Cellular Automata Simulation of Three-dimensional Building Heat Loss

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Abstract

Conventional design development and simulation methods provide a top-down approach towards exploration of design solutions. This research identifies this limitation and presents a bottom-up approach framework inspired by nature. Natural interaction processes operate based on component to component interaction. This research re-creates such natural interactions using principles of cellular automata and complexity. Developed simulation models represent the various components of the building fabric and re-create complex natural processes such as heat-loss. The result is an emergent pattern in response to the heat-loss process. This pattern can be utilised as a starting point by designers for design exploration. The contribution of this research is that, through this bottom-up approach it visualises the complex interaction processes of heat-loss and empowers built-environment professionals with a stronger understanding of the building behaviour.

Introduction

Contemporary Building Simulation Methods and Its Shortcomings

The current state-of-the-art approach for building simulation and optimization stems from the profound development of mathematical knowledge in the past few centuries. Methods, such as Finite Element Method, Topology Optimization, Shape Optimization etc. have lent themselves to provide a new plane for analysis of building behaviour. These methods gained popularity from the structural field with the work of Bendsøe (Bendsøe, 1989) etc. and soon propagated to other fields such as fluid-flow (Hansen et. al., 2005), acoustic (Wadbro and Berggren, 2006), aero-elasticity (Maute and Allen, 2004) etc. While these methods generate solutions, they represent the domain as system of equations. As a result, the solutions developed are approximations. These methods provide a top-down approach where the problem is brought closer to the solution through simplification. Furthermore, complex solving methods such as Finite Element Analysis and Navier-Stokes equations require significant number of iterations, information and assumptions to generate an output for a specified time period and in the case of the latter solutions cannot be solved.

In his book, Wolfram (2002) states that traditional mathematics, over the last three hundred years, has only managed to reproduce some of the simplest natural behaviours. As contemporary building simulation tools use traditional mathematics that use systems of equations to develop solutions, this leads to incomplete solutions and to a performance gap.

The approach is comprised of and is founded upon the need for solving complex mathematical equations. Here, a physical system is defined as a whole, using a system of equations that are solved through iteration (Jankovic, 2017). Additionally, the approach requires the user to provide information in great detail, resulting in a time consuming model development process. As a result of this top-down approach, designers are forced to resort to simplifications “while compromising result accuracy” (Jankovic, 2017).

How can these shortcomings be overcome? This research investigates a more direct approach to simulation and investigate insulation design, which follows the heat-loss gradient. In order to do this, self-organising emergent models are needed, which attempt to serve as a more direct interface to enable our stronger understanding of complex natural processes.

Building thermal behaviour is a natural phenomenon, where the overall system behaviour occurs as a result of complex interaction processes of physical entities and is devoid of complex equations. Kauffman (1995) explains that the reductionist approach presents limitations in being able to explain the complex natural behaviour by breaking it into smaller parts. How can this limitation of the reductionist approach be overcome to provide a stronger understanding of the natural process of building behaviour? Natural phenomena are based on the process of component to component interaction, which results in much faster processes than that presented by the reductionist top-down approach. Furthermore, Kauffman (2002) presents the argument that this top-down approach is unable to explain natural behaviour, stating that it would require knowledge of initial conditions in great detail and in infinite precision. This is practically not possible to achieve. Instead, the use of simple behavioural rules provides much more information, in the form of ‘emergent’ behaviour and pattern, than what is initially put into the model, empowering a strong understanding of natural behaviour.

The focus of this paper is to investigate the use of cellular automata (CA), where, autonomous entities representing various components of the building fabric will be created,

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and where their interaction gives rise to emergent behaviour. The paper will illustrate how, through this approach, heat transfer is simulated and the heat-loss process is visualised. Further, the paper will demonstrate how the emergent behaviour can be captured and used as a starting point for designers to explore the design space.

