Changing the Culture of Building Simulation with Emergent Modelling

Ljubomir Jankovic
Director, Zero Carbon Lab
Birmingham City University, Birmingham, UK.
Lubo.Jankovic@bcu.ac.uk

Abstract

Dynamic simulation models of buildings have been predominantly based on a top-down approach, which defines the system as a whole with equations, simplifies the representation to make the solutions computable at the expense of accuracy, and then seeks solutions to the system using numerical methods. This traditional approach, evolved as result of the development of traditional mathematics over the past 300 years, differs considerably from the way building physics operates. Building materials do not solve systems of complex equations. Instead, heat transfer occurs as result of neighbour to neighbour interaction of molecules. That leads to a much faster process than the one calculated by equations. This paper investigates an approach that replaces the system of equations with neighbour to neighbour interaction between autonomous components representing groups of molecules, giving rise to spontaneous emergence of the system behaviour.

Introduction

Why emergent modelling?

A long awaited pedestrian Millennium Bridge was opened to the public in London on 10th August 2000. As thousands of people went to walk over it, the bridge developed a lateral wobble, and had to be closed for the next two years for extensive redesign and modifications. As discussed by Jankovic (2012), the bridge was designed using standard structural analysis software tools based on the top-down approach, in which a system is defined with equations, and a solver is deployed to find a solution, making simplifications along the way that compromise the result accuracy. Thus, the solution method did not address the entire solution space, leaving this critical aspect of performance unexplored, and prone to catastrophic failure.

The process is very similar to the way building simulation methods work. Dynamic simulation models of buildings have been predominantly based on a top-down approach, which defines the system as a whole with equations, and then seeks solutions to the system using numerical methods. This traditional approach, having evolved as result of the development of traditional mathematics over the past 300 years, differs considerably from the way building physics operates.

Natural phenomena are devoid of the systems of complex equations. These representations of natural phenomena have "*in the past few hundred years reproduced the simplest of behaviours*" (Wolfram, 2002). The neighbour to neighbour interaction that is the basis of computation in natural systems results in much faster processes than those represented by systems of equations. Kauffman (2010) attributes this increase in the process speed to a parallel search that is an intrinsic characteristics of emergent models, and proposes a new scientific worldview in which emergence is the basis of all natural processes. Holland (2000) discusses emergence as system behaviour that is greater than the sum of parts, and that gives back to the system model designer more than his/her own knowledge that was put into the model design.

One of the most striking examples of emergence-based approach to modelling is the flocking model by Reynolds (1987), published in his seminal paper entitled 'Flocks, herds and schools'. Using only three parameters for bird to bird interaction on a local level, and without an overall system control mechanism, Reynolds achieved realistic flocking behaviour in his model that emerged from the bottom up: a flock of artificial birds formed spontaneously, flew around the model space with a number of vertical column obstacles, broke up into two flocks while approaching an obstacle, and re-joined into a single flock after passing the obstacle. As defined by Jankovic (2012), the state space of the Reynolds's flocking model can be defined as

$$D = S^N \qquad (1)$$

where

D – number of design possibilities, i.e. the state space
S – number of states of each system component
N – number of components.

Assuming that there are three rules of bird to bird interaction, plus two rules for boundary and obstacle detection, therefore $S = 5$, and say there are 30 artificial birds ($N = 30$), the state space of this model becomes $D = 5^{30} = 9.31 \times 10^{20}$. The scale of this number is hard to comprehend, as it is by far greater than the number of seconds since the big bang (4.57×10^{17}). Yet Reynold's model worked in the real time due to its massively parallel topology. Had it been a top down model, significant simplification would have had to be made, leaving large parts of the system behaviour unexplored, as was the case with Millennium Bridge.

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This limitation of top down models is particularly evident in the case of computational fluid dynamics (CFD) simulations, characterised with prolonged preparation and execution times. CFD modelling has been based on Navier-Stokes system of equations, which implement Newton's Second Law and incompressibility of fluid. Although Navier-Stokes equations were developed in the first half of the19th century, no complete solutions exist to this date, so that only particular cases can be represented and modelled (Atiyah and Tate, 2000). In order to get to the particular case that can be solved, the problem description needs to be simplified. The consequences are a reduced accuracy and prolonged running times of simulation models. Effectively, the problem is adjusted to the solution method, rather than vice versa, at the expense of accuracy and interactivity, potentially leading to catastrophic failure.

