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Integration of agent-based modelling of social-spatial processes in architectural parametric design

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Abstract

Applications of computational parametric design in architecture have been associated with radical new form. The recent promotion of such association has led to detachment of other design parameters foundational to architecture, particularly in areas concerning the social and spatial processes of inhabitation. An explicit representation framework is required for modelling the social-spatial processes of inhabitation. In this paper, we introduce an agent-based modelling framework with a computational model of social-spatial dynamics at its core. Here, architectural parametric design is performed as a process of modelling the temporal characteristics of spatial changes required for members of a social group to reach social spatial comfort. We have developed a prototype agent-based system implemented on the Rhino-Grasshopper platform. The prototype system employs a human behaviour model adapted from the PECS (Physical, Emotional, Cognitive, Social) reference model first proposed by Schmidt and Urban. The agent-based modelling was evaluated by comparative modelling of two real Vietnamese dwellings: a traditional vernacular house in Hue and a contemporary house in Ho Chi Minh City. The evaluation shows that the system returns differentiated temporal characteristics of spatial modifications of the two dwellings as expected. We close the paper with ongoing work to extend the agent-based framework.

Keywords: architectural parametric design, social-spatial processes, agent-based modelling, human behaviour modelling, social-spatial comfort

1. Introduction

The recent development in computational design has made algorithmic methods and multi-dimensional modelling tools more accessible to architectural design. Computational parametric modelling is now widely taught at schools of architecture and employed by design practices. Most notably, applications of computational parametric design have been increasingly associated with form-finding in realising unconventional radical architecture with advanced digital fabrication technologies (Schumacher, 2009; Schumacher, 2012). However, global promotion of such associations has also led to detachment of other design parameters foundational to architecture. In particular, qualitative or normative factors in the social and cultural spheres receive much less attention or even exclusion (Neumann, 2014). In a critique of 'Parametricism', Coyne (2014) writes "There are parametric definitions of crowds, swarms and mobs, but as yet nothing that models human sociability and responses to environments in total — the stuff of architecture." Arguably, the social processes of human inhabitation as sources for shaping built spaces over time can be complex (Brand, 1994; Dickinson, 2014), thus human behaviour and sociability in relation to the built environment is less amenable to quantification required by current parametric design workflows. Over the past two decades in the research fields such as Complexity, Artificial Intelligence, and Computational Anthropology, there have been attempts at modelling human behaviours, social relations and human societies as complex systems (Kohler & Gummerman, 2001). One of the significant outputs from such enquires was the development of agent-based modelling (ABM) methods and software tools. More recently, taken as a methodology, ABM has been applied to domain-specific assessment of building performance such as fire evacuation (Ren et al., 2009; Kasereka et al., 2018), or crowd movement control (Henein & White, 2005; Zafar et al., 2016). Users of buildings are modelled as agents of certain social-psychological profiles (traits) who act and interact in the simulated events. However, aspects of the built environment in all such studies were modelled as static spatial or functional boundaries fixed during the simulation. To apply agent-based modelling in the planning and design processes, an explicit representation of spatial environments is required such that spaces are modelled as variables.

In this paper, we present a new framework for integrating agent-based modelling in computational architectural design. The aim of the proposed computational framework is to enable agent-based modelling of human social-spatial processes (as representation of 'inhabitation') to interact with parametric architectural geometry (as representation of a changeable built environment). More specifically, the framework is developed to address the following requirements:

1. Identification of parameters to represent and characterise a dweller's states of (dis-)comfort and (dis-)satisfaction
2. Construction of a computational model for specifying the behaviours and social relations of a number of agents representing a generic contemporary household
3. Expression of architectural design in computational parametric geometry
4. Simulation of inhabitation as the social-spatial processes where a given architectural design in its entirety is modified towards the agents' individual and collective dwelling comfort and satisfaction
5. Evaluation of the validity of the proposed framework with test case studies

In the sections followed, we first present a review of selected references on agent-based modelling of human behaviours and social-spatial processes. A conceptual framework is then proposed for modelling social-psychological interaction with a dynamic virtual environment constructed in parametric architectural geometry. Following the conceptual framework, we describe our current prototype system design and implementation on the Rhino-Grasshopper programming platform. In evaluating the validity, we applied the prototype to comparative modelling of two well-known Vietnamese dwellings – Hue Garden House (a historical vernacular house in Hue) and House for Trees (a contemporary residence in Ho Chi Minh City designed by VTN Architects). Representing members of a generic hypothetical household, the same set of agents was applied to the two dwellings modelled in parametric geometry according to the original designs.

The simulation of inhabitation of the two dwellings returns very different temporal-spatial characteristics of house design change over the simulated timeframe. We discuss the validity of our current prototype experiment and the implication for further work to extend this new framework.

2. Agent based modelling of human behaviours and social spatial processes: Selected references

Over the past two decades, the study of human behaviour and social interaction as the basis for creating 'agents' or 'agency' in a virtual world has developed interesting conceptual frameworks and experimental digital systems in the field of Interactive Storytelling. Mateas (1999) proposed six requirements in building 'believable' agents or life-like characters in interactive drama: *Personality*, *Emotions*, *Self-motivation*, *Change*, *Social relationships*, and *Illusion of life*. The programming language 'Hap' was created specifically for building believable agents and was later further developed into 'ABL' (A Behavior Language) by Mateas and Stern (2004). Spierling and co-workers developed a modular system for interactive storytelling that employed a 'belief-desires-intentions' (BDI) architecture to implement deliberative capacities of an agent character (Spierling et al., 2002). Using ABL, Reidl and Stern (2006) built agents to handle interaction with the user (of interactive storytelling) modelled as accomplishing joint goals enacted by multiple agents. Further development in affective computing and intelligent interaction has enabled creation of autonomous agents capable of forming social relations in an interactive narrative (Dias & Paiva, 2011). Lately, Paradeda and co-workers showed how interactive storytelling could be used to elicit users' personality traits following the Myers-Briggs Type Indicator (MBTI) (Paradeda et al., 2017).

Somewhat different from the Interactive Storytelling research, the field of classical or behavioural Artificial Intelligence has developed agent-based modelling that seeks more of the general principles by which the interactions between agent and environment can be described. For instance, the MASSIS (Multi-Agent System Simulation of Indoor Scenarios) (Pax & Pavon, 2016) and Event-based model (Schaumann et al., 2016) have developed proposals for indoor crowd simulation by simplifying human behaviour into two categories: high-level (decision-making process) and low-level (environmental perception and communication) behaviours. Although the agent structure is different, their approach is similar in using agents' behaviours, which includes expected behaviours (scheduled or user-defined) and unexpected (random) behaviours to evaluate the simulation environment, in this case, the architectural space.

Hong and Lee (2018) developed a process using game engine and Revit toolkits to bring designers and students into the human-computer interaction through 3D visualisation of agents' behaviour. By exploring combination of behavioural data modelling with rule based systems from architectural social science, Jorn and Shin (2013) showed that the social psychology of spatial modification behaviours can be modelled and simulated. Another related study in social science has suggested that human behaviours are greatly impacted by elements of the surrounding built environment (Bittencourt et al., 2015). These studies indicate the prospect of how architectural parametricism may be redefined and enriched with inclusion and synthesis of spatial-social dynamics in computational design process to facilitate co-design and evidence-based design.

However, because of the simplification in agent behaviour calculation, existing systems tend to treat architectural users as similar entities with binary decision ability, e.g. to move or to stand, violent or non-violent behaviour, while in real life, human behaviour decision process is much more complicated and strongly affected by individual personality (Ratti & Claudel, 2015). Proposed by Bernd Schmidt in "The Modelling of Human Behaviour" (2000), the PECS (Physical, Emotional, Cognitive, Social) reference model has been applied in a number of studies, in which researchers tried to model certain aspects of human behaviour with reference to the built environment. One example is the simulation system used for security force training (Kvassay et al., 2017) under project EUSAS (European Urban Simulation for Asymmetric Scenarios), dealing with threats in urban context, such as rioting crowds, insurgents, or terrorists. Sibbel and Urban (2002) applied the model into a hospital management project, by evaluating the architectural performance based on users' behaviour and decision making. Another application of the framework is in public transportation safety (Briano et al., 2011), which looks into crowd modelling in motorway tunnel emergency evacuation.

