Termite-inspired techniques for decentralised street planning

Abstract

In the previous report, the case for agent-based models as a basis for urban planning practice was explored, and a set of desiderata for a model's application to a street planning scenario were defined. In this report, a cellular automaton based on the behaviour of termite *Macrotermes* in the early stages of nest construction is proposed as a method of modelling decentralised urban planning, specifically relating to street layout. Different implementations of the model are analysed according to the desiderata, and a general rule-set for a decentralised street mapping 'city game' is explored. We determine that the current model of termite behaviour is unsuitable for street mapping according to these metrics, and produce and analyse visualisations of the 'towns' created for different efficiencies. The limitations of the model are discussed, and a set of possible extensions and adaptions is proposed.

1 Modelling Urban Complexity

Cellular automata are a class of agent-based model that define complex systems in terms of simple, local interactions between individual agents in an environment. In [18, 19], Wolfram distinguishes cellular automata from models of 'second-law' systems (ones with increasing entropy), as systems that may decrease their local entropy by means of self-organisation. The cellular automaton is used in modelling emergent behaviours, which would appear to create an 'order out of chaos', and is thus attractive as a mode of rendering self-organising systems as an executable algorithm, either for the purposes of research, or as a basis for physical computation [1, 4, 10, 15, 18, 19].

1.1 Agent-based models in architecture

Agent-based models in architecture take many guises, from stochastic models of urban segregation [13], to generative models for ancient temple designs [14]. In [1], Batty establishes the first robust and comprehensive overview of urban expansion and evolution using cellular automata, defining the agent-based model as "The new science of cities". He outlines different sets of cellular automata, from simple 1D visualisations of traffic flow to giant city-scapes iteraing over years of development and expansion.

Mörçol[10] explores theories of urban sprawl and complexity using agent-based models to simulate transformations between micro-and macroscopic behaviours in dynamic urban processes. He defines sprawl as a product of lack of centralised control or poor management in lieu of control, and advocates for a non-linear and complexity-based understanding of sprawling urban systems. Using case studies of public policy failings – including British sprawl containment approaches implemented in the latter half of the 20th century – he examines the issues of attempting to apply universal rules to a system which appears to self-organise. Nuñez-Ferrara [11] also promotes the applications of complexity and agent-based models to urban systems, using hierarchical agents to establish micro- and macro- systems of flow in temporary settlements. Central to this argument is that decentralised control mechanisms, even when based on simple rule-sets, can form far more accurate and nuanced analyses of urban interactions than centralised models[8, 10, 11].

As established in the previous report, Tan incorporates cellular automata into her architectural practice as a basis for 'city gaming' methods which seek to engage communities in urban design using decentralised and playful [15, 16]. Tan also establishes a discussion on the *nature* of rules, and proscriptive ('banning')/prescriptive ('describing') rule-sets, arguing that the former are more conducive to creativity, and more reflective of the constraints present in the natural world that engender so-called 'bio-creativity' [15].

The critical design project *'I've Heard About...'* [5] proposes a direct implementation of biological cellular automata in constructing new urban environments, defining abstract, 3D spaces through self-organising algorithms. Whilst the exploration of these design possibilities is theoretical, their approach derives directly from existing natural construction systems, taking inspiration from ant and termite-built structures to envision citizen re-appropporiation of urban spaces, pushing the boundaries of distributed development.

1.1.1 Urban rules

In defining agent-based models to mediate and modulate urban environments, instruction-sets must be developed to discretise the cityscape into a set of conceptual rules, from which a 'city game' might be played [7, 15].

Lehnerer [7] establishes a comprehensive guide to formulating urban rules, establishing a requirement for good rule-description as the basis for self-organisation. He describes over 115 different rules, governing variables such as vertical assembly, building base height, facade transparency and tower-blocks-per street, based on direct observation of different urban environments. In choosing a rule to modulate, a set of constraints may be established that surround the manifestation of that rule, as applied to the city.