The focus of this paper

This paper investigates a radically different approach to building simulation, which replaces the system of equations with autonomous components representing groups of molecules, and giving rise to spontaneous emergence of the system behaviour through the interaction between these components. It will be shown in the paper how this approach facilitates interactive simulation of air flow. This approach enables the user to draw a sketch of an enclosure, start the simulation, add or delete heat sources, heat sinks and obstacles, as well as to switch wind on or off, while the simulation is in progress, and observe immediate response to these interventions.

Previous work

There has been a considerable body of work in this field since the 1970s, when lattice gas (LG) models were developed, based on interaction of fluid particles on a square lattice (Hardy, Pomeau, and de Pazzis, 1973). This emergence-based model, named *HPP* after the authors' initials, had the behaviour restricted in orthogonal directions only, with no diagonal movement.

The *HPP* model was superseded by *FHP* model (Frisch, Hasslacher, and Pomeau, 1986), which interacted with cells in six directions, therefore overcoming the restrictions from the previous work. The authors demonstrated that despite discrete Boolean nature of the lattice, it was possible to simulate Navier-Stokes equations, and that this approach "*can be used to design simple, massively parallel computing machines*".

In the 1980s researchers realised that the lattice gas models were in fact Cellular Automata (CA) models, which in turn are a representation of physical systems with finite set of values and in a discrete spatial and temporal domain. In this period Salem and Wolfram (1985) worked on fluid modelling using CA and developed an emergence-based model of hydrodynamic flow around a plate, leading to a publication of a basic theory of cellular automaton fluids (Wolfram, 1986).

Toffoli and Margolus (1987) used CA to develop simple models of fluid flow. Using simple rules, they achieved emergence-based behaviour of flow tracing, flow passed an obstacle, circular waves, and others. They explain that this method is devoid of numerical instabilities and delivering solutions, and that their ethos is guided by the notion of "*when things are what they seem, we can safely let them do what they must*".

A number of researchers used the Boltzmann equation to replace the need for solving Navier-Stokes equations, thus developing lattice Boltzman methods for modelling fluid flow (see for instance He et al., 1988).

Developments of structured approaches to using CA for CFD modelling have continued through the 1990s, with significant contributions to modelling physical systems with CA (Chopard, B. and Droz, M., 1998), and through the 2000s on application of lattice Boltzmann techniques with CA to modelling fluids (Chopard, et al., 2002).

Bagnoli and Rechtman (2008) investigated entropy and chaos in lattice gas CA and achieved a model that exhibits characteristics of hydrodynamic and thermodynamic behaviour.

Toffoli (2009) explained similarities and differences between Cellular Automata and Lattice-Gas automata, which have been intertwined in almost all of the previous work. Although these approaches to modelling fluid dynamics are "*two different styles of parallel computation*", "*CA provide a quick modelling route to phenomenological aspects of nature*", giving rise to emergence of complex behaviour, "*while LG are unmatched as a source of fine-grained models of fundamental aspects of physics*".

Despite the considerable body of work in the application of CA to CFD modelling over the past four decades, it appears that very little has changed in CFD simulations of buildings. The ethos described by Toffoli and Margolus (1987, pp. 171 – 184) with words "*when things are what they seem, we can safely let them do what they must*" has not found its way into changing the culture of building simulation. The models are still based on systems of top down Navier-Stokes equations, instead of developments in the direction of emergence-based CFD.

Method development

This paper focuses on a solution method that overcomes the need for Navier-Stokes equations, whilst still using the same fundamental principles of Newton's Second Law and incompressibility of fluid on a local component level. Components are defined as miniature 'parcels' of material or air, effectively representing groups of molecules. The equations are replaced with the interaction between the neighbouring components, reflecting natural processes.