Previous Work

A considerable body of work exists exploring the use of CA models to study fluid-flow behaviour since the early 1970s. Some of the most noticeable work has been done by Hardy, Pomeau and dePazzis in 1973 and is known as the HPP model. This model was developed to study fluid behaviour based on a square lattice which provided orthogonal interaction between fluid particles. As this model did not facilitate any diagonal movement it was superseded by the FHP model. The FHP model was developed by Frisch, Hasslacher, and Pomeau (1986) and was designed based on a hexagonal grid, which provided cellular interaction in six directions. Jankovic (2017) examines that model and states that through the model the authors demonstrated that it was possible to simulate fluid behaviour despite the discreet Boolean nature of the lattice. Building upon these models, Salem and Wolfram (1985) developed emergence-based model of hydrodynamic flow around a plate. Wolfram subsequently published a theory on cellular automata fluids (Wolfram, 1986). Toffoli and Margolus (1987) developed CA-based emergence models simulating flow tracing, flow around obstacles, circular waves etc. Guided by the notion that "*when things are what they seem, we can safely let them do what they must*" they advocated the use of CA as a means of delivering solutions as it is devoid of numerical instabilities. Outside this body of work there are several CA models developed within the fields of social and medical sciences, urban traffic and public movements etc.

Methodology

The methodology of this research stems from the work by Bharadwaj et. al. (2017) and is comprised of three stages;

1. Development of a CA model simulating the natural phenomenon of heat-loss through the building fabric.
2. Capturing and Assessment of generated self-organized emergent pattern using dynamic simulation tools such as IES-VE.
3. Development and refinement of a solution based on the emergent behaviour of the model.

Bharadwaj et. al. (2017) explain the creation of a two-dimensional model using a multi-agent-system (MAS) based approach. This model focused on capturing the emergent self-organization behaviour of insulation cells in response to heat-loss when instantiated within the test space. Results from that model provided more appropriate insulation design solutions that can be refined and aesthetically enhanced by designers. Key findings of that research were: (a) solutions generated through this process matched more closely with the complex processes observed in nature; (b) these solutions provided higher thermal performance compared to solutions developed using conventional methods; (c) real-time visualisation of heat-diffusion enabled identification of parts of the building fabric significantly affected by heat-loss phenomenon; (d) research enabled increased understanding of the building behaviour. However, the work presented in this paper has some key differences, in that: (1) The models developed in this research utilise principles of CA and complexity. Here, the environment has been initialised as a tightly packed grid of cells, such that at any instance of time and location on the grid is occupied by a single cell. (2) The research investigates and assimilates the emergent behaviour of insulation cells and the building in response to the phenomenon of heat-loss when subjected to new test models;

a. What is the self-organised pattern created when insulation cells are instantiated outside the test-space?
b. What is the building behaviour when the convection processes are modelled based on complexity and CA?

This paper will further explain the different stages of the methodology and illustrate the creation of the CA models. Further, the paper will also illustrate how the results from the experiments are captured, evaluated and analysed to develop appropriate design solutions.

Model Development

This research utilises models which are developed based on principles of CA, similar to those developed by Bharadwaj et.al. (2017). Models in this research share some common attributes and are comprised of two major components;

1. A global environment.
2. Cells, which represent building blocks of the building fabric components such as Wall, Air and Insulation.

Bharadwaj et. al. (2017) explain the role of these components of the model, where the global environment provides the cells in the model with a traversable environment in the test space and enabling interaction with other cells. The global environment is set-up such that the edge wrapping is prevented by truncating the Moore neighbourhood cells beyond the edges.

Cells are the analogue representation of different components of the building fabric and can be thought of as groups of molecules representing specific parts of the physical system (Bharadwaj et. al., 2017). In this research, four cell-types are instantiated in the global environment;

1. Air
2. Wall
3. Insulation
4. Heat-source

The interaction between the two major components (global environment and cells) of the model is based upon simple behavioural rules that are specified at an individual cell level. Each cell type is specified with a set of rules unique to its own role. These rule-sets replace the need for solving complex equations by modelling interactions that are "similar to those between building materials and air" (Jankovic, 2017). The behavioural model for the cells is discussed later in this paper.

