of the model did not allowed for enclosed volumes to be shaped. Even the last and most close-to-nature model of collective construction (Ladley, 2004) has not achieved reasonably realistic results. Although it responds in a much more pragmatic way than the previous ones to termite behaviour, in terms of parameters, however the end structures of a hemispherical dome and a type of tunnel seem quite abstract and biased. They are not integrated and appear 'artificial', in terms of building material deposition and generated shapes.

The present study contributes quite plausibly to the simulation and the outcomes of the generative process of termite collective construction. Moreover, it involves an approach which seeks to bind together the very generative process of the emerging, self-organizing termite structures with the notions of homeostasis and adaptation, and their application to architectural design and construction. However, the code itself did not manage to fully replicate the complete intricate internal architecture which integrates the homeostatic functions in actual termite mounds. Consequently the results of the project achieved moderately to respond to the main research question, which was to invent prospective innovative construction techniques, so as to sustain adaptive and homeostatic human-made structures.

At this point, it is essential to underline the fact that due to time constraints, only endogenous environmental parameters, such as building material, pheromones dispersion or termites input have been taken into account. Extrinsic environmental factors such as light, heat or wind, which could have probably caused the completion of the mound structure (in more details below), have been unfortunately left out. This involves, for instance, the simulation of the parameter of heat, which would cause the pheromones evaporation, affect the diffusion's mechanics, and consequently material deposition and the final architectural form. Nonetheless, there are some important stages that have been reached through the research process, which involve potential impact both on physical concepts and architectural and construction practice. Below they are discussed in turn.

4.1. Creation of an agent-based, self-organizing model

The creation of an agent-based self-organizing model entails the challenge of understanding the process of collective construction, as well as the significance of the individual, autonomous agent in the generative process. The present thesis emphasizes the importance of the complexity which can emerge by simple individual behaviour. The results clearly demonstrate that in the absence of any form of centralized control or direct communication, agents can successfully exercise simple rules to construct complex architectures. Thus, the study of a termite-like system can be highly informative for architectural models of collective construction.

The project explored the concept of emergence, in terms of the complex, orderly patterns which arose from the interactions amongst simple, homogeneous subjects. Eventually, we tested and demonstrated that order can emerge from randomness, and that a self-organizing system does not get stuck on local optima while seeking for global organization. Hence we managed to simulate a self-organizing system, that is, a system which is governed by the interactions amongst its autonomous agents and characterised by the attributes of parallelism, recursion, iteration and adaptation. Due to parallelism, multiple tasks can be performed simultaneously, such as the concurrent activities of the similar units of termites. Iteration and recursion allow the termites to react to environmental stimuli, and at the same time to modify their environment, which means that forthcoming actions by a termite will have to take these contextual changes into account. Analogous to global aim-seeking, in order for the universe to shift coherently from one state to the next, prior states must be recalled, which means that recursion and iteration exist as a form of memory that binds locally occurring moments in time. It is precisely the synergy of parallelism and iteration within a competitive environment with finite resources that allow an organism or a system to be adaptive (Flake, 1998).

4.2. Implementation of physical constraints and parameters in the process of collective construction- the quest for adaptation

Adaptation is a key feature of living organisms that allows them to adjust to environmental changes, increasing thus their fitness. Every environmental change affects the function of an adaptive organism triggering consequent changes in function and/or organization of the organism that will allow it to adjust to the new conditions, and eventually to affect the environment within which it lives. The project managed to simulate such an adaptive system, where the environment is given equal status to the termites-agents that inhabit it, mainly because the communication amongst the agents was accomplished through the environment itself. In particular, the results show that in the absence of sophisticated individual-memory or new internal representations the termites made an effective use of information present in the environment objects, capitalizing on the exploitation of distributed "cognition" within their artificial world.