This approach is implemented using CA rules. Each cell on the grid is an independent object, and it contains formulae for the calculation of temperature, pressure and density, and for the accumulation of forces received from the interaction with the neighbouring cells. From this information, the acceleration, velocity, direction and distance of movement are calculated. The latter two parameters are implemented using CA rules, based on the interaction of each cell with the neighbourhood (Figure 1), sequentially processing all cells on the grid.

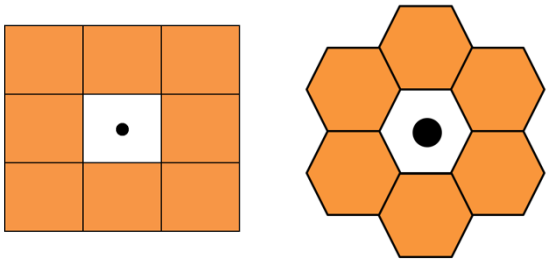
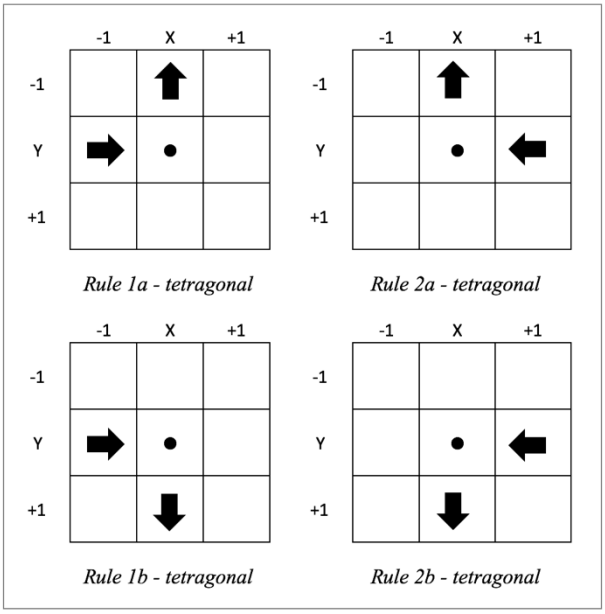
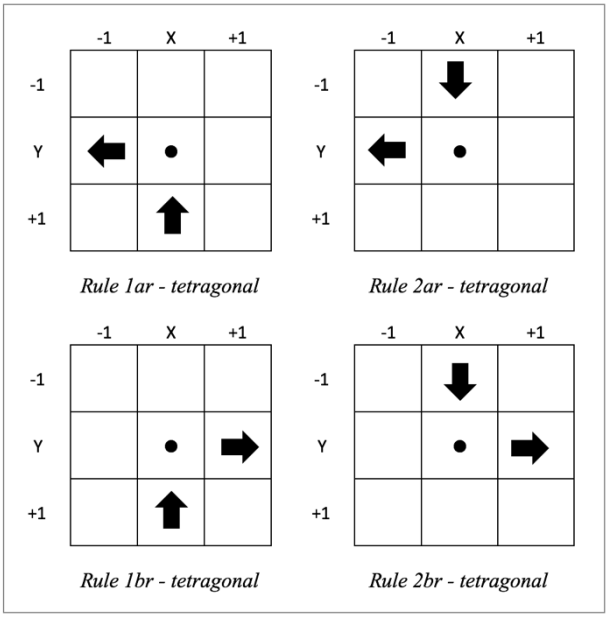


Figure 1: Cellular automata rectangular (left) and hexagonal (right) neighbourhoods



a) Rule set 1



b) Rule set 2

Figure 2 Square grid with tetragonal interactions

Grid topologies

Three different grid topologies and corresponding interactions were tested with bespoke models developed in Java: a square grid with tetragonal interactions (Figure 2); a hexagonal grid (Figure 4); and a square grid with octagonal interactions (Figure 5). Why are these different grids and interactions investigated?

The starting point in the development was a square grid with tetragonal interactions (Figure 2). Although this topology developed a realistic free flow, its flow around obstacles did not exhibit pronounced turbulent behaviour occurring in reality. Wolfram (1986) worked on a basic theory of cellular automaton fluids using hexagonal grids, and obtained realistic formation of turbulent structures from a hexagonal rather than a square grid. Subsequently, Toffoli and Margolus (1987) corroborated the findings that simulation through interactions on a hexagonal grid exhibit more realistic behaviour than the simulations based on tetragonal interactions on a square grid.