Tan [15] compiles a list of possible urban 'rule-sets' for use in city games, taking inspiration both from Lehnerer, and earlier urban social theorist Jane Jacobs. Developing literal 'building blocks' based on the rule that is developed – ranging from modular courtyard-building sets used to map *gekecondu* developments in Turkey, to entire community centres and parks used in a project in the Netherlands – Tan facilitates a game that allows participants to shape the application of these rules to an urban environment.

1.2 Termite simulations

A number of simulations have been produces that seek to model termite behaviour in different environments, focussing on a range of construction, environmental adaption and interaction behaviours.

In [6], a model for changes in construction behaviour with temperature is investigated. The model proposed (based on direct experimental observation of termite *Rhinotermitidae*) investigates group intelligence in challenging environments, observing changes in behaviour on both the agent- and the swarm-scale.

The TERMES project [17] – a distributed construction and robotics project developed in Harvard's Wyss lab – examines the 3D construction abilities of termite colonies, examining social behaviours that allow termites to navigate around one another during delicate construction processes. The particular goal of the project is to use swarming agents to construct structures far in excess of their own size, investigating potential for automation in the construction industry.

Cortois and Heymans define a cellular automaton that initialises the tunnel layout of a *Macrotermes* nest structure, establishing clusters of pillars and emergent tunnel systems [2]. In particular, their model explores environmental resilience of nest structures in response to variables such as prevailing wind or heat distribution, modelling the motion of termite agents through the system according to directions of attraction/avoidance.

2 Building the Macrotermes Simulation

The cellular automaton implemented is based on the *Macrotermes* model defined by Cortois and Heymans [2], to incorporate metrics for thresholding, efficiency and walkability that allow it to be built as a street plan. The original model, and all additional implementations are written in C++, with data visualisation in Terminal (basic visualisations) and Matlab (full analysis). The full code, along with instructions to compile and run is included in Appendix B.

2.1 The cellular automaton

Agent-based cellular automata must be defined in terms of a discrete set of immobile 'cell' states, and a second set of mobile 'agent' states. Here we define a simple urban rule that relates the height of building on a square to the movement of constructing agents that may navigate through a static grid. The Cortois-Heymans model [2] is here defined using the formal notation outlined in [18].

The model used in this investigation defines a square cell-grid environment $C_{i,j}$ of area $citySize * citySize$, inhabited by termites T_x, whose population size, $termPop$ does not change. Termites pick and place units of $earth$ on cells $C_{i,j}$, dependant on both the local and global distributions of chemoattractant $pheromone$. The height of $earth$ on any cell ($C_{earth_{i,j}}$) may not exceed $maxHeight$ and the constant k_{decay} defines the rate of decay of the pheromone signal.
For each cell $C_{i,j}$, we define a neighbourhood nb that consists of cells directly adjacent (including diagonally adjacent) to which a termite may move.
At time $t = 0$, each termite is initialised as carrying earth with a probability of 0.5,
The probability of a termite with no earth in $C_{i,j}$ picking some up is given by:

$$P_{pick_{i,j}} = \frac{k_{pick} C_{pheromone_{i,j}}}{\sum_{i=1}^{citySize} \sum_{j=1}^{citySize} C_{pheromone_{i,j}}} \tag{1}$$

When a unit of earth is picked from a cell at time t, the termite T_x and cell states $C_{i,j}$ at $t+1$ are given by:

$$\begin{aligned} &T^{t+1}_{earth_x} = 1 \\ &C^{t+1}_{earth_{i,j}} = C^{t}_{earth_{i,j}} - 1 \end{aligned} \tag{2}$$

The probability of a termite placing a unit of earth on $C_{i,j}$ (provided this placement does not exceed $maxHeight$) is proportional to the ratio of the global pheromone concentration to the pheromone concentration in $C_{i,j}$:

$$P_{drop_{i,j}} = \frac{k_{drop} \sum_{i=1}^{citySize} \sum_{j=1}^{citySize} C_{pheromone_{i,j}}}{C_{pheromone_{i,j}}} \tag{3}$$