It should be noted that the PECS reference model is based on what was later called 'causal partition' (Kvassay et al., 2017), in which the output decision is quantified from the contribution of various numerical inputs (Figure 1). This approach allows the model to dynamically modify the relative importance of agents' *motive* values during the simulation process, thus it can predict human behaviour by collecting their psychological data. But at the same time, it requires identification and documentation of instances of emergent behaviours in order to successfully model them into the PECS framework (Heppenstall et al., 2016). However, at the present, the knowledge about how people react and perceive the architectural space they inhabit is still limited, and we may not entirely understand how close a PECS-like system is to reality. Nevertheless, it may be possible in the near future that there will be enough individual and social behavioural data as open data allowing for empirical verification of simulated human spatial perception and the underlying mechanism involved.

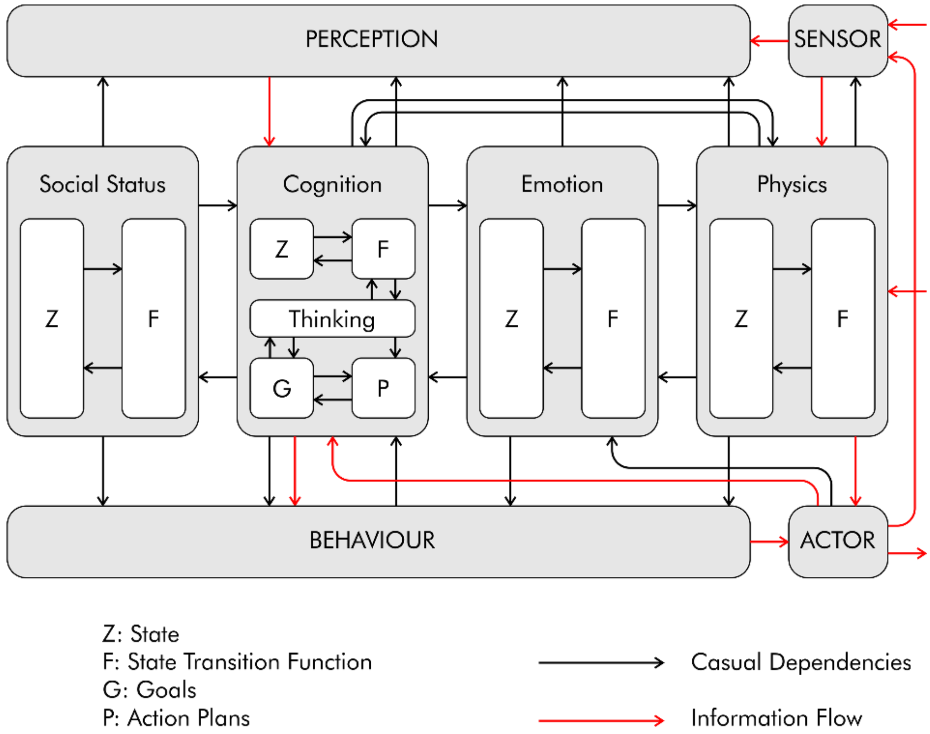


Figure 1. Conceptual structure of the PECS reference model adapted from Schmidt (2002)

Adopting the PECS framework, human behaviour can be computable if it is simplified and modelled as a combination of several Richards' curves. Formulated by F.J. Richards (1959) as an extension of the logistic or Sigmoid function, allowing for more expressive S-shaped curves, the formula is widely used in computational growth modelling which was considered applicable in modelling human psychological motivation (Schmidt, 2002). Overall, the Richards' curve provides an S-shaped mathematical function, which has the *Y* value (Behaviour Intensity) gradually increasing from 0 to 1 over the *X* value (Behaviour Time). Here the Richards' curve can be modified from linear to non-linear, with *X* as an independent variable representing behaviour time. More specifically, when a behaviour is chosen and executed by an agent at time x, it means that the agent does not have the urge, or motivation to do that behaviour anymore, the intensity of the behaviour (y) returns to 0 at time x (Figure 2).

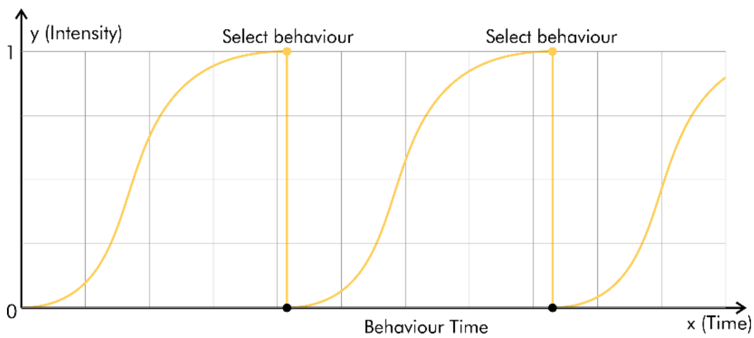
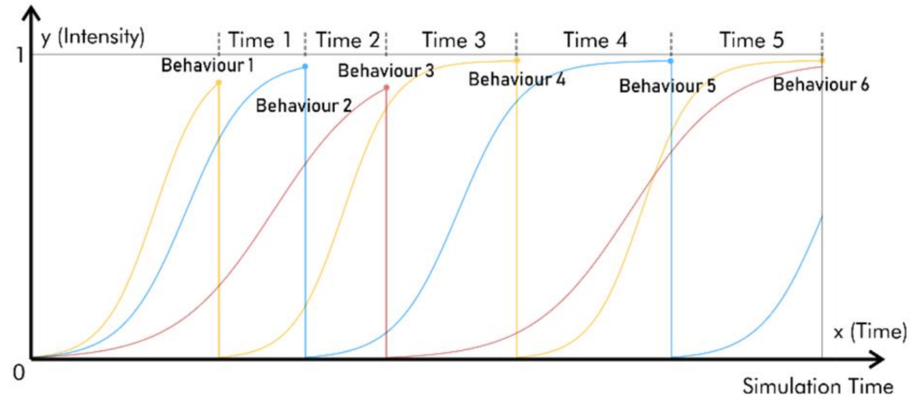


Figure 2. Use of Richards' curve for modelling a single human behaviour over time

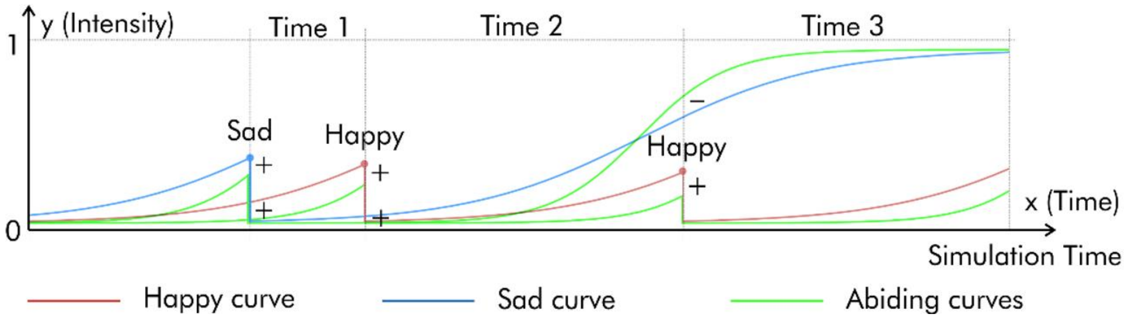
By combining a set of non-linear Richards' curve models with different *D* values (representing Motive), a mechanism of behaviour selection and calculation is proposed (Figure 3). This algorithm compares the *Y* values of the Richards' curves of a given simulation time (x) and selects the behaviour with the largest *y* at the time *x*. In this extended model, an agent's psychological motives are quantified as *D* values which can be linked to the set of behaviours known to the system (Schmidt, 2000); the motive value *D* of a behaviour is set at the beginning of simulation and does not change over time (a constant). The *X* value is obtained from the simulation time. Hence, *Y* the intensity of behaviour is governed by *D* over time according to the logistic function (Schmidt, 2000). Since each behaviour requires a period of time to complete, the selection process is repeated at different intervals, thus increasing the diversity of chosen behaviours of agents. The running of this system over time means that behaviours with higher motives *D* values to be chosen more frequently than those with lower *D* values.



$$y = \frac{1}{1 + e^{-\left(\frac{10}{1+\left(\frac{5}{D+0.01}\right)\cdot 4}\right)\cdot\left(x-\left(\frac{1+\left(\frac{5}{D+0.01}\right)\cdot 4}{2}\right)\right)}} \quad \text{(Eq. 1)}$$

Figure 3. Behaviour calculation for one agent with multiple behaviours according to the logistic function (Eq. 1) (Schmidt, 2000)

The Richards' curve can also be used to determine an agent's *emotional state*, which introduces the element of 'randomness' into an agent's behaviour selection process. This can be modelled by a two-curve system made of the paired *Emotion* curve and the *Abiding* curve (Schmidt, 2000). Here the parameters include *SP* (Self-perception value) and *EQ* (Emotional intelligence value). Conceptually, agents with SP > EQ will be affected more by their emotion states, while agents with SP < EQ have better control over their decisions. As such an agent-based modelling system built with four Richards' curves can be used to model an agent's two emotion states, for instance, *happy* and *sad*. Each emotion state is modelled by a pair of emotion and abiding curve governed by its corresponding equation (Figure 4). The emotion states of an agent are continuously evaluated over simulation time. At each interval of evaluation, subtractions between the y values of *Emotion* curve and *Abiding* curve of two emotional states are compared. If one subtraction is positive and larger than the other one, the agent is pointed to have that emotional state (happy or sad).