For these reasons the initial model was recast onto a hexagonal grid. This was not a trivial task, considering that all software programming languages, including Java used in this case, use Cartesian coordinates to specify arrays. Thus the hexagonal grid was represented by a modification to a rectangular grid, where rows and columns were offset to approximate the hexagonal pattern. Additionally, the cell neighbourhood had to be extended to a 3 x 5 topology, thus achieving the hexagonal neighbourhood by selective exclusion of cells (Figure 3).

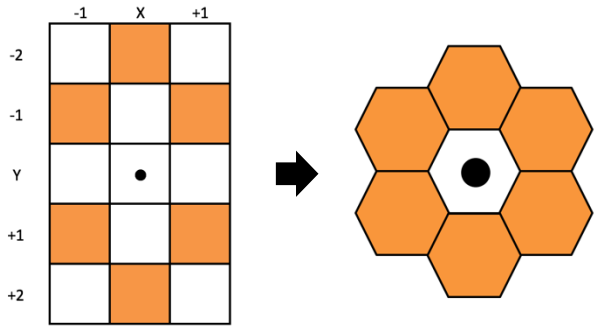


Figure 3: Representation of a hexagonal neighbourhood using rectangular neighbourhood – only orange cells (left) are included in the hexagonal neighbourhood (right)

The rules of interaction on the hexagonal grid were then specified as shown in Figure 4.

Due to the additional complications of handling the hexagonal grid as illustrated in Figure 3, an additional alternative was specified, in the form of a rectangular grid with octagonal interactions (Figure 5). This '135°-grid' has two advantages over the purely square grid with tetragonal interactions, and over the hexagonal grid: it provides programming simplicity of the square grid, as well as angular interaction similar to the hexagonal grid, except the angle of interaction is 135° in the octagonal arrangement, rather than 120° in the hexagonal arrangement.

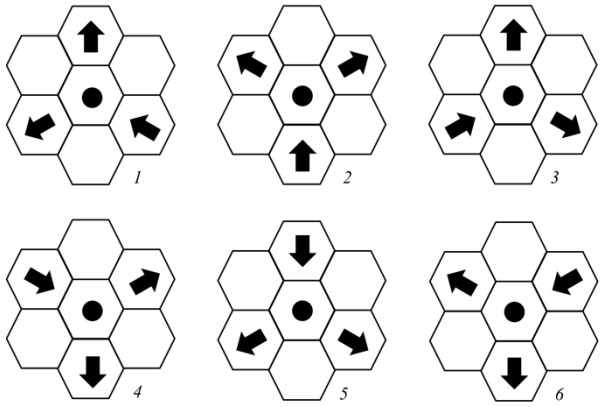
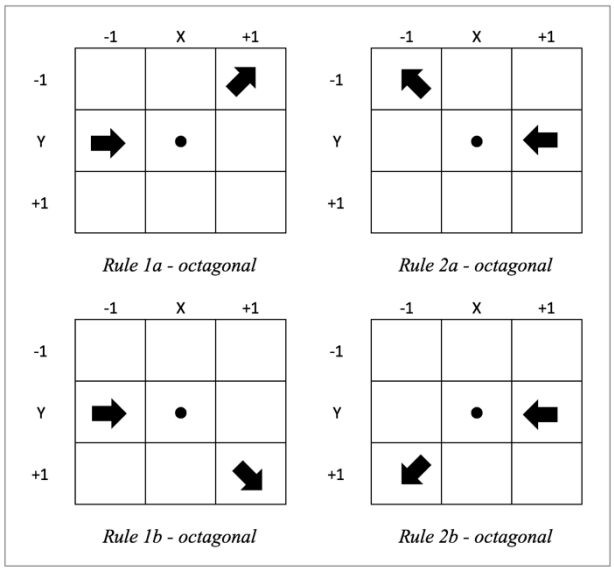
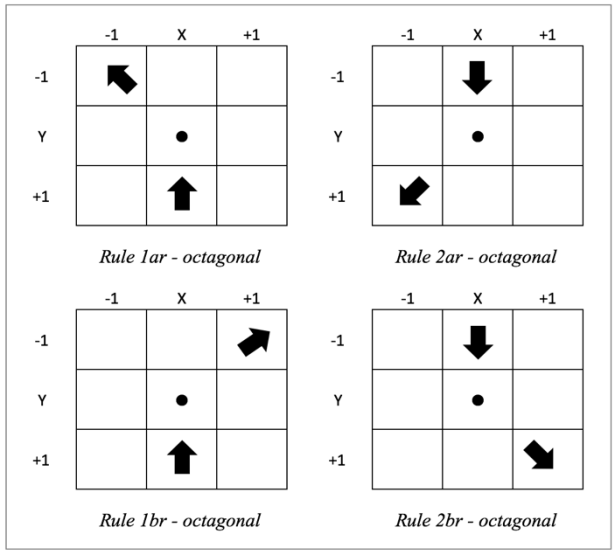