When a unit of earth is placed in a cell at time t, the termite T_x and cell states $C_{i,j}$ at $t+1$ are given by:

$$\begin{aligned} &T^{t+1}_{earth_x} = 0 \\ &C^{t+1}_{earth_{i,j}} = C^{t}_{earth_{i,j}} + 1 \\ &C^{t+1}_{pheromone_{i,j}} = C^{t}_{pheromone_{i,j}} + 10 \end{aligned} \tag{4}$$

Each cycle, termites migrate in a direction determined by the maximum attractant vector $max(A_x)_{nb}$ if carrying earth, or the minimum attractant vector $min(A_x)_{nb}$ if not carrying earth. A_x has a component in the direction of each neighbouring cell $C_{i,j(nb)}$, according to the normalised pheromonal signal from neighbouring cells $C_{pheromonei,j(nb)}$, and a random factor $Rand_x$, which is a perturbation between zero and 1.

$$\begin{aligned} &C_{attract_{i,j(nb)}} = \frac{C_{pheromone_{i,j(nb)}}}{\sum_{nb} C_{pheromone_{i,j(nb)}}} \\ &A_x = C_{attract_{i,j}} + Rand_x \end{aligned} \tag{5}$$

Lastly, the pheromone concentration in each cell decays with each cycle according to a constant decay factor' k_{decay} (where $0 < k_{decay} < 1$).

$$C^{t+1}_{pheromone_{i,j}} = k_{decay} C^{t}_{pheromone_{i,j}} \tag{6}$$

3 Findings and Interpretations

The modifiable parameters of the model – namely population, thresholding and the directional parameters – are here tested for their effects on the efficiency and walkability of the urban plans formed. A framework is proposed for determining walkability, and issues with coherence are addressed. A potential improvement to the model is tested, and shown to have little effect.

3.1 Land efficiency and thresholding

The raw data generated by the simulation (see Appendix A, figs. 1(a)(b)) are not immediately legible as a useable urban space. In order to produce a 2D street plan, thresholded 'slices' are taken through the plot, and a series of street plans are generated, where squares with earth below the threshold are taken to be streets, and this above buildings. A Terminal graphic of the formation of such a street plan is included in the appendix, along with a series of street plans for different threshold levels.

The land efficiency, η_{grid}, is simply defined as the ratio of squares above the threshold (e.g. non-streets) to the total number of squares:

[1] the accumulation of 'building'-type structures in distinct groups

$$\eta_{grid} = \frac{\sum_{grid} C_{earth_{i,j}} > threshold}{\sum gridC_{i,j}} \tag{7}$$

3.2 Modifying population parameters

Modifying the termite population encouraged variation in the rate of clustering[1], but only changed the shape of the city for very low efficiencies. As can be seen from the thresholded data visualisations in Appendix A, smaller termite populations demonstrate more legible clustering in low efficiency cities, whilst, for the same number of cycles, a larger population will produce a more efficient but less coherent cityscape. Fig. 1 shows the rate of increase in efficiency for different termite populations, with populations lower than $citySize$ reaching a plateau far below the desired efficiency.

3.3 Walkability

Walkability – a somewhat more intangible concept than land efficiency – is here quantified as the average distance needed for an agent to navigate from one random square of the grid to another. Whilst this is a trivial calculation for regularised patterns such as grids, the random nature of the termite-defined streets call for a more general model.

To measure the walkability, the start $s_{i,j}$ and destination points $d_{i,j}$ are randomly generated from any two 'street-type' cells in the city. An agent is then initialised at the start point, and the distances of each neighbouring cell $C_{i,j(nb)}$ from the destination point are calculated. If the cell nearest to the destination is a street (e.g has an earth level below the threshold), it moves to that cell; if not, the next-nearest, and so on.