A (SP): Self-perception value; *E* (EQ): EQ value

Emotion curve formula:

$$y = \frac{1}{1 + e^{-\left(\frac{10}{1+4 \cdot A}\right) \cdot \left(x - \frac{A}{1+4 \cdot A}\right)}} \quad \text{(Eq. 2)}$$

Abiding curve formula:

$$y = \frac{E}{1 + e^{-\left(\frac{20}{1+4 \cdot A}\right) \cdot \left(x - \frac{A}{1+4 \cdot A}\right)}} \quad \text{(Eq. 3)}$$

Figure 4. An example of modelling the *emotional state* involving paired *Emotion* curve (Eq. 2) and *Abiding* curve (Eq. 3) as modelled by the logistic functions respectively (Schmidt, 2000)

3. Modelling social-psychological interaction with parametric architectural geometry: A proposal

In this paper, we propose a theoretical framework for encoding human psychological information in social and spatial processes to computable datasets. This framework will provide a road map for implementing an agent-based modelling system that has a computational model of social dynamics at its core to interact with 3D virtual environment modelled in parametric architectural geometry. The system design, implementation and evaluation of the prototype will be presented later in Section 4 & 5.

3.1 A definition of social-spatial dynamics

Factors such as geometrical shape, material, and environmental comfort have long altered and produced perception and experience for spatial users (Figure 5). However, architectural science has always treated users as a group with similar physical and psychological characteristic (Ratti & Claudel, 2015), while nowadays, we know that our society is highly diverse, in terms of individuality and sociability. To address the lack of human-architecture identification, we propose the term 'Social-Spatial Dynamics' as the goal of developing an agent-based modelling system.

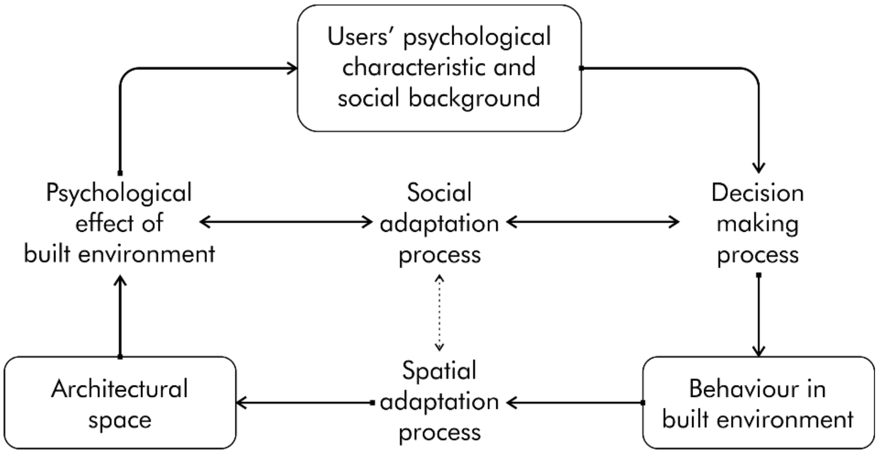


Figure 5. Relationship between users (dwellers), architectural spaces and behaviours

Social-Spatial Dynamics (SSD) is defined as the temporal characteristics of spatial changes for member(s) of a social group inhabiting a space to reach satisfactory psychosomatic state individually and collectively. In other words, by combining humans' individual characteristics with architectural parametric geometry, the aim of an agent-based modelling is to simulate the dynamic interaction between users, their behaviours and the built environment through continuous social-spatial evaluation and modification until a satisfying state is achieved (Figure 6). This approach allows computational designers to input users' detailed psychological and social data; their behaviour profiles, spatial perception and how the spaces of the architecture can be modified to meet their needs and preferences.

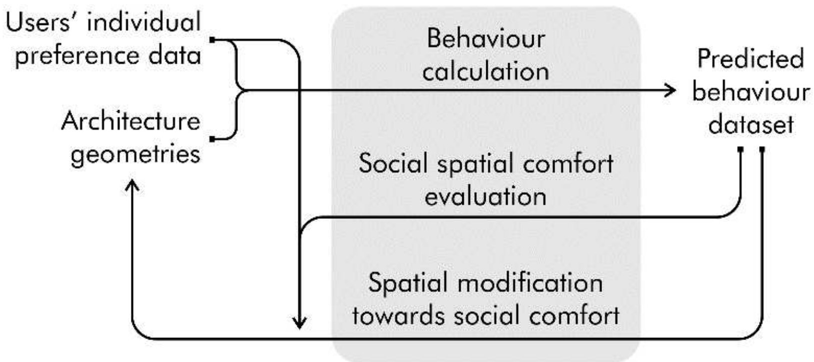


Figure 6. A proposed dataflow framework for simulating the Social-Spatial Dynamics of human-behaviour-architecture interaction

3.2 Calculation of an agent's behaviour

As an agent can have a large set of behaviours that links to a smaller set of motives, the Richards' curve system may generate a set of expected behaviours with equal motive intensity. This set is then filtered and chosen based on three other factors including:

- The relationship of an agent and other agents: An agent will tend to choose the behaviour which can help her/him to be in the same place with her/his favourite agent, and avoid interaction with the least favourite one.
- The locations of behaviours: The agent will tend to choose behaviours that have less travel distance from her/his current location.
- The emotional state: If an agent is happy, he/she will tend to choose behaviours which are driven by certain motives such as the *Life Enjoyment* and *Sociable Value* motives. If it is sad, behaviours driven by *Life Enjoyment* and *Sociable Value* motives will be temporarily suspended from the behaviour set to prevent the agent to choose those behaviours.

Agents' emotional states not only affect their decision-making processes, but they can also change their psychological motive values. For example, an agent in a happy state will automatically increases her/his *Sociable* and *Life Enjoyment* values, while a 'sad' agent will decrease those motive values. This combination of these factors is expected to better reflect the complexity of the agent's behavioural decision process, or in other words, being perhaps more 'human life like' (Figure 7).

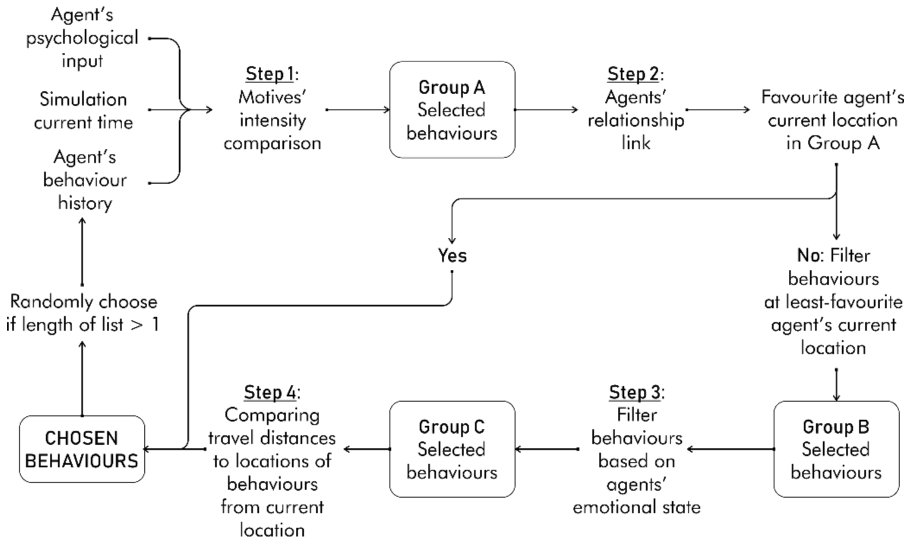


Figure 7. Calculation of an agent's behaviour

3.3 Analysis and evaluation of Social Spatial Comfort (SSC) value

To evaluate the social comfort of an architectural space, we define Social Spatial Comfort (*SSC*) value as a behaviour-led measurement. The *SSC* value is developed from three main factors influencing human spatial experiences (Sussman & Hollander, 2014; Bittencourt et al., 2015):