Figure 4:Rules of interaction on a hexagonal grid



a) Rule set 1



b) Rule set 2

Figure 5: Square grid with octagonal interactions

However, there are also disadvantages of the '135°-grid', as the airflow simulation easily penetrates thin diagonal barriers. This was initially suspected to be a fault in the code, but a subsequent analysis confirmed that this was to be expected. A thin diagonal line made from pixels does not provide a barrier for octagonal interactions, but can be made impenetrable by doubling-up the pixels, thus making the diagonal barrier line thicker.

The model physics

The processes in cells in the above cellular structures were subsequently populated with rules based on the fundamental principles, including Newton's Second Law, whilst incompressibility of fluid was imposed by the cellular grid itself. The role of the solver in Navier-Stokes equations was replaced by cell to cell interaction within the surrounding neighbourhood of cells in the respective topologies shown in Figure 1 and Figure 3, and as specified in Figure 2, Figure 4, and Figure 5.

Heat balance of each cell is calculated using Fourier Law:

$$Q = -\sum_{1}^{n} k \frac{\Delta T_i}{\Delta l} \times A \qquad (2)$$

where

Q – heat flux (W)
k – conductivity (W/(mK))
ΔT_i – temperature difference between the current cell and i-th neighbour (K)
l – distance (m)
A – area (m^2)
n – number of neighbours for each cell.

Cell temperature T is subsequently calculated for each cell on the grid as

$$T = \frac{Q}{\rho \times V \times c} \qquad (3)$$

where

ρ – density (kg/m^3)
V – volume (m^3)
c – specific heat (J/(kg·K)).

Density and pressure of each cell is calculated using standard formulae for moist air at 60% relative humidity.

The force acting upon each cell is calculated as

$$F = F_w + F_g - F_b + \sum_{1}^{n} (F_{p,i} - F_{f,i}) \qquad (4)$$

where

F_w – wind force acting upon each cell
F_g – gravitational force, applied in vertical direction only
F_b – buoyancy force, applied in vertical direction only
F_p – pressure force $F_p = \Delta P_i \times A$
ΔP_i – pressure difference between each cell and each of its i-th neighbours
F_f – friction force
n – number of neighbours for each cell.

Acceleration, velocity and change of position are then calculated for each cell on the grid as

$$a = \frac{F}{\rho V} \qquad v \mathrel{+}= \frac{a}{t} \qquad \Delta l = \frac{v_l}{t} \qquad (5)$$

where
a – acceleration
v – velocity
Δl – change of distance in x or y direction, or in one of the six directions on the hexagonal grid
v_l – velocity in the direction of l
t – time step
+= – calculation accumulator.

After an observation of air flow patterns formed under the three different grid topologies, it was decided to focus on the rectangular grid with octagonal interactions, on the basis of simulation stability, simplicity of sketching, and behaviour around obstacles.

Simulation experiments and results

An example result obtained from this approach is shown in Figure 6. A linear horizontal heat source was first drawn in an enclosure representing a room and the simulation was initiated (Figure 6a), showing upward heat flow (Figure 6b and 6c). Subsequently, an obstacle was inserted into the rising heat (Figure 6d), and a flow pattern developed around it (Figure 6e). A beginning of a chimney was subsequently drawn in Figure 6f.