Once the global environment is set-up, initial conditions of the model are specified to provide a starting point for the simulation. Heat-loss phenomena are simulated by specifying the initial cell temperature of the wall and internal air cells at 25°C thereby representing a uniformly heated internal environment. External winter environment conditions are specified by initialising much lower cell temperature for outside air cells to be at 2°C. This was chosen as an average temperature from the annual temperature graph for Birmingham obtained from IES-VE. Insulation cells were randomly instantiated outside the physical test-space and were specified with a constant cell temperature of 2°C. Material specification of the building fabric was chosen as a generic construction template, where, wall and insulation cells represent properties of brick and wood-fibre insulation respectively.

The next step after specifying initial conditions for the model is the specification of the behavioural rule-sets for the cells. This is discussed in the model physics section of this paper.

Model Physics

To capture emergent behaviour of the CA model, each cell in the model is provided with a set of behavioural rule-sets. These rule-sets can be thought of as algorithms that are the most compact description of the behaviour of a phenomenon (Kauffman 1995) and are not based on the need to solve complex mathematical equations. These directives enable each cell to make autonomous responses as it encounters various circumstance during the simulation.

In their paper, Bharadwaj et. al. (2017) discuss the model physics for developing such CA models. The models presented in this paper are developed utilising similar principles. This is illustrated further in this paper. Each agent in the model is an autonomous and independent entity and is specified with behavioural rule sets that can be categorised into three sets;

1. Heat-transfer,
2. Temperature calculation, and
3. Movement

Heat-transfer in the environment is achieved by implementing Fourier's law, as explained by Jankovic (2017) and is expressed as

$$Q = -\sum_1^n k \frac{\Delta T_i}{\Delta l} \times A \qquad (1)$$

Where,
Q = heat flow (W)
K = conductivity (W/(m·K))
ΔT_i = Temperature difference between the current cell and its i-th neighbour cell (K)
l = distance (m)
A = Surface area (m^2)
N - Number of neighbour or each cell

Cell temperature 'T' for each agent in the environment is calculated as

$$T = \frac{Q}{\rho \times V \times c} \qquad (2)$$

Where,
Q - heat flow (W)
ρ - density (kg/m^3)
V - volume (m^3)
c - specific heat (J/(Kg·K))

Density and volume for each air cell are specified in two ways for the two different model types;

(a) In the case of the heat-conduction model, density and volume are specified at a constant value of unity.
(b) In the case of heat-convection model, density is calculated using standard calculation methods and volume is specified at a constant value of unity.

In both cases, heat-gradient for the wall and insulation cells us calculated using values specified for volume and specific heat based on their material properties viz. brick and wood-fibre insulation respectively for the purposes of this simulation. Heat-gradient is calculated at each discreet time-step using equation 1.

Movement

Interaction and movement for each cell in the environment are based on the specification of behavioural models. The behavioural model can be thought of as a rule-set provided to the cell which is specified at an individual level. These rule-set enable the cell to perform autonomous actions based on conditions encountered within the simulation at a discreet time-step progression. The motivic force acting on each insulation cells is the attraction towards higher heat-gradient area of the building envelope.

Initially, the simulation was developed using the HPP (Hardy et, al. 1973) interaction model, which provides tetragonal interactions on a square grid (Figure 1), however as this did not produce the realistic turbulent flow, the model was recast to use the FHP (Frisch et, al. 1986) interaction model. The FHP interaction ruleset facilitates hexagonal interactions (Figure 2), this was utilised by Wolfram (1986) to develop a theory for cellular automaton fluids resulting in the key findings showing a realistic turbulent flow of fluids. This finding was later corroborated by Margolus and Toffolli (1987). This grid was then simplified (Figure 3) to implement the FHP interaction ruleset on a rectangular grid.

This is the end of the first stage of the methodology. Once satisfactory fluid-flow behaviour was observed using the FHP interaction ruleset, simulation experiments were developed to assimilate the emergent behaviour and how it can be utilised to develop a design solution.