At $t = 0$, the position of the agent $C^0_{i,j} = s_{i,j}$ Each step may be represented by the algorithm:

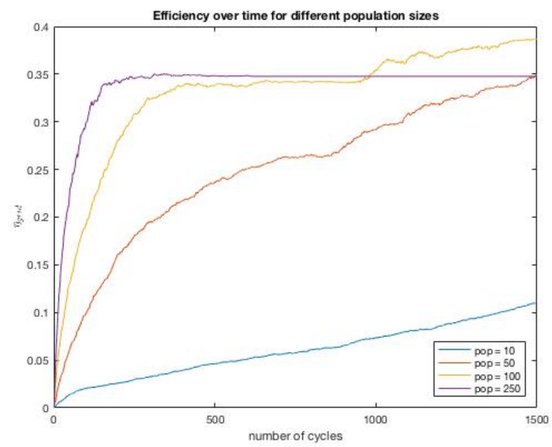
$$C^{t+1}_{i,j} = C^{t}_{i,j(nb)_{\min}}(||C^{t}_{i,j(nb)} - d_{i,j}||) \tag{8}$$

Each successive step is stored in a path vector P. At the point $C^t_{i,j} = d_{i,j}$, the length of P is added to the total distance travelled, $dist_{total}$ and the average distance travelled, $dist_{av}$ updated. When normalised by the size of the city, this gives a measure of the walkability, W that can be applied to grids of any size.

$$\begin{aligned} &dist_{av} = \frac{dist_{total}}{n} \\ &W = \frac{dist_{av}}{citySize} \end{aligned} \tag{9}$$

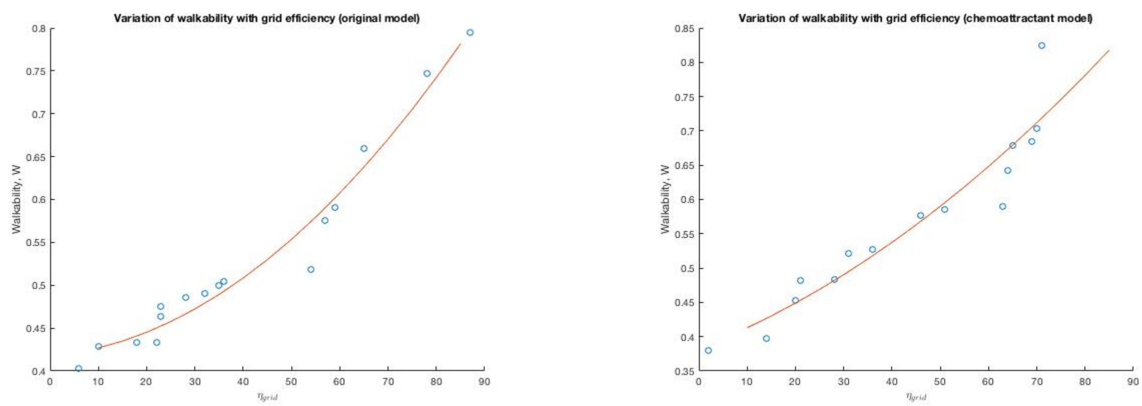
Where n is the number of tests of the walkability. This gives an iterative, meandering path which gives a somewhat realistic representation of a human navigating a city, with

Figure 1: Efficiency over time for different population sizes



Graph showing the change in percentage built area (η_{grid}) against the number of elapsed building cycles for different termite populations, citySize=50; termPop = 10 (blue), 50 (orange), 100 (yellow), 250 (purple); maxEarth = 15