- The *convenience* of traveling between functional spaces, in term of distance and accessibility
- The *dimension* of space and how it supports users' activities that happen inside the space
- The *openness* of space which provides views and connections to the outside of the space

With reference to how human experience the spatial characteristic every time an agent uses (inhabits) a space, these factors can be asserted in each agent's behaviour. Since each behaviour of an agent is integrated with a unique set of spatial requirements, these three values represent the agent's behavioural comfort by evaluating the set of spatial requirements with the actual architectural geometry in terms of the following:

- Moving Distance (*MD*) = The distance from agent's current location to the location of chosen behaviour (metre)
- Dimensional Comfort (*R1*) = (Location dimension / Chosen behaviour required dimension) %
- Openness Comfort (*R2*) = (Location openness / Chosen behaviour required openness) %

Therefore, a set of comfort assessment values can be generated from the set of agents' output behaviours. By grouping this dataset based on the behaviour's location (or space name), a system can calculate the set of average spatial comfort parameters for each space based on the following four values, each ranging from 0% to 100%:

- *Li* (Importance level) = (Time spent at location) / (Total simulation time)
- *Lf* (Moving distance comfort) = 100% - [(Total distance to move to location) / (Total moving distance)] %
- $\overline{R1}$ (Dimensional comfort) = Average all Behaviour's dimensional comfort (*R1*) at location, weighted by behaviour's time proportion
- $\overline{R2}$ (Openness comfort) = Average all Behaviour's openness comfort (*R2*) at location, weighted by behaviour's time proportion

Finally, the Social Spatial Comfort (*SSC*) value of a dwelling (i.e., whole building) is defined as the average comfort of three factors: moving distance (*Lf*%), dimension ($\overline{R1}$%), openness ($\overline{R2}$ %) of all spaces inside it, weighted by the time proportion that agents spent at each space *Li*% (*j*: number of spaces):

$$SSC = \sum_{j=1}^{n} (Li\%)_j \cdot \left(\frac{Lf_j + \overline{R1}_j + \overline{R2}_j}{3}\right) \qquad \text{Eq. (4)}$$

Therefore, it follows that the more time agents use (inhabit) a space, the more it affects the overall *SSC* value positively or negatively. Table 1 gives an example dataset containing three agents (A, B, C), three spaces (Living, Dining, Bedroom) and six behaviours. Each behaviour has a set of spatial requirements (MD, R1, R2). In this example, the overall Social Spatial Comfort value of the dwelling is the sum of the A% values weighted by Li%, equal to 52.74% (Table 2).

Table 1. An example of output behaviour dataset

Agent	**Behaviour**	**Location**	**Time** (hour)	**MD** (m)	**R1** (%)	**R2** (%)
A	Reading books	Living room	1.0	6	20	100
	Sleeping	Bedroom	6.0	8	100	30
B	Eating	Dining room	1.0	5	80	60

	Cleaning	Bedroom	0.5	2	15	80
C	Watching TV	Living room	4.0	10	50	90
	Sleeping	Bedroom	1.0	15	20	10
Total simulation time and total walking distance			**13.5 hours**	**46 metres**		

Table 2: An example of social spatial comfort (SSC) calculation

Space	**Total time spent**	**Li** (%)	**Total distance**	**Social Spatial Comfort (SSC) values**			
				Lf (%)	$\overline{R1}$ (%)	$\overline{R2}$ (%)	**Average (A%)**
Living room	5 hours	37.04 %	16 m	65.22 %	44.00%	92.00%	67.07%
Dining room	1 hour	7.41 %	5 m	89.13 %	80.00%	60.00%	76.38%
Bedroom	7.5 hours	55.56 %	25 m	45.65 %	43.76%	30.67%	40.03%
Overall SSC	**52.74%** (the sum of A% values weighted by Li%)						

3.4 Spatial modification process

The fact that people change their buildings over time suggests the necessity of a system to perform a spatial modification process, as though agents inhabit to modify the virtual architecture in order to maximise the SSC value. However, since architectural design often involves many other inputs, we propose to start with a general spatial modification process involving only four functions as specified below:

- Modifying interior spaces' areas to reach their $\overline{R1}(\%)$ expectation values, by increasing their dimensions towards the exterior spaces.
- Modifying interior spaces' opening levels to reach the $\overline{R2}(\%)$ expectation value, by increasing their window sizes
- Modifying spaces' locations by switching them with more suitable functions that share similar areas and higher Lf% values.
- Creating canopy on top of exterior space if they are frequently used as transportation space (the space used to go from one destination to another) more than 20% of simulation time.

The above set of rules allows an agent-based system to modify the input parametric geometries towards agents' satisfactory psychosomatic state as measured by the social spatial comfort values over simulation time, individually as well as collectively.

4. System implementation of agent-based modelling of social dynamics in a parametric design environment

Our current system design and implementation of an agent-based modelling environment is based on the Rhino-Grasshopper platform with a view of future release of the system development as a Plug-In via the food4Rhino developer community (https://www.food4rhino.com/).

4.1 System architecture

The proposed system architecture consists of three layers (Figure 8). The core layer (Layer 1), namely the Virtual World of Agent, is where all the simulation results are stored as interaction between the three main components: The *Agents*, the *Behaviours* and the *Environment* (ABE). The inner layer (Layer 2), the Controller, provides all the mathematical functions that link the datasets of the ABE components together inside the simulation loop. The outer layer (Layer 3), the User Input, provides the user interface. The computation process is a sequence of exchanges of data and methods between the three layers. By repeating this sequence continuously, each entity in the three main entities (Agents, Behaviours, Environment) can affect one another during the simulation period, imitating social-spatial processes of human inhabitation over time.

Since each layer in the system architecture operates with different data and functions in the simulation process, the layers make their own contribution to the system's overall performance. The interaction between them is initiated and maintained by computation processes hosted on Layer 2 (see Table 3). Working together sequentially, they go through loops until social spatial comfort maximisation is reached in every simulation run (Figure 9).

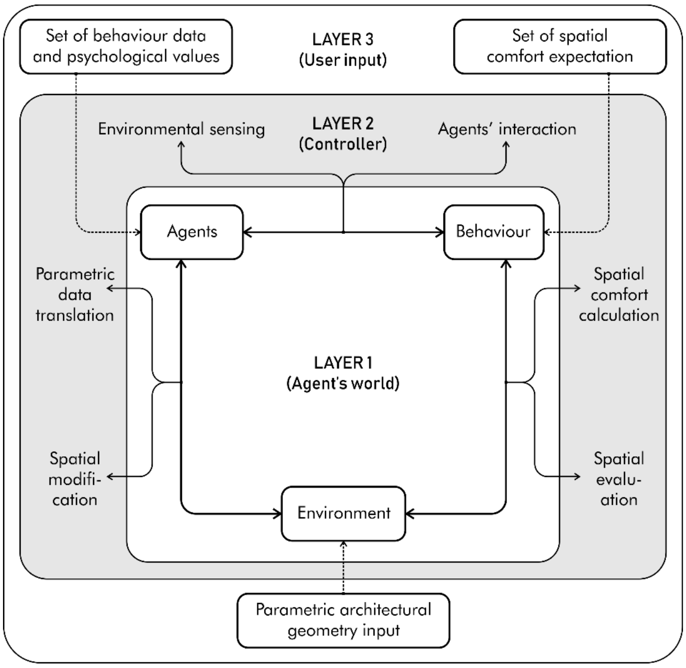


Figure 8. The three layers of the proposed system architecture

Table 3. Relationship between three structural layers

Layer 1: Entity interaction	**Layer 2:** Computation methods	**Layer 3:** User input
Agents and Behaviours	**(a) Behaviour calculation process** - Choosing behaviour based on the comparison of agents' behaviour motives - Choosing behaviour based on agents' virtual environment sensing (agents' locations, space dimension, space openness) - Choosing behaviour following interaction of other agents	Set of agents' psychological and physical values Set of agents' behaviours, motives and schedules
Behaviours and Environment	**(b) Output analysis and social spatial comfort (SSC) evaluation process** - Comparison between behaviour's spatial requirements and current environment's characteristics - Evaluation of the environment based on behaviour's expectation and users' preferences	Set of behaviours' spatial requirements Set of users' preferences