Simulation Experiments and Capture of Emergent Behaviour

Stage two of the methodology is the development of simulation models replicating conditions of heat-loss through the building fabric and the capture and investigation of the resulting self-organised emergent behaviour. The model development process has been described by Bharadwaj et. al. (2017), to be comprised of developing a test environment with dimensions of 100x100 cells. This environment is then populated with different configurations of cells emulating different physical properties. By deploying these models, based on a discreet time-step, emergent behaviour was observed almost instantly. The self-organisation behaviour is visualised in real-time and illustrates the complex interaction of the cells amongst themselves and with the environment leading to the creation of an emergent pattern. Once a pattern is observed, a designer can intervene and capture the pattern from the simulation in any form best suited for their work. This process usually takes about one minute. For this research, it was decided to capture the emergent pattern in the form of an image which can be exported from the Repast Simphony (North et. al. 2013) simulation environment and utilised further to develop appropriate design solutions. This paper will now illustrate the development of the simulation models and the discuss the resulting emergent behaviour.

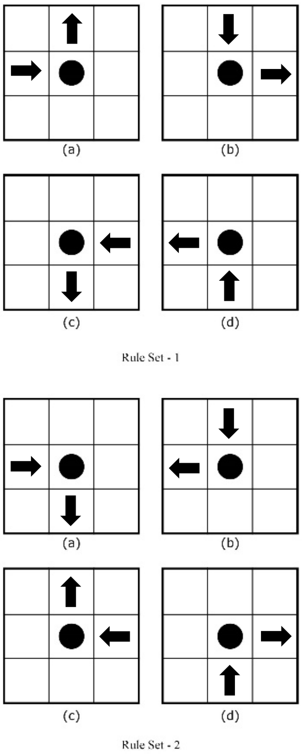

Figure 1. HPP Interaction Rule Set on a Square Grid

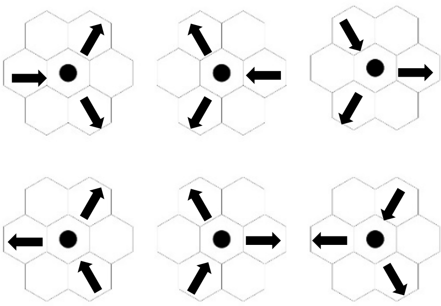

Figure 2. Interaction on a Hexagonal Grid

Experiments and Results

Two models were developed to assimilate the emergent behaviour when subjected to different conditions. Both models use generic shapes, a square in this case, to examine the shape of the emergent pattern, when the model is subjected to a uniformly heated physical space. The heat diffusion box model provides a 2D plan view of the physical test space, the convection model provides a secondary 2D sectional view of the physical test space in the investigation of the heat-diffusion process within a uniformly heated physical space.

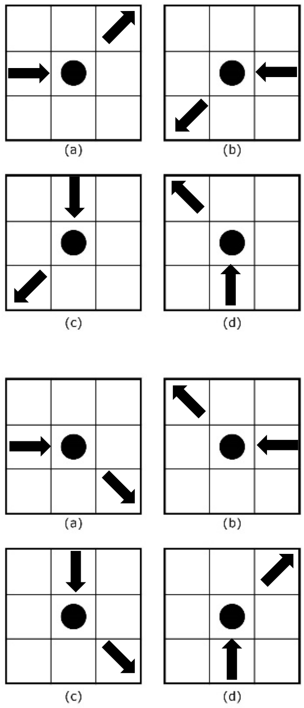

Figure 3. FHP Interaction Rule Set on a Square Grid

Heat Diffusion Box Model

Utilising the test environment developed above, a box model was developed (Figure 4) where wall cells (bright green) were instantiated forming a closed physical space representing a plan view of a room within the global environment. Heat-sources (dark red) for the experiment were instantiated along with the internal perimeter of the physical space and remain stationary throughout the simulation. Air cells were instantiated across the global environment, such that, cells inside the room are initialised to a temperature of 25ºC (light red), thereby simulating a uniformly heated internal space. Air cells instantiated externally to the physical space are initialised to 2ºC (light green) emulating conditions of a cold external environment. Insulation cells (orange) were randomly instantiated externally to the closed physical space. This model was then run to observe the emergent behaviour exhibited by the model. This is discussed in the next section.