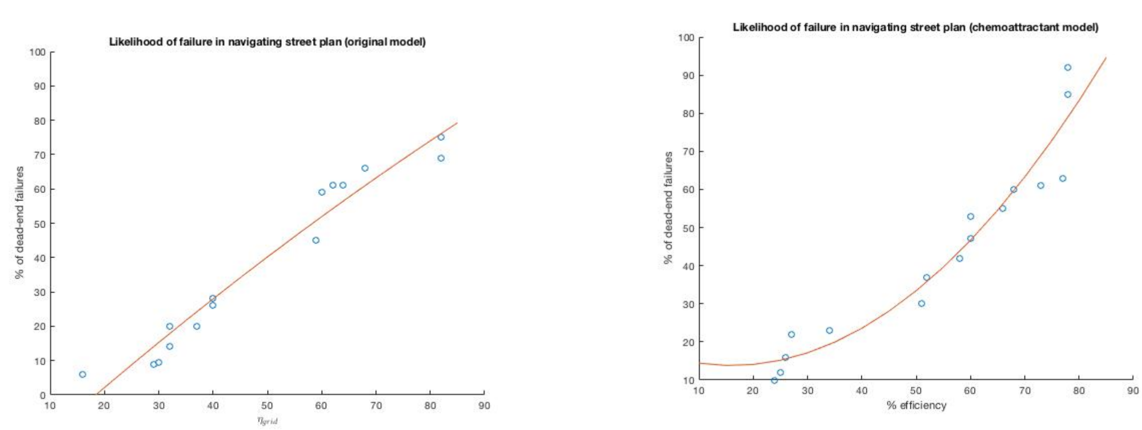
Figure 2: Walkability against efficiency for different models



(a) *Graph of the walkability (average point-to-point distance) variation with η_{grid} for the original model, citySize=50, termPop = 10, maxEarth = 15*

(b) *Graph of the walkability (average point-to-point distance) variation with η_{grid} for the updated model, citySize=50, termPop = 10, maxEarth = 15*

Figure 3: Failure rate against efficiency for different models



(a) *Likelihood of route failure against η_{grid} for the original model, citySize=50, termPop = 10, maxEarth = 15*

(b) *Likelihood of route failure (e.g. dead end, disconnected street) against η_{grid} for the updated model, citySize=50, termPop = 10, maxEarth = 15* global knowledge of a destination but not necessarily local knowledge of the immediate environment (e.g. with google maps). Fig. 2(a) shows a graph of the normalised walkability against efficiency for a 50 by 50 block city, showing an approximately linear variation in the distance travelled with η_{grid}. An animation of this process is shown in Appendix B, *walkability.mov*, and may also be observed by compiling *termites1.cpp* (original model) or *termites2.cpp* (updated model).

3.3.1 Failure rates

An issue discovered with walkability measurements was that many iterations of the 'distance travelled' failed due to the termite-designed streets being irregular or disconnected. With no guarantee that one point is reachable from another, and a high frequency of dead-ends, the algorithm had to be updated to account for failures to navigate the grid.

Upon reaching a dead end (where the agent may only travel backwards), or if the number of steps taken exceed twice the size of the city, the algorithm stops and a 'penalty distance' of $\sqrt{2} * citySize$ (e.g, the distance from one corner of the city to another) is added to the total distance travelled – analogous to a pedestrian becoming lost in an incoherent urban environment.

This failure rate indicates an obvious problem with the termite-designed scheme, and one that has not been satisfactorily resolved. Fig. 3(a) shows a graph of the failure rate against layout efficiency for the original model. At 20%, the failure rate incurred at anything above 20-30% efficiency is prohibitively high, rendering un-useable urban environments in the range of the 72% desired value specified in the last report.

3.4 Modifying directional parameters

Cortois and Heymans describe an effect observed when the random perturbation component $Rand_x$ of the attractant vector A_x is prohibited in some directions, for example privileging vertical migration by setting $Rand_{NE} = Rand_{NW} = Rand_N$, perturbing A_x North as opposed to North-west or North-East [2].

This causes a slight qualitative change in the structure as observed in [2] (a greater directionality in the formation of clusters), but does not translate into a sufficient difference in street coherence to observe a change in the walkability.