Environment and Agents	**(c) Spatial modification process** - Modification of the environment based the evaluation result - Translation of the architectural parametric geometries to agents' readable environment	Set of parametric architectural input

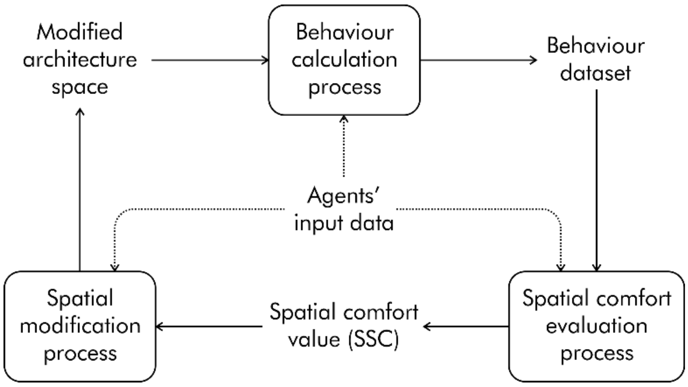


Figure 9. The loop of three computation processes (behaviour, SSC, spatial modification) towards social spatial comfort maximisation

4.2 The input data framework

To conduct simulation, the following input data in three categories are required:

- 3D architectural spatial construction: Modelling the dwelling environment in the system's parametric geometry components and function network
- Agent construction: Constructing the agents as inhabitants of the dwelling environment based on their input psychological parameters, physical parameters and their behaviour dataset in relationship with the architecture.
- Agent relationship construction: Representing the social relationship of agents, e.g. *Antagonistic*, *Amicable*, *Concordant*, which will be used in some numeric values in the simulation process.

Similar to the PECS reference model, agents' behaviours are mainly driven by their psychological input values, or motive values. Here, an agent is built with five psychological parameters including:

- Sociable value (Sp): an agent's inclination to interact with other agents, which is linked to social behaviours.
- Carefulness value (Cp): the extent an agent attends to get immediate surroundings organised, which is linked to behaviours such as cleaning, washing, and organising.
- Life enjoyment value (Ep): an agent's desire to be stimulated, pursue interests, have fun, and is linked to relaxing, or entertaining behaviours.
- Self-perception value (SP): an agent's ability to identify and perceive her/his own emotion and motives, and is linked to emotion perception.

- EQ (EQ): an agent's self-awareness level, or the ability to carry on behaviours without being highly influenced by other internal values such as emotion and physical state, and is linked to emotional restraint.

A summary of the input data framework is presented in Table 4. Although the framework requires detailed psychological and physical input data, the system allows for multiple components for one set of input (e.g. multiple behaviours for one agent). In case where a large number of agents involved (e.g. hundreds or thousands of agents), input values could be provided by a random choice generator (yet to be implemented). Therefore, the agent-based modelling system has the potential to run simulation of different scales, depending on the modelling objective.

Table 4. The input data framework

<table>
<tr><th colspan="2">Category</th><th>Component</th><th>Parameter</th><th>Parameter type</th></tr>
<tr><td colspan="2" rowspan="8">Architecture space</td><td rowspan="4">Interior Space</td><td>Geometry</td><td>Closed poly-surface</td></tr>
<tr><td>SpaceName</td><td>String</td></tr>
<tr><td>Windows</td><td>List of curves</td></tr>
<tr><td>MaximumNumberofPeople</td><td>Integer</td></tr>
<tr><td rowspan="2">Exterior Space</td><td>Geometry</td><td>Planar surface</td></tr>
<tr><td>SpaceName</td><td>String</td></tr>
<tr><td rowspan="2">Network Generation</td><td>SpaceInfo</td><td>Interior Space and Exterior Space output</td></tr>
<tr><td>SpaceConnection</td><td>List of couples of strings</td></tr>
<tr><td rowspan="19">Agent construction</td><td>Name</td><td rowspan="9">Agent Construction</td><td>AgentName</td><td>String</td></tr>
<tr><td rowspan="5">Psychological data</td><td>Sp</td><td>Float (0.0-1.0)</td></tr>
<tr><td>Cp</td><td>Float (0.0-1.0)</td></tr>
<tr><td>Ep</td><td>Float (0.0-1.0)</td></tr>
<tr><td>SP</td><td>Float (0.0-1.0)</td></tr>
<tr><td>EQ</td><td>Float (0.0-1.0)</td></tr>
<tr><td rowspan="3">Physical data</td><td>Age</td><td>Float (1.0-100.0)</td></tr>
<tr><td>Gender</td><td>Boolean (True: Male, False: Female)</td></tr>
<tr><td>Mobility</td><td>Float % (0.0-100.0)</td></tr>
<tr><td rowspan="10">Behaviour dataset</td><td rowspan="4">Scheduled Behaviour</td><td>Name</td><td>String</td></tr>
<tr><td>Location</td><td>String (Choose from the list of SpaceName)</td></tr>
<tr><td>Begin</td><td>Time (0:00 – 24:00)</td></tr>
<tr><td>End</td><td>Time (0:00 – 24:00)</td></tr>
<tr><td rowspan="6">Behaviour Construction</td><td>Name</td><td>String</td></tr>
<tr><td>Location</td><td>String (Choose from the list of SpaceName)</td></tr>
<tr><td>Time</td><td>Float (0.0-24.0)</td></tr>
<tr><td>Motive</td><td>String (Choose from Sp, Cp, Ep, Ps)</td></tr>
<tr><td>DimensionRequirement</td><td>Float % (0.0-100.0)</td></tr>
<tr><td>OpennessRequirement</td><td>Float % (0.0-100.0)</td></tr>
<tr><td colspan="2" rowspan="3">Agent relationship</td><td rowspan="3">Relationship Construction</td><td>Agent1Name</td><td>String</td></tr>
<tr><td>Agent2Name</td><td>String</td></tr>
<tr><td>Value</td><td>Float (-1.0 to 1.0)</td></tr>
</table>

5. **Evaluation of the prototype system: Comparative modelling of two Vietnamese dwellings**

To evaluate the current version of the prototype, we conduct two case studies to examine the differences of the simulation outcome in terms of the temporal characteristics of spatial changes evaluated and generated by the system. Given that real-world vernacular architecture can be seen as the outcome from the working of Social-Spatial Dynamics as a reference, we chose two contrasting residential buildings in Vietnam. While the Hue Garden House (HGH) is an example of Vietnamese vernacular house architecture, the House for Trees (H4T) on the other hand is a contemporary house in Ho Chi Minh City recently built in an unusual radical form (Figure 10).

Figure 10. The House for Trees (left) [https://www.archdaily.com/518304/house-for-trees-vo-trong-nghia-architects], The Hue Garden House (Nguyen & Kobayashi, 2015)

More specifically, HGH is an applauded traditional archetype of Vietnamese heritage architecture. Based in Hue, the old capital of Vietnam, the house is famous for its combination of outside and inside spaces, as well as shared and private spaces (Nguyen & Kobayashi, 2015). In contrast, the H4T by Vo Trong Nghia Architects attracts some criticism. Some articles comment that the building is devoid of cultural values, since it does not provide an enjoyable or even liveable environment. Drawing from the Vietnam National Architecture magazine, March 2016: 'The building is hardly suitable to Vietnamese people's psychology, preferences and also aesthetic notion.' Specifically, they pointed out that living in the H4T, the family member's spaces are 'scattered, isolated, and are forced to stay at their very private corner.' The detailed geometric specifications of the two houses can be found in Supplement Table 1 (Hue Garden House) & Supplement Table 2 (House for Trees).

5.1 Agent construction and input data

In modelling the two dwellings, we use the same set of input data in Agent Construction and Agent Relationship. The Architecture Space data and behaviours' locations are translated from the real world architecture. For Agent Construction, three agents were built for a hypothetical three-member family, namely Father, Mother and Son. In a way similar to a narrative approach in interactive storytelling, these family characters were exemplified by life-like scenarios construed by one of the authors who is a native of the Vietnamese culture. The psychological input data (Table 5) specify the outlook of virtual personality of each agent. With his high values of *Carefulness* (Cp) and EQ, the Father agent is modelled as a careful, thorough man who mostly takes care of the housework. In contrast, the Mother agent is likely to be relaxing high *Life Enjoyment* (Ep) value and easily to be affected by emotion (SP > EQ). The Son agent, on the other hand, is sociable (high *Self-Perception* SP value) and is likely to spend most of his time outside the house.