Emergent Behaviour

The emergent behaviour of the model is split into two parts, internal and external. Internally, at the beginning of the simulation, patterns akin to thermal bridging begin to form and appear at the junctions of the physical test space (Figure 5). This is highlighted by the changing colour of air cells around these specific areas of the building fabric.

As the simulation progresses, convection currents can be seen forming and moving inwards from the corners of the geometry (Figure 6) illustrating the dynamic movement of air within the physical test space. This continues visualising the heat-loss process.

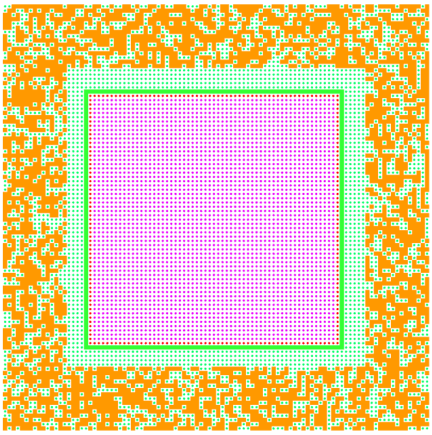

Figure 4. Box model simulation comprised of Wall (Green), Insulation (Orange), Air (Light Green and Light Red) and Heat-Source (Dark Red).

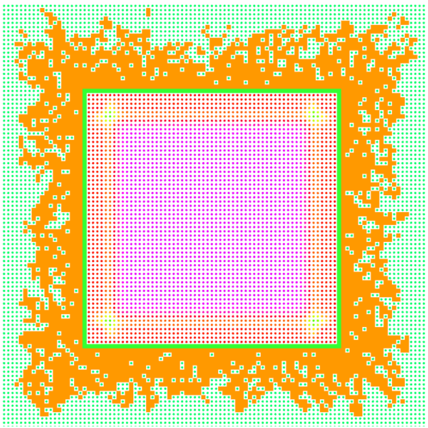

Figure 5. Internal thermal bridging pattern and swarming behaviour of Insulation cells (Orange)

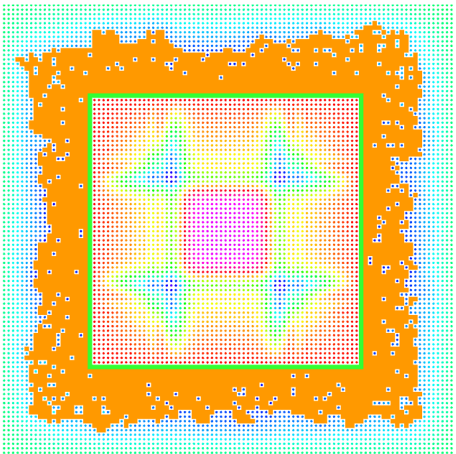

Figure 6. Convection currents and heat-loss through the building fabric. Formation of swarming behaviour of the insulation cells.

Externally, at the beginning of the simulation, insulation cells can be seen swarming towards the building fabric (Figure 7) as they get attracted towards the cells with higher cell temperature, forming a crude self-organised pattern encapsulating the building fabric. As the simulation progresses, heat-loss through the building fabric can be seen, highlighted by the changing colour of the air cells from light green to blue. Simultaneously, insulation cells are seen to adhere closely to the building fabric resulting in the manifestation of an emergent insulation pattern (Figure 7), which is organic in form. With further progression of the simulation, the emergent pattern stabilises (Figure 8), at which point the simulation can be intervened by a designer and the emergent pattern can be captured from the simulation environment for further analysis.

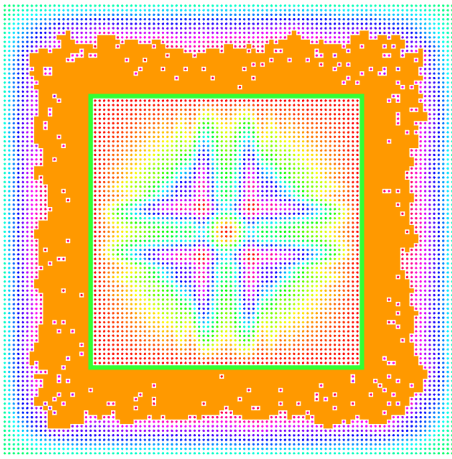

Figure 7. Manifestation of an emergent pattern.