However, as aforementioned, time constraints permitted the simulation of only 'intrinsic; environmental parameters, such as building material, pheromones dispersion or termites input, while extrinsic environmental parameters such as light or wind were not modelled. To this end, the observed adaptiveness relates only to the intrinsic parameters, while possible variations in the mound shapes because of the latters' adaptiveness to environmental stimuli -like in nature- have been unfortunately left out.

4.3. Initial generation of architectures similar to those observed in natural termite colonies- Potential of application in human-generated architecture

As already shown in Figure 19, the generated structures represent the main elements of the termite mound, such as the royal chamber and a primary mound shell. However, the full intricate and complex architecture of real mounds was not generated because of methodological and practical constraints, such as the simulation of 'intrinsic' parameters only and the limited computational capacity of the workstation used within the available period. Nevertheless, our main intention to achieve a complete termite mound would be an exceptionally fertile paradigm of architectural inspiration, as it would constitute a crucial step towards the realization of a living architectural structure, a homeostatic system, a 'breathing' organism in equilibrium with its ecological environment. A precise simulation and rapid prototype of the complete intricate termite architecture would reveal its high-level integration of morphology and function. The complex structural design and geometry of the mound, could serve as a basis for (i) the precise modelling of embedded self-regulatory mechanisms, and (ii) a novel designing approach to various generative architectural forms.

(i) Embedded self-regulatory mechanisms involve the sustainable handling of solar and wind energy, as well as the mass transfer in the inner mound. Subsequently, ‘smart’ architectures which imitate the adaptive architecture of termites would be informative for optimizing the design and construction of self-sustainable buildings. Novel methods, including embedding sensory mechanisms -still with ‘ordinary’ ways and materials, such as for instance light or heat sensitive kinetic cladding systems into structures-, that could sense external changing conditions, in a similar way that the mound shell perceive the outer environmental stimuli. Consequently, these sensory mechanisms could activate internal respiratory and thermo-regulatory systems, analogous to the intricate ducts and canals, which are incorporated under the outer mound skin. These structures, operating like the sophisticated termite systems, would enable continual adaptation to dynamic exterior influences, such as heat, rain or wind. In addition, the termite mechanisms have the capacity to serve the restoration of the total structure: when a damage caused by external factors is detected through the differences caused in internal conditions, the termites respond by fixing the damage in order to re-establish equilibrium. In a similar way, man-made systems could be developed to detect possible building mutilations and respond due to their advanced function in order to sustain structure’s form and inner climate. In consequence, these innovative techniques, acquired from the natural phenomenon of the termite mound morphogenesis, could contribute to the design, constructions and maintenance of ‘breathing’ human-made structures and provide a climatic balance for architecture, termed structural homeostasis (Potter, 2007).

(ii) The simulation of the very process of adapting to versatile and ever-changing environmental stimuli would also inform the design of generative architectural forms. In termite colonies, the architecture is inspired from the environmental conditions in the location of construction (see also Figure 1), reinforcing, thus, the quest for a site-specific architecture, which should be the aim of a 'motivated architect' (Konstantinides, 1998). We can be both inspired and skilled by the termite paradigms and the richness of natural behaviours, to design and construct emerging architectural forms, which are improved with the extent and quality of acclimatization in their context –social, cultural, environmental. Genuine architecture is not about the creation of impressive visually-compelling objects which can land in any territory, without the ability to reflect or the potential to adapt to their particular milieu (Le Corbusier, 1947). By observing the various termite mounds, we can comment to the totally enclosed, unadorned structures which are generated in cold climates, and their opposite to the extrovert, embellished architectures that are formed in warm environmental conditions. In addition, the materials used in each site differ, because they come from the local ground and the indigenous tree and soil varieties. We can be motivated by termite techniques to wrap our buildings in living, responsive skin, generated by the integration of the external, site-specific stimuli and native, ecological materials. We would then have created emergent, adaptive, homeostatic architectural systems. The form of our buildings would be designed not from a limited, commercial computer tool and geometric metaphors (Salingaros, 2004), but from the synthesis of new design methodologies based on emergent systems and physiological processes (Stewart, 2001; Stewart & Golubitsky, 2003). Current multidisciplinary approaches across fields dictate the need for a genuine understanding of the biological processes that underpin the function of large-scale systems (e.g. universe, earth climate), as well as small-scale systems (e.g. nervous system, embodied cognition) and their active exploitation by architecture (Stewart, 2001; Stewart & Golubitsky, 2003). In order to facilitate the balance between the architectural form and its context, architects should aim to be more concerned with ‘evolving’, rather than ‘non-evolved’ structures (Salingaros, 2004). The end product should reflect the influencing parameters and its dynamic environmental stability during the phase of synthesis, which is related to notions of wholeness such as vitality and beauty of the created structure (Goodwin, 2001). Prospective manufacturing facilities should enable architecture to embed and sustain multiple performance capacities in the textile of buildings. This can be made possible by making several mechanisms part of collective construction practices, directed by constant adjustments to individually sensed internal and external conditions. It is precisely because termite agents detect external stimuli, sniff pheromones, follow the gradient and perceive other agents, that their architectural activity reflects on its outline the process of ‘collective intelligence’ (Steil, 1987).