3.5 Redefining Chemoattractant Parameters

In an attempt to correct the failure rate of the model, an extension to the existing model is proposed that privileges clustering behaviour seen with low populations. In addition to the pheromone released on a chosen cell $C_{pheromone_{i,j}}$, the termites also release a smaller pheromone signal to the adjacent cells $C_{i,j(nb)}$, to encourage the placement of earth near existing build zones. Thus, if earth is placed on cell $C_{i,j}$ at time t:

$$C^{t+1}_{pheromone_{i,j(nb)}} = C^{t}_{pheromone_{i,j(nb)}} + 5 \tag{10}$$

The code for this implementation may be compiled and run from the file *termites2.cpp*, Appendix B.

3.5.1 Results of added chemoattractant

The addition of the chemoattractant extension increased the clustering of built areas' somewhat, meaning lower failure rate when the urban density was low, however it increased the number of 1- or 2-block streets in higher-density environments, leading to a far greater number of dead ends. Fig. 3(b) shows the variation of failure rate with η_{grid} for the chemoattractant model, showing a lower failure rate for low-efficiency cities, with a sharp increase as η_{grid} increases past 40%. Fig. 2(b) shows a similar variation with walkability between the initial and chemoattractant models, with little to no effect on the average distance travelled.

3.6 Sketchup visualisations

In order to envision a realistic picture of how a termite-built town might look, segments of plan views of the town data are visualised using Sketchup for four different efficiencies (see Appendix A). For the street efficiency of 62% (slightly less than the land efficiency of a grid), the layout appears open, though there are discontinuities in the street plan. For a street efficiency of 76.5% (an efficiency equitable to that of the fused grid specified in the desiderata), there are several discontinuities even within a local area, producing dead-ends and non-navigable routes.

4 Conclusions

4.0.1 Dimensionality

As discussed in 3.3.1, the prohibitively high failure rate (Figs. 3(a)(b)) of the walkability model due to dead ends and un-connected roads renders the city virtually un-usable. When this failure rate is accounted for, the walkability-efficiency ratio (Figs. 2(a)(b)) drops sharply as the number of buildings is increased. Part of the reason for this model's failure is the limits of dimensionality in defining a 2D environment using a 3D model. Termite nests are highly complex, 3-dimensional structures, and the information loss in the thresholding used means that the coherence is lost. The Cortois-Heymans model is optimised to define initial stages of nest-building in *Macrotermes*, the first stage in a multi-level operation.

4.0.2 Additions to the model

The addition of the chemoattractant promoted a greater rate of clustering within the simulation (e.g, an area already built upon was more likely to be developed), which worked well in very low-efficiency layouts, as the city formed in defined 'lumps', allowing easy motion between the rest of the squares. However, more issues were caused by the clustering behaviour as the built coverage became greater, as it generated larger numbers of isolated 1- and 2-cell streets enclosed within built clusters, and thus a far greater number of dead ends.

4.0.3 Urban coherence

The biomimetic, agent-based networks of [1, 3, 10, 11] are important step in understanding urban complexity, but in engineering legible environments, there is a base level of coherence that must be achieved. Street planning requires a very strong set of rules to ensure global usability, and, whilst it might be possible to produce useful rule-sets by considering the behaviour of other organisms, termite pillar-building strategies (which are predicated on 3D clustering, rather than 2D linear layouts) do not form suitable models when considering metrics such as point-to-point navigation.

This model shows that purely aggregation-based strategies (eg. privileging build areas as a result of previous building) do not lend themselves to 2D layout problems in which a high degree of coherence is required. In [15], Tan's 'city games' mediate and modulate sets of urban rules; the tighter the constraints on the problem, the more rules in the game. The games are also supervised by town planners, giving a far more rigidly-defined framework from which to develop creatively. A framework with a greater number of initial constraints – albeit one that deviated more from the biomimetic framework – might have given a more useable model. Agents in *real* city games far exceed the complexity of the simple pick-place binary between the entities defined in this system.

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Appendix A

A portfolio of generated cityscapes and architectural models are available in the file *portfolio-afc39.pdf*.

Appendix B

Code, animations, compilation instructions and 3D models are available in folder *biomimetics-afc39.zip*.