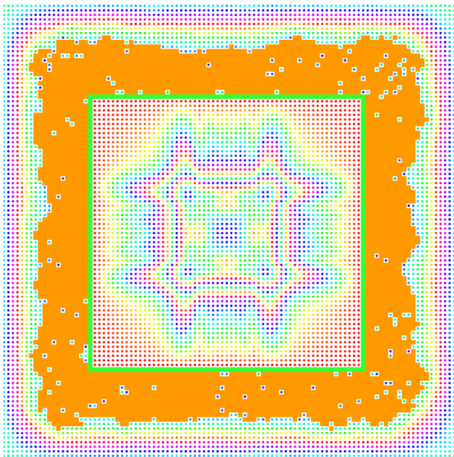

Figure 8. Stabilised emergent pattern.

Convection Heat-Diffusion Model

Another 2D box-model was developed similar to the box model explained above, however, this model has some key differences in that, it was designed to simulate the effect of convection process of air on the building behaviour. Additionally, this model is designed to provide a sectional view of the building. The environment in this model (Figure 9) has been developed such that, the wall cells are placed towards the edge of the global environment, thus emulating conditions of solid ground. Internal floor slabs, for different storeys, have been specified using the wall cells that are instantiated internally to the test space. Like in the 'Box Model', cell temperature of the air, that are instantiated internally and externally are specified at 2ºC and 25ºC. Heat-sources were placed along the internal perimeter at the bottom of the box-model and specified at a constant cell temperature of 50ºC. Insulation cells were then randomly instantiated externally to the test space.

Emergent Behaviour

Internally, at the beginning of the simulation, thermal bridging is visualised at the junctions of the obstacles and the walls of the physical test space. This is highlighted by the change in the colour of the air cells in the region. Convection process is visualised almost instantly as warmer air cells rise upwards and flow around the obstacles. Convection currents result in the formation of cold corners at the junctions of the geometry, highlighted by the change in the colour of air cells in the region.

Externally, at the beginning of the simulation, insulation cells can be seen swarming and moving closer to the building fabric, as they get attracted towards higher temperatures. Simultaneously, heat-loss from the building fabric can be observed, as the air cells close to the building fabric, start rising upwards. The heat-loss through the building fabric occurs through the side walls of the physical test space, instead of the roof. Insulation cells begin to illustrate a crude emergent behaviour, as they adhere to the side walls, signifying higher intensity of heat-loss through the building fabric (Figure 10). Insulation cells form an organic self-organised pattern encapsulating the wall of the building fabric, alleviating heat-loss through them, while also appearing to encapsulate the roof slab, where significant heat-loss is visualised.

When the emergent pattern has formed and has stabilised, the simulation is stopped, and the emergent pattern is captured as an image which can be exported out of the Repast Simphony simulation environment, to be used for further development (North et. al. 2013).

Observations

Why are there voids in the emergent patterns? Holland et, al. (1995) found that modelling simple interaction rules of agents resulted in the emergence of high-level complex behaviours such as interaction and competition for resources. Similarly, voids in the emergent pattern of the simulation can be attributed as the complex behaviour of insulation cells in response to the competition to occupy a location of higher cell temperature than their own, as specified by the behavioural rulesets.

The inability of the insulation cells to completely encapsulate the building fabric can be attributed to the behaviour of the simulation itself. As the warmer air cells rise towards the edge of the global environment, creating convection currents, their rate of heat-loss is slower than what the environment can compensate for. This results in the accumulation of warmer air cells at the top of the global environment, creating a heat-pocket. As a result, some insulation cells move towards the cells with higher cell temperature and get attracted towards the air cells instead of the wall cells, therefore resulting in the partial encapsulation of the building fabric.

How are the captured emergent behaviour patterns analysed to assimilate and develop design solutions? This is discussed further in the next section.