The approach of homeostatic architecture proposed in the present project can be coupled with other current approaches on ecologic generative design. Turner (2002, 2003) proposed an ecological generative tool for design that is based on the biological concepts of ecomorphology and structural coupling as proposed in autopoietic theory (Maturana & Varela, 1980). Structurally coupled environments are those whose form is shaped directly by the use that they afford (Gibson, 1979). Agents move in a given environment, which in response adapts to their performance by changing the relationship of the local to the global structure of the system in order to achieve intelligibility. For example, a possible system of ecomorphic evolution can be implemented in an art gallery; the design is generated through the natural interaction between people and artworks within it. This approach demonstrated how an architectural structure can be generated as an ecomorphic response to inhabitation (Turner, 2002, 2003).

4.4. Potential impact on swarm intelligence construction/ robotics

The existing literature and the present results suggest that termites have the ability to generate exceptionally complex structures in spite of the absence of a centralized coordinator and despite their limited perception. Both the termite building activity and its outcome represent phenomena that are directed by local interactions (i) amongst termites-agents, and (ii) between each termite-agent and its pheromone-occupied close environment. The simulation of such a collective building behaviour has important applications for the potential use of swarm robotics, in order to face engineering challenges (Stewart & Russel, 2004). This type of collective construction mechanisms are operative in conditions where more 'simple' agents than fewer complex ones are needed, where direct communication and coordination are difficult to attain, and also sparing use of time and material is needed. In a latent swarm system, the swarm- agents can be homogeneous and equipped with minimum memory which perceives only their direct environment. Thus, the generalization of the building algorithms of termites can produce a kind of decentralized control which can be implemented in cases of constructing complex structures (Mason, 2002). The use of self-assembling robots (Sahin et al, 2002; Wawerla, Sukhatme & Matari 2002) and the execution of automatic repair or construction of structures in extreme scales or inaccessible building sites (Stewart & Russel, 2004) are examples of engineering challenges that might be upgraded from a termite behaviour-inspired approach.

5. Conclusion

5.1. Further work

There are many facets of this study which could be extended in future work, and contribute to a more complete answer to the main research question.

The logical next step will be to include the simulation of extrinsic environmental factors such as light, heat or wind in addition to intrinsic ones. The inclusion of extrinsic factors will probably contribute to (i) the completion of the mound structure and (ii) variations in the mound shapes, because of the latters' adaptiveness to environmental stimuli. For instance, the implementation of a heat variable, would affect the diffusion's mechanics, and consequently the material deposition and the final architectural form. Therefore, it would be crucial to investigate the structure's adaptation and homeostatic responses to the combination of both endogenous and exogenous environmental factors. The more realistic the simulated environment becomes, the more complex life-like structure would probably emerge, and thus inform genuinely man-made architectural practice. More importantly, the generation of a complete mound structure would allow an accurate assessment of the homeostatic processes (e.g. temperature regulation) in controlled experiments and the translation of this knowledge to man-made structures.