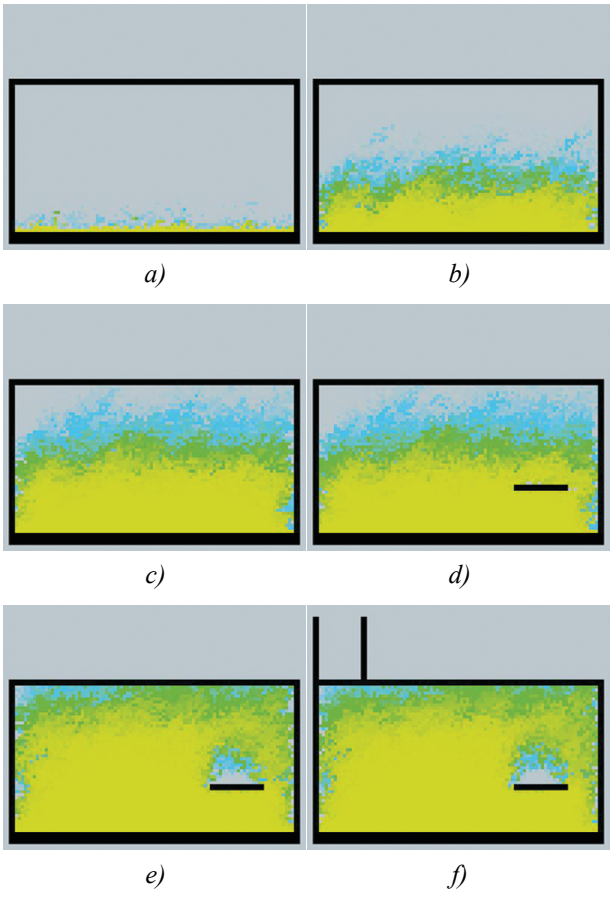


Figure 6: Emergence-based simulation of air flow in a room

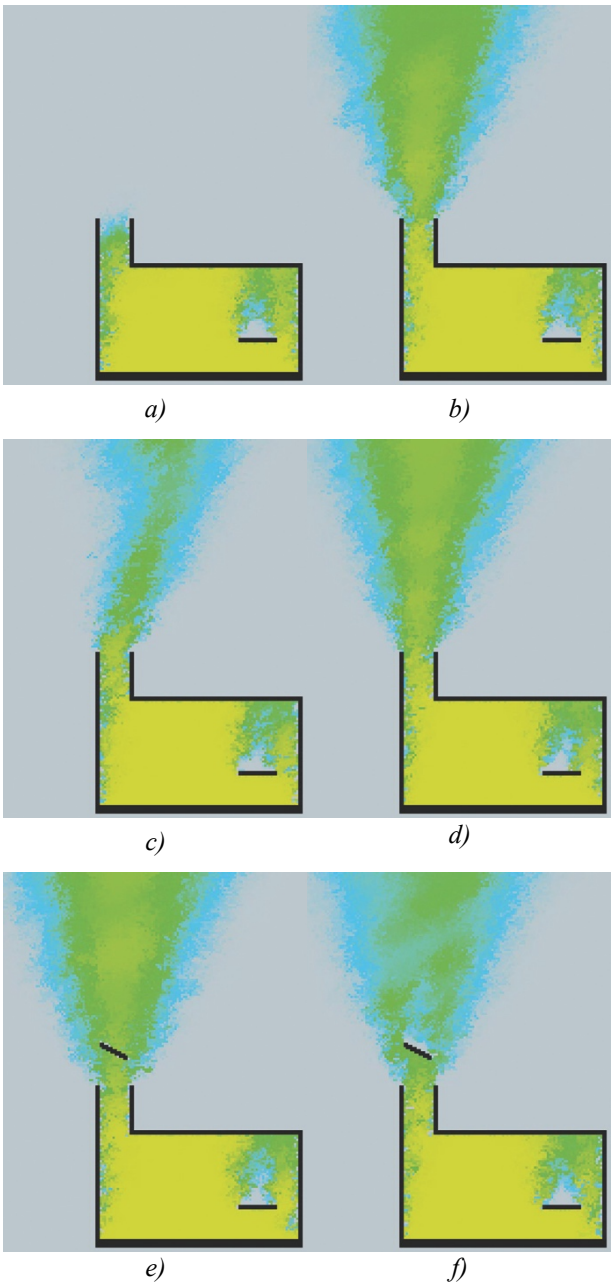


Figure 7: Emergence-based simulation of air flow out of a room

The interaction sequence then continued by completing the chimney in Figure 7a, and air flow out of the room through the chimney developed in Figure 7b. West wind (from the left) was switched on in Figure 7c and the air plume swayed to the right. Wind was then switched off, allowing the plume to become vertical in Figure 7d. Subsequently, an obstacle was inserted above the chimney in Figure 7e, and a flow pattern developed around it, with eddies emerging past the obstacle.

Thus real time user interaction was achieved by the model, whilst exhibiting realistic behaviour.

In the next step we wanted to investigate whether the self-organising nature of this method could deal with air flow in irregular organic-looking forms. For this purpose, a simple sketch of a termite mound was drawn using the

program's sketching facility and by consulting photographs of cross sections of termite structures available online.