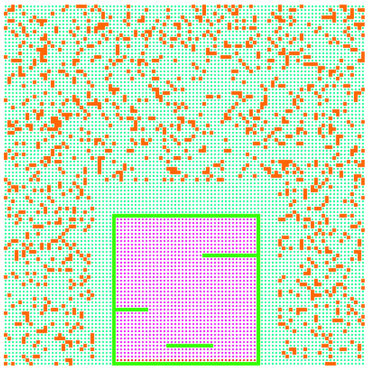

Figure 9. Convection Heat Model View. Air cells (Light Green and Light Red), Wall (Green), Heat-Source (Dark Red) and Insulation (Orange).

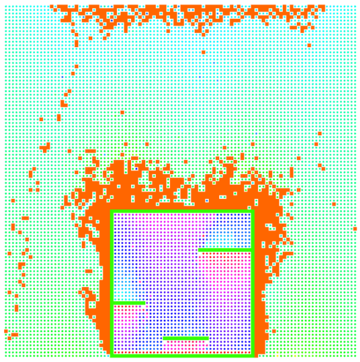

Figure 10. Heat-loss based convection process, through the junctions of the geometry and swarming of insulation agents towards the building fabric.

Uptake and Validation of the Captured Emergent Behaviour

The emergent pattern observed in the above experiments illustrates how simple rules of local interaction can result in emergent behaviour and self-organised pattern of cells in response to conditions of heat-loss through the building fabric. Bharadwaj et. al. (2017) point towards the need for assessing the effectiveness of the emergent pattern stating that, the models developed using CA are a representation of a physical space, hence the emergent pattern captured as a result "can be considered as conceptual solutions that can be enhanced by the designer" (Bharadwaj et. al. 2017). However, as this cannot be done without modelling the physical system in great detail using CA, a decision was made to utilize available design performance analysis tools such to investigate the appropriateness of the emergent solutions. As IES-VE provided a quicker interface to build a test model, a decision was made to use it to undertake the necessary performance tests.

Validation using IES-VE

The effectiveness of conceptual solutions was investigated by developing box models in IES-VE of 3m x 3m x 3m in dimensions. The model was then subjected to two simulations, (a) base case model uniform insulation thickness application, and (b) application of emergent pattern as an insulation design solution. In the these models a decision was made to eliminate high density materials and specify only wood fibre insulation material as the building fabric. This was done to allow for a true comparison between the two simulation cases. In the emergent pattern simulation, insulation was placed to approximate the pattern obtained from the CA model. Thus, external insulation material of 600mm thickness was placed across 500mm from each corner of the model (Figure 11), and the rest of the surfaces were covered with 250mm of insulation. In the base case model (Figure 12), the insulation thickness was calculated by dividing the entire insulation volume of the emergent pattern case by the total surface areas of the box. Thus, the uniform insulation thickness in the base case was calculated to be 367mm.

The simulation results illustrated that the total energy consumption and carbon emissions showed a reduction of 10%. Table 1 shows the results of the two simulations.

Table 1: IES-VE Simulation Results.

Iteration	**Total Carbon Emissions ($kgCO_2$)**	**Space Conditioning Sensible (MWh)**
Base Case	136.7	0.6329
Emergent Pattern Simulation	122.0	0.5648

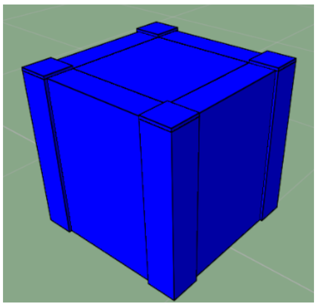

Figure 11. Emergent Pattern Model

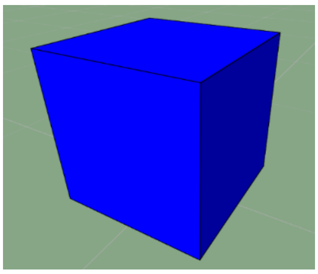

Figure 12. Base Case Model

Discussion

We shall now discuss the CA models and their results demonstrated in this paper and aim to answer some of the questions that arise as the authors introduce this new approach towards of design exploration of building behaviour.