A further interesting goal, again inspired by the real termite colony performance, would be to test the system's response to different particular occasions (e.g. an external threat to the mound structure, like an animal's attack or the occurrence of extreme environmental conditions). The use of a realistic scenario in a simulation would allow the investigation of a range of parameters and demonstrate the structure's specific performance: the potential restorative mechanisms, the defensive behaviour of the system, the impact on the mound's infrastructure, on termite communication and further collective actions. Again, that study would contribute to the understanding of the self-restorative mechanisms of self-organizing system; mechanisms which operate in order to maintain the homeostatic structure and inform in turn innovative engineering and design methodologies, with respect to issues of sparing application of materials, consumption of energy and peripheral services.

5.2. Conclusion

This thesis has reflected on the generation of homeostatic, adaptive and self-organizing architecture. The starting point of the research involved the biological paradigm of the collective construction process of a termite mound, where function is integrated in a complex form and thus generates a structure which adapts dynamically to the changing environmental conditions and maintains homeostasis.

The main research question addressed the innovative techniques of design, construction and materials that can prospectively be developed and eventually applied to construct and sustain man-made structures which are adaptive and homeostatic, without the need of a vast supply of materials and peripheral services. The approach linked together the emerging, self-organizing termite structure through the use of generative processes to implement homeostatic and adaptive performance.

The main objective has been firstly to simulate the collective construction of termites mound in a three-dimensional model, in order to comprehend the underlying rules and collective mechanisms which regulate their homeostatic self-organizing structure. Subsequently, the objective was to study the potential impact on human construction methods, and enlighten new engineering and architectural design methodologies, with respect to issues of sustainability, sparing application of materials and small consumption of energy.

The methodology followed was recommended as a model for the study of self-organizing systems (Camazine et al., 2001). The project started from the biological observation of the system, continued with the simulation of a biologically plausible model of collective construction and behavioural repertories on the platform of Processing programming language, and resulted in the successful completion of the main critical parts of a termite colony super-organism.

For the results to be meaningful, it was essential that the behaviour of the simulated system corresponded well to the actual natural phenomenon of termite-mound construction as described in biological models (Bruinsma, 1979; Grassé, 1959; Stuart, 1967, 1972). To that end, the developed model managed reasonably to capture the real termite colony system performance in terms of both its structure and the underlying physical parameters. The implemented code was a combination of agent-based approach, 3-dimensional representation and use of local information, analogous to the information found in a termite environment. The results showed that the simulation outcomes matched closely the observed natural structures, such as the queen chamber and the external shell of the termite mound. The mechanics of pheromone diffusion in combination with the sensible modelling of termite movement- and building constraints were the keys for the even, natural-like generative process, and have resulted for the first time to the formation of the basis of a whole termite mound, and as the rapid prototypes demonstrate, they managed to manufacture performance.

The simulation succeeded in creating an agent-based, self-organizing model which served the process of collective construction. This represents an approach towards an homeostatic architecture similar to the one observed in natural termite colonies, and its potential application in human-generated architecture. The complex structural design and geometry of the mound, could serve as a basis for (i) the precise modelling of embedded self-regulatory mechanisms which involve the sustainable handling of energy, and contribute to structural homeostasis, and (ii) a novel designing approach to various generative site-specific architectural forms, based on local environmental conditions and native materials.

The ecological and collective intelligence (Steil, 1987) through which nature operates has stimulated this project. The biological underlying principles of self-evolving living systems and the global concepts which motivate their performance could be considered as the generative factors of an emergent, context-adaptive, architecture. The multidisciplinary study of the complex natural structures, where ecological functions are wisely embedded and award the living system with high-level qualities, would be beneficial for the conception of novel sustainable engineering and design methodologies. Their translation to human architectural practice could contribute towards the achievement of homeostatic architecture.

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