Table 5: Agents' physical and psychological inputs representing a generic household

Agent, Age, Gender	Father, Male, 35	Mother, Female, 30	Son, Male, 17
Carefulness Value (Cp)	0.8	0.4	0.2
Sociable Value (Sp)	0.6	0.5	0.9
Life Enjoyment (Ep)	0.4	1.0	1.0
Self-Perception (SP)	0.7	0.7	0.6
Emotional Quotient (EQ)	0.9	0.6	0.6

Beside the set of physical and psychological input data, each agent is assigned with a set of behaviours of two types: (1) scheduled behaviours, and (2) non-scheduled behaviours. A scheduled behaviour which includes a location and a time range is to simulate human's daily activity, i.e., studying, working; while each non-scheduled behaviour is connected to one of psychological motives, and is determined by the behaviour calculation process. To give an example, the agent construction for 'Father' is shown in Table 6. The agent construction for 'Mother' and 'Son' can be found in Supplement Table 3 and Supplement Table 4 respectively.

Table 6. Agent construction of 'Father' for House for Trees (H4) and Hue Garden House (HGH)

Category	Parameter Name	Type and Range	Value	
			H4T	HGH
Physical Data	Age	Float (1.0-100.0)	35	35
	Gender	Boolean	True (Male)	True (Male)
	Mobility	Float % (0.0-100.0)	100%	100%
Psychological Data	Carefulness Value (Cp)	Float (0.0-1.0)	0.8	0.8

(*D* values)			Sociable Value (Sp)	Float (0.0-1.0)	0.6	0.6
			Life Enjoyment (Ep)	Float (0.0-1.0)	0.4	0.4
			Self-Perception (SP)	Float (0.0-1.0)	0.7	0.7
			Emotion Quotient (EQ)	Float (0.0-1.0)	0.9	0.9
Behavior Setting	**Scheduled behaviours**	0	Name	String	Working	Working
			Location	String	Front yard	Front yard
			Begin	Time (0:00 – 24:00)	8:00	8:00
			End	Time (0:00 – 24:00)	11:00	11:00
		1	Name		Dinner	Dinner
			Location		Dining room	Dining room
			Begin		18:00	18:00
			End		19:00	19:00
		2	Name		Sleeping	Sleeping
			Location		Bedroom 1	Bedroom 1
			Begin – End		22:00	22:00
			End		6:00	6:00
	Non-scheduled behaviours	0	Name	String	Cleaning	Cleaning
			Location	Choosing from list	Dining room	Common space
			Time	Float hour (0-24)	1 hour	1 hour
			Motive	Choosing from list	Carefulness value	Carefulness value
			DimensionRequirement	Float % (0-100)	60%	60%
			OpennessRequirement	Float % (0-100)	90%	90%
		1	Name		Inviting friends	Inviting friends
			Location		Dining room	Socialising space
			Time		3 hours	3 hours
			Motive		Sociable value	Sociable value
			DimensionRequirement		100%	100%
			OpennessRequirement		80%	80%
		2	Name		Fixing things	Fixing things
			Location		Storage	Storage 1
			Time		2 hours	2 hours
			Motive		Carefulness value	Carefulness value
			DimensionRequirement		50%	50%
			OpennessRequirement		50%	50%
		3	Name		Shower / Toilet	Shower / Toilet
			Location		Bathroom 1 or 2	Bathroom
			Time		0.5 hour	0.5 hour
			Motive		Physical State	Physical State
			DimensionRequirement		30%	30%
			OpennessRequirement		30%	30%
		4	Name		Watching TV	Watching TV
			Location		Bedroom 1	Common space
			Time		2 hours	2 hours
			Motive		Life Enjoyment	Life Enjoyment
			DimensionRequirement		70%	70%
			OpennessRequirement		50%	50%
		5	Name		Reading book	Reading book
			Location		Library	Bedroom 1
			Time		2 hours	2 hours
			Motive		Life Enjoyment	Life Enjoyment
			DimensionRequirement		20%	20%
			OpennessRequirement		90%	90%
		6	Name		Having tea	Having tea
			Location		Central yard	Pond garden
			Time		2 hours	2 hours
			Motive		Life Enjoyment	Life Enjoyment
			DimensionRequirement		40%	40%
			OpennessRequirement		90%	90%

In addition, the input dataset of Agent Relationship and its interpretation is shown in Table 7. When choosing behaviour, an agent chooses the one that can take place in the same location with his/her favourite agent(s), and avoids the least favourite one(s).

Table 7. Agent Relationship input

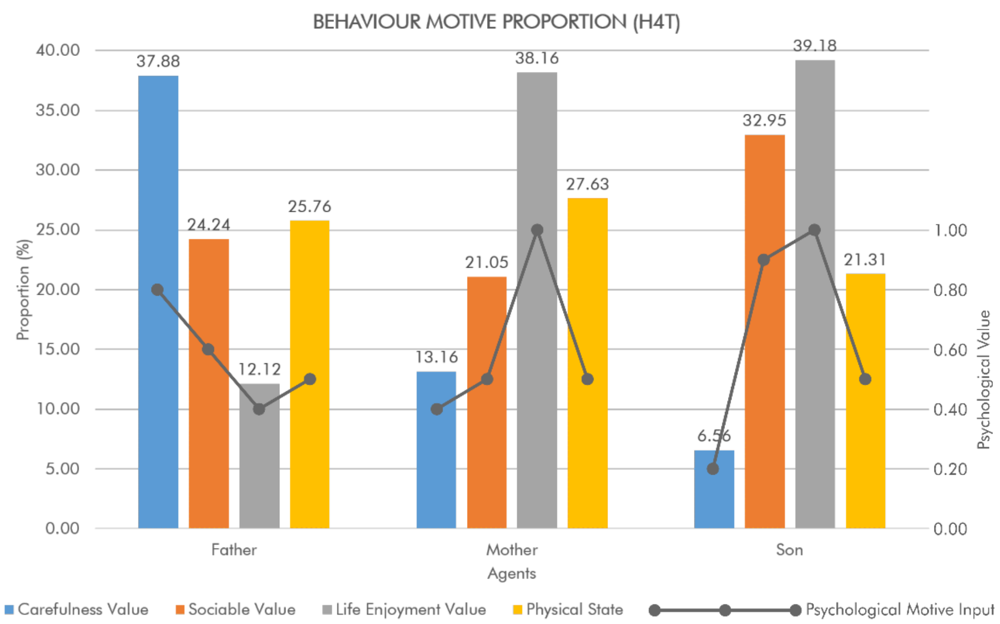
Agents	**Relationship Value** (-1.0 to 1.0)	**Meaning**
Father – Mother	-0.8	Antagonistic, Discordant
Mother – Son	1.0	Amicable, Affectionate
Father – Son	0.5	Mutual, Concordant

These input data define a detailed profile of each agent's individual personality, and the social relationships with other agents. Since the behaviour selection is driven from these data, which plays a significant role on interacting with architectural spaces, we implemented a framework for modelling potentially diverse individuality and sociability in connection with parametric design process. This also means that a computational designer working with the agent-based system would require a good understanding of both the architectural geometry and its intended dwellers in constructing the input datasets.

5.2 Agents' behaviour output and analysis

The simulation was set to run for 365 days. The main output is the dataset of agents' behaviours (including behaviour name, location, time, motive, walking distance, dimensional and openness comfort). As an example, Figure 11 shows the proportion (%) of behaviours of the three agents categorised by four driving motives (Carefulness value, Sociable value, Life Enjoyment value and Physical State) in the two dwellings. This analysis is to visualise the relationship between the behaviour outputs and the agents' psychological inputs. For instance, the Father agent has the highest Carefulness value (0.8, Table 5), and Son the lowest (0.2, Table 5), their behaviour outputs correspond to similar profiles. The Son also has a highest ratio of behaviours driven by Life Enjoyment value, similarly to his input (1.0, Table 5). On the other hand, the Mother agent also shows highest proportion of Life Enjoyment driven behaviours (input 1.0, Table 5), which is the lowest in the Father's case (0.4, Table 5).