What do these models explain about the building behaviour? The CA models demonstrated above have illustrated the ability to recreate building geometry in the form of emergent self-organised patterns, representing a 3D heat-loss field. These models are designed on the basis of local neighbourhood interactions, thus replacing the need for solving complex mathematical equations. The heat-loss process is visualised in real-time providing an increased understanding of the building behaviour. The emergent pattern formed by insulation cells highlights the parts of the building-fabric that are more affected by the heat-loss process.

These simulations visualise the dynamic nature of the heat-loss process through the building envelope, which is invisible with use of available design analysis tools. Thus, providing designers with a stronger understanding of the building behaviour in response to heat-loss. Furthermore, it points towards how the building morphology, i.e. the design form in conjunction with the external environment, affect the design performance of the building. Through the creation of a self-organised emergent pattern, these simulation models lend themselves to the process of design exploration by providing a starting point to designers.

Why should the emergent-self-organised patterns be analysed for their performance? As the CA models are designed to re-create the conditions of heat-loss, these models provide a qualitative solution in the form of an emergent pattern. While CA models can be designed so that each individual entity in the model provides a tabular output of the result of its functions, such as cell temperature, location, heat-diffusion and heat-gain etc. at every discreet time-step, doing so would add another level of complexity to the model. As the result obtained would have to be sorted and computed, this would be a time-consuming process. Therefore, the uptake of the emergent pattern as a starting point by built-environment professionals would provide them with an avenue for design exploration, enabling them to refine and enhance to meet aesthetic and performance criteria. The refined solution can be assessed for its appropriateness and performance using available design analysis tools such as IES-VE, Design-Builder, Energy Plus etc. where professionals can examine the performance in greater detail and fine-tune the concept to quantify and deliver a high-performance solution.

How does the utilisation of CA model and this bottom-up approach help the built-environment professional? Cellular automata provide a level of abstraction, where the need for developing models in great detail is alleviated, as evidenced in the demonstration of the above models. The utilisation of behavioural rule-sets instead of complex mathematical equations provides a faster and simpler avenue for developing simulation models and "generating effective design solutions" (Jankovic, 2017).

As the models utilise behavioural rule-sets they visualise the complex interactions processes in real-time, in response to heat loss, providing an easier process to develop computational fluid dynamic (CFD) models. This process allows itself to be integrated with the design process from very initial stages, enabling designers to analyse various design concepts and explore the design space. This process, therefore, empowers professionals in the built-environment sector with a stronger understanding of the building behaviour, enabling them to respond to causal mechanisms through a "process analogous to its own evolutions" (Sullivan, 1896). Bharadwaj et. al. (2017) elucidate the benefits of utilising this bottom-up approach stating that, the ability of a designer to explore the design space is strongly dependent upon archived research, designer's own experience, and their ability to conduct an extensive investigation. Thus, the extent of design exploration carried out is severely limited as designers are unable to explore the vast solution space for an appropriate design solution through a top-down approach. However, designers with varying levels of experience can use this bottom-up approach to examine and explore the design space for an appropriate set of solutions, as this method will automatically eliminate non-viable design options, providing them with a set of conceptual solutions for further development.

The emergent behaviour observed in the model identifies specific points of the building morphology that are highly affected by heat-loss. Identification of these thermal-bridging nodes provides designers with the essential information to iterate the design to achieve increased design performance. This can be done by iterating over the building design itself or by the uptake of the self-organised solution to improve the insulation design strategy.

Conclusion

In this paper it has been demonstrated how emergent simulation models of thermal insulation are created and can be used as a much faster and simpler pathway towards exploring the design space. These models are developed using simple behavioural rule-sets and result in the real-time observation of the complex interactions between the environment and the building, thereby creating self-organised emergent patterns which can be utilised to explore the design space and develop efficient and appropriate design solutions. The self-organisation behaviour of cells resulting from this research has illustrated that the utilisation of this bottom-up approach based on local cellular interaction using simple rules provides much more information, than what is initially specified by the modeller. In doing so, this research aims to provide professionals with a framework, enabling them to explore the design space and increase their understating of the building behaviour.

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