The results of this simulation are shown in Figure 8. At the start, a heat source was inserted into the main chamber of the nest (Figure 8a). The flow through multiple chimneys started developing in Figure 8b, and created a plume of rising air after leaving the chimneys in Figure 8c. In Figure 8d west wind (from the left) was switched on and the plume of warm air swayed to the right. In Figure 8e one of the chimneys was blocked, and the flow pattern continued through other chimneys in Figure 8f.

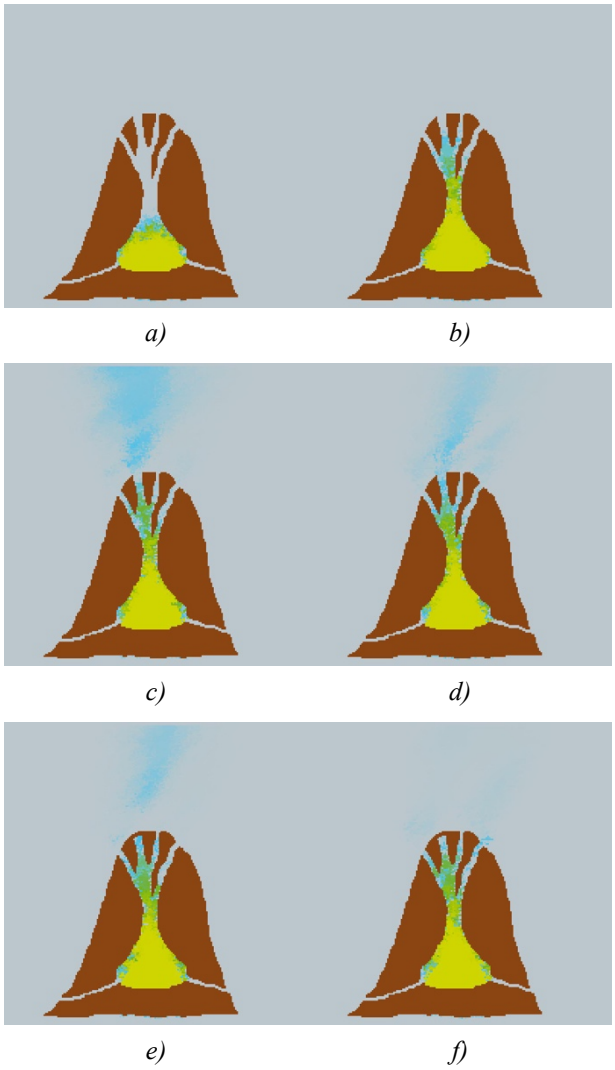


Figure 8: Emergence-based simulation of air flow in a sketch of a termite mound

Discussion

As it can be seen from the method specification above, this approach is based on dynamic heat transfer, and therefore could become a replacement for the traditional approach to dynamic simulation.

Under what conditions could this approach take over the traditional approach? Although this method requires additional development and validation, evidence from our computational experiments shows a 10k times increase in simulation speed in comparison with the Naiver-Stokes method. The method could therefore become the basis for rapid analysis of dynamic thermal performance of sketch designs, drawn by architects and engineers at the conception stage of a design scheme. This facility can be provided online, and therefore it can be made easily accessible worldwide.