(a) House for Trees



(b) Hue Garden House

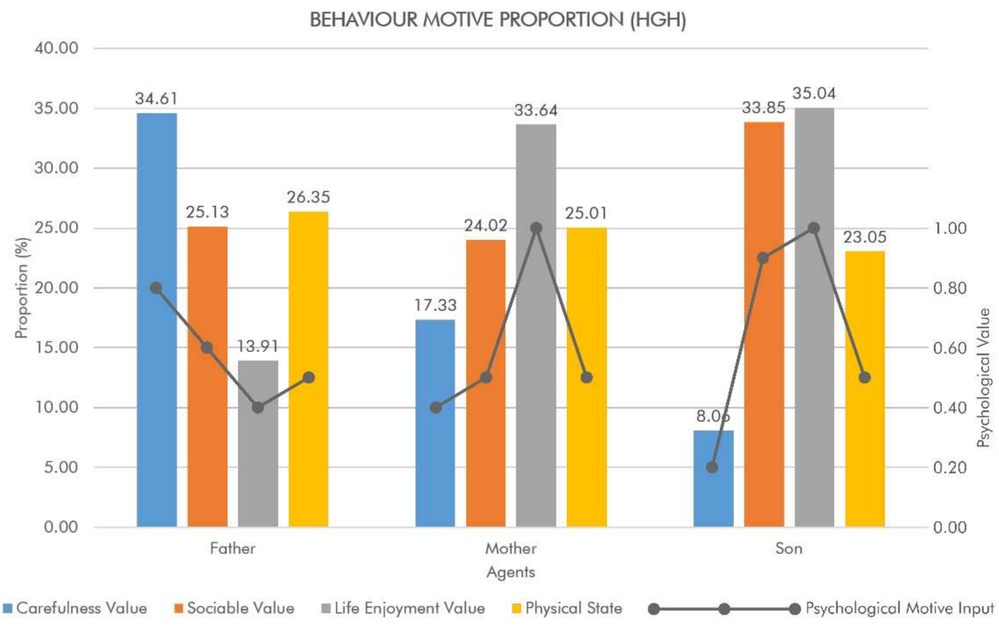


Figure 11. Behaviour proportion (%) based on Motives (0.00-1.00): Father, Mother and Son in (a) House for Trees, and (b) Hue Garden House

5.3 Comparison of Social Spatial Comfort (SSC) values

During the simulation time (365 days), the system continuously evaluated and modified the architectural data to increase the *SSC* value. The output data showed a clear difference between the two houses, in which the *SSC* value of Hue Garden House (starting from 89.7%) exceeded the *SCC* value of House for Trees (starting from 77.9%) (Figure 12). The duration of how the *SSC* values reach their highest positions also suggests the efficiency level of modification processes in the two dwellings. For example, while the House for Trees needs 40 days to reach 100%, while the Hue Garden House requires only 17 days. This can be explained by the points below:

- The functional network of HGH affords more efficient movements between spaces, thus increasing the distance comfort (Lf) value.
- The spaces of HGH are interlinked together, thus creating more dimensional (R1) and openness (R2) comfort.
- The exterior spaces of HGH are more defined, providing more room for spatial modification and thus increase of SSC values.

In addition, agents' individual SSC values also show the difference between agents' spatial perceptions and comfort preferences. For example, on the whole, Mother and Son have higher social spatial comfort values, suggesting that they enjoy the spaces for relaxation since most of their behaviours are driven by Sociable and Life Enjoyment values. Meanwhile, because agent Father has lower social spatial comfort value, it can be interpreted that spaces where Carefulness-driven behaviours take place most are less socially comfortable.

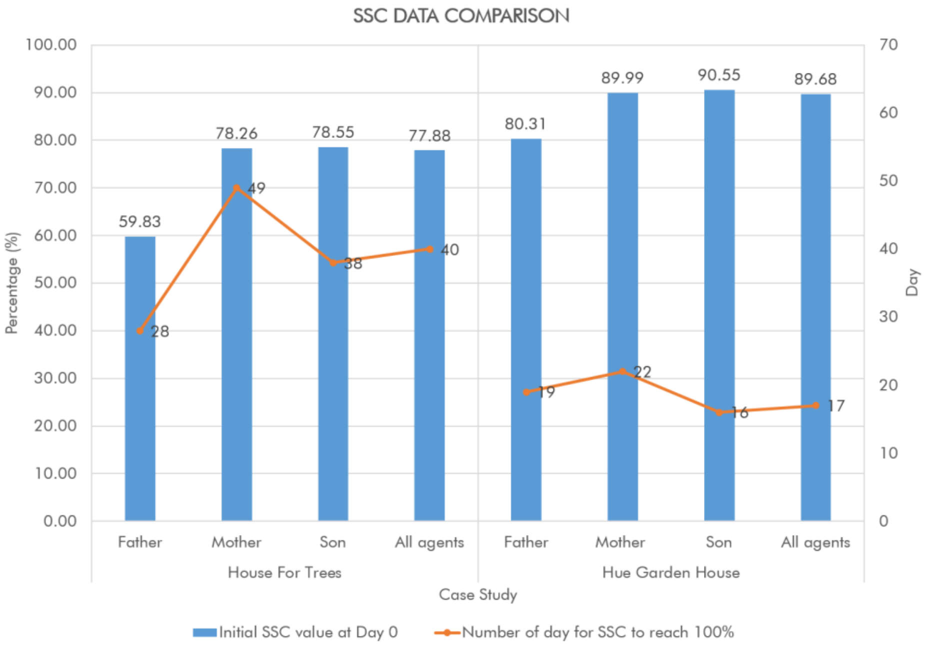


Figure 12. SSC value comparison: Father, Mother and Son in House for Tress vs. in Hue Garden House

5.4 Outputs from the spatial modification process

As presented in the coloured boxes in Figure 13 & 14, the spatial modifications are categorised into four groups: dimensional change (red), openness change (blue), canopy generation (grey) and function swapping (green). It can be seen that there was no functional and limited dimensional changes in the Hue Garden House case. Both case studies have canopies generated, i.e., the Central Yard of House for Trees and the Pond Garden of Hue Garden House. Since the goal of modification is to maximise SSC value, the case with less changes (Hue Garden House) reaches 100% of SSC faster (Day 30).

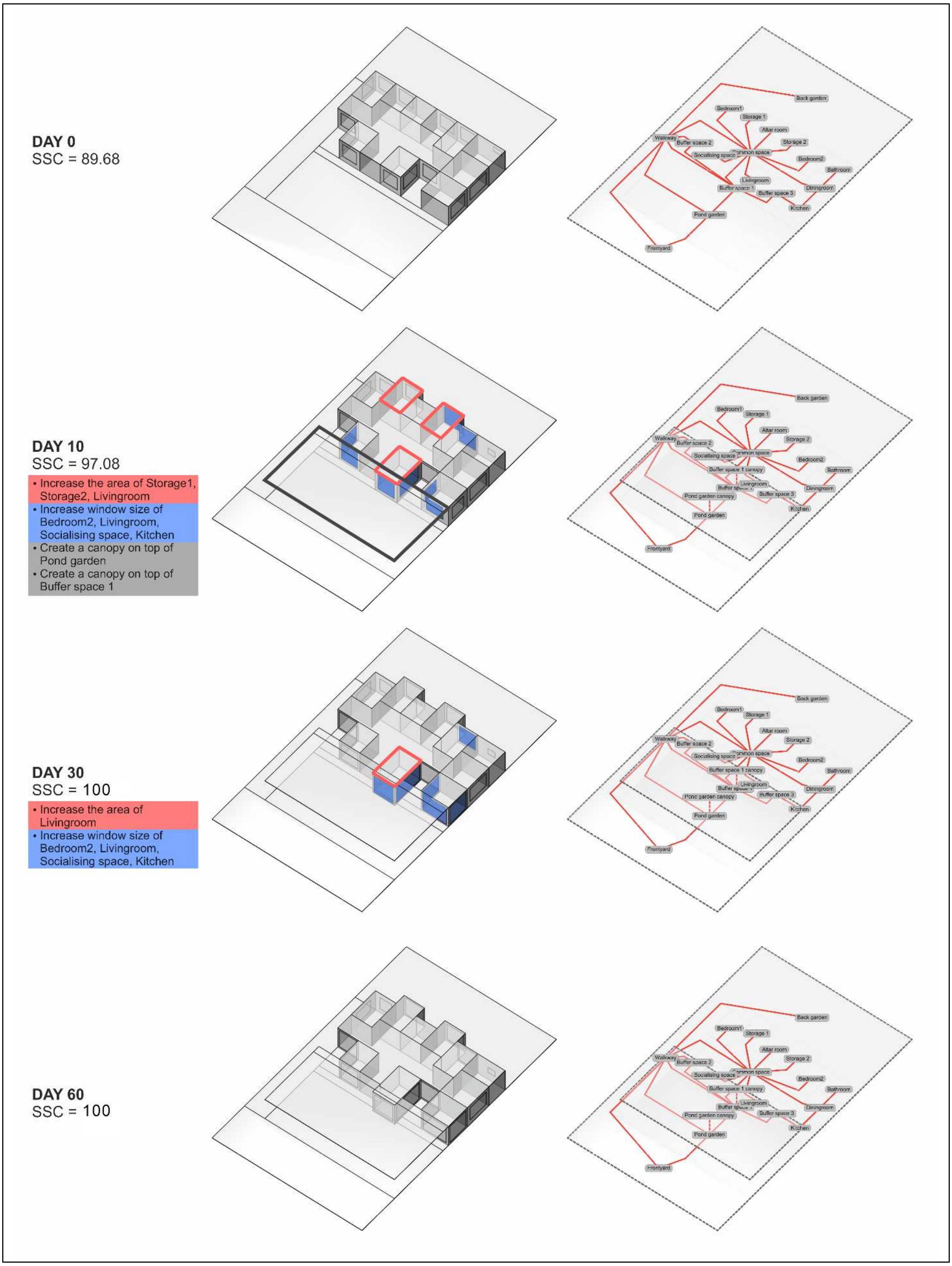


Figure 13. The spatial modification process for the Hue Garden House (HGH) from Day 0 (Social Spatial Comfort = 89.68) to Day 60 (Social Spatial Comfort =100.00)