The next level up of this approach would be a full dynamic simulation model, expanded into three dimensions, and dealing with multiple building zones. The computational speed advantage arising from parallel computation can facilitate time-stepped CFD simulation driven by an hourly weather data file over the entire year.

A validated model of this kind and an easy access would be the pre-requisites for this approach to compete with or take over the traditional approach.

Although there has been previous work in this area, as reviewed in the introductory part of the paper, buildings are still being simulated from the top down rather than from the bottom up.

The proposed emergent modelling method based on Cellular Automata is similar to Lattice-Boltzmann method. As explained by Toffoli (2009), Lattice-Boltzmann and other Lattice-Gas methods provide "*fine-grained models of fundamental aspects of physics*", whilst Cellular Automata methods provide "*a quick modelling route to phenomenological aspects of nature*". The aspiration for the proposed method is to combine the two approaches. The main difference between the proposed method and other methods is that it enables both sketching of building enclosures and running their thermal simulation, including real time interaction with the model whilst the simulation is in progress.

How could this approach provide better results than previous works in this area? The proposed approach models building physics in a more direct way than the traditional approach, as it does not use systems of equations and solvers, but effectively an agent based approach representing individual miniature components of a building and air inside the building. It works through self-organisation of the system model through the interaction of components, analogously to the way the flocking model by Reynolds (1987) works to describe a natural phenomenon. Had Reynolds's model been developed from the top down, there would have been no real time flocking in it, but instead it would have presented the user with a 'frozen' state of the flock one frame at a time, just like the current CFD models present the user with a 'frozen' snapshot of an air flow pattern. The real time interaction and execution speed whilst being based on fundamental principles are the true advantages of the proposed approach.

Validation is critical for development of new methods, and it is dependent on laboratory facilities and funding. To validate this approach, full scale experiments are needed in fully instrumented settings for internal and external environments. Whilst laboratory facilities exist at other organisations as described below, this method has

not yet had the necessary funding, and that is one of the next steps that this research will focus on.

The validation in internal environments would involve a comparison with a building in a fully controlled climate chamber, such as the Salford Energy House at the University of Salford, UK (Fitton and Pandraud, 2013). This facility is a typical Salford 1919 terraced house that has been reconstructed in a fully environmentally controllable chamber, in which climatic conditions can be set and maintained. Climatic conditions (rain, snow, wind, temperature) in this laboratory can be generated independently of the outside weather, enabling the monitoring of the consequences on internal conditions in the house.

The validation in external environments would involve an atmospheric wind tunnel and a downburst simulator. The former has the ability to rotate individual models at different speeds, thus enabling a variety of different wind conditions to be established, for measuring, research and analysis. The latter is a device that models the winds which can arise during a thunderstorm downburst, and in which a column of air descends rapidly on the ground and spreads outwards (McConville et al., 2009).

Experimental validation in respect of external and internal conditions in the facilities as described above would bring this method into the mainstream of CFD applications.

What will be the ultimate contribution of this paper? Even though this method has not yet been experimentally validated, the paper gives a glimpse into the future in which we might model and simulate buildings differently from now, in the same way as they actually work, rather than in the way that the available solution methods developed by traditional mathematics currently influence our simulation approach.

Conclusion

The real time interactive CFD reported in the paper is a glimpse into a future step change in the development of building simulation methods. In comparison with traditional methods, which can take many hours of CPU time to simulate just a single snapshot of air flow pattern in a building, the emergence-based approach introduced in this paper is 10k times faster and interactive in the real time. This creates opportunities for development of interactive CFD tools and for simulation methods that perform hourly time-stepped CFD analysis throughout the simulation year.

Although the proposed method is yet to undergo experimental validation, the purpose of this paper is to stimulate future development of this approach, and to stimulate future thinking in this direction. Focusing the building simulation field on the basis of principles of how buildings actually work, rather than on the basis of solution methods offered by traditional mathematics, would give us much more back than we put in, thus capitalising on the essence of the emergence-based approach.

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