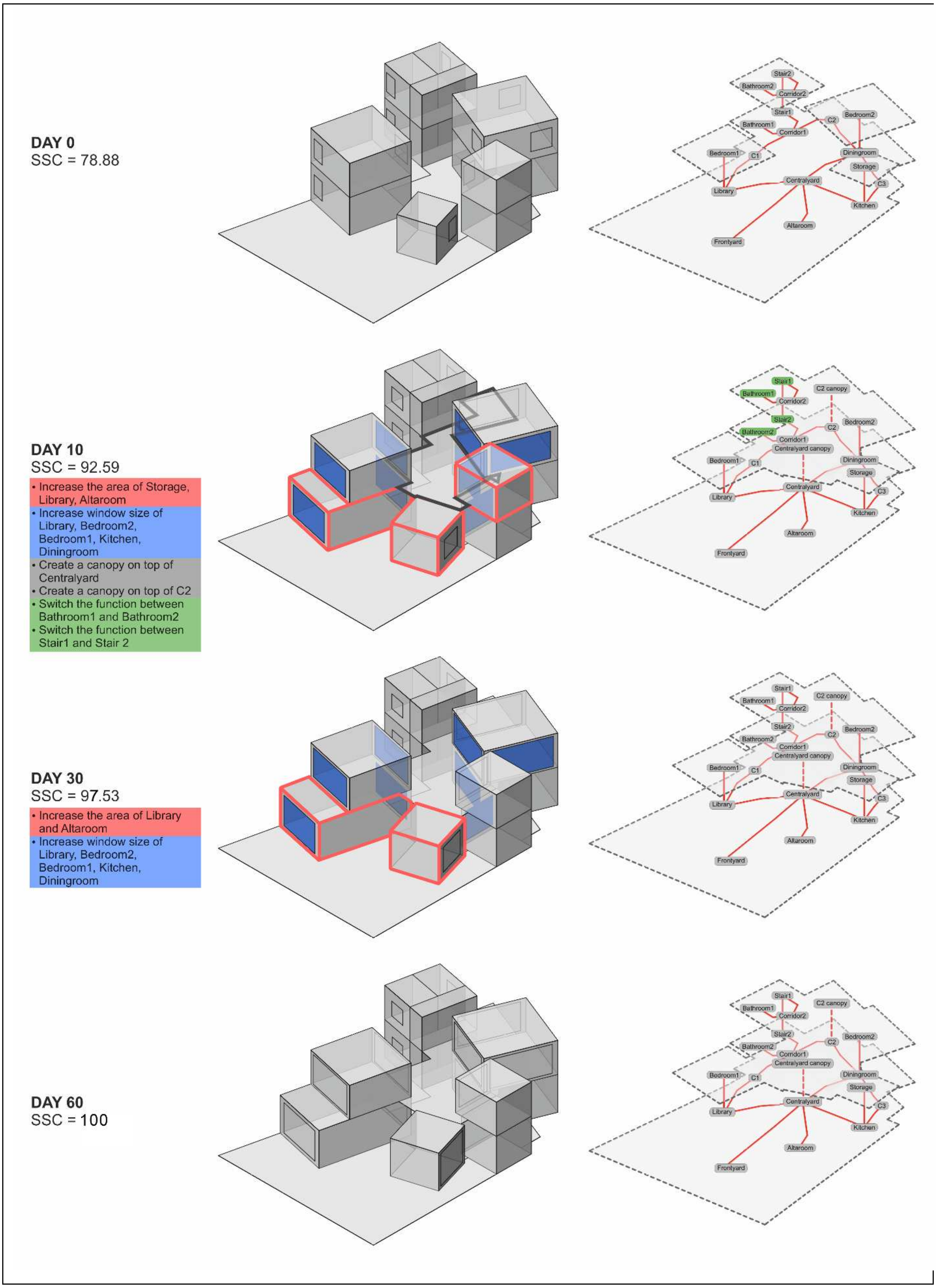


Figure 14. The spatial modification process of the House for Trees (H4T) from Day 0 (Social Spatial Comfort = 78.88) to Day 60 (Social Spatial Comfort =100.00)

6. Conclusions and further work

To address the absence of human inhabitation as parameters foundational to architecture, we introduce a new framework for integrating agent-based modelling of social-spatial processes in architectural parametric design. The framework is implemented in our prototype development. Agents are built according to a model of social-spatial dynamics adapted from the PECS reference model of human behaviour first proposed by Schmidt and Urban in early 2000s. Driven by the behaviours and social relations of a set of dwelling agents, the agent-based system executes spatial modifications of an architectural design expressed in parametric geometry over a simulated timeframe. Intended as an initial validity check of the prototype development, comparative modelling of the two test case dwellings was performed to evaluate if the system could return different outcomes in terms of (1) the simulation time (days) taken for the agents to reach 100% social-spatial comfort level individually and collectively, and (2) the extent of spatial modifications exhibited.

As expected from the contrast between a historical Vietnamese vernacular house and a contemporary house of an unusual form in Ho Chi Minh City, the comparative modelling shows that the agent-based system returns very different temporal-spatial characteristics of house modifications as inhabited by the same set of household agents. As an example of a vernacular architecture, which has been lived in and adapted to the dwellers' needs for more than 150 years, the Hue Garden House has performed very differently from the House for Trees, a test case of contemporary radical house design. The validity of the agent-based model is confirmed for the moment on the ground of the known differences of the two dwellings reported in the literature and social media. It should be pointed out that the agents formed for the validity test were hypothetical, representing members of a generic contemporary household. Nonetheless, we deployed the same set of agents in both simulation runs as though the same household had inhabited both houses over the same simulated timeframe. Secondly, parametric geometry provides the agent-based simulation with changeable virtual environments amenable to rule-based spatial modifications. Parametric geometry expresses explicitly what a proposed building is composed of and how the design may be manipulated according to agents' needs and their (inter-)actions.

The philosophical and ethical position of performing agent-based modelling in architectural design should be further clarified by testing future versions of the prototype system in real participatory or co-design processes. In this scenario, prospective users/dwellers can express their life experiences and preferences as inputs to the social-psychological parameters in the agent construction process. Architects can then employ the platform to engage with the participants by interpreting the simulation outputs and exploring responsive design moves with reference to real social-psychological data. For example, how motive values may represent a real social group or a population. To clarify this factor and upgrade the behaviour selection workflow, there are three areas to be further resolved: (1) The assumption that a person or a social group prefers shorter travel distances; (2) The link between agents' behavioural decisions and their relationship with other agents; and (3) The effects of group behaviour on an agent's individual decision-making.

For the behaviour decision process, future research should consider other social-spatial comfort factors to be included in the calculation process, especially how people respond to colours, lights, shapes, and spatial layouts subconsciously. A more systematic articulation of the connection between individual psychological motives and social groups' characteristic relationships will improve the credibility of input data. In addition, extending the social-spatial comfort evaluation framework into 3D domains will enable integration with agent-based modelling of environmental comfort. Clearly, more advanced computational models of social-spatial dynamics is required for agent-based modelling to tackle larger and more complex architectural settings such as high-rise offices, schools, hospitals, intercity transportation hubs, housing neighbourhoods, university campuses, and skyscrapers. Our longer-term research goal is to develop an open source agent-based modelling platform linked to large social-spatial datasets such that the architects' conscientious search for novel architectural forms may be congruent with the social-spatial processes of human inhabitation.

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