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Flow

Agent Simulation Framework with Spatial Choice for Multilevel Buildings

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ABSTRACT

Simulations of users' movement paths and activities assist architects in designing buildings that operate effectively and provide comfortable user experiences and natural wayfinding. Effective objective analysis and supporting visualisations allow stakeholders to efficiently assess and align priorities for intervention in the design of existing or new buildings. Here, we present Flow, a framework that enables experts to construct agent simulations in multilevel buildings reflecting both strongly and loosely programmed behaviour.

Agent modelling tools used in Space Syntax analysis have been based on either exploratory movement without explicit destinations, or predetermined movement flows between origins and destinations. The objective of the agent simulation framework presented here is to support the creation of simulations that show differences in activation, user experience and operational performances between design options, but where destination selection is influenced by attributes such as angular or metric distance and visibility. It includes Space Syntax centric metrics and evaluates three-dimensional configurations for spatial choice behaviour.

Through a case study, we show how the framework can be used to simulate customer activities and movement paths inside and around a shopping mall. We found that while the process of setting up the simulation and adding bespoke behaviours was more time consuming than manually creating origin-destination tables for the initial simulation, once the system had been set up, we were able to test updated versions of the design with significantly faster iteration cycles. Tracing the full journey of each simulated agent throughout the building enabled the creation of animations which proved useful for communicating the simulation processes and results to stakeholders.

KEYWORDS

Agent simulation framework, Spatial choice, Destination selection, Multilevel simulation, Space Syntax

1 INTRODUCTION

During the last two decades, agent modelling has been widely used in consultancy to inform design strategies by predicting and assessing movement flows in various buildings and cities (for example see Uyar et al. 2017). Agent simulations can help stakeholders forecast patterns of use and movement in buildings at the design stage. They help evaluate comfort levels and potential pinch points, comparing visitor density levels between retail units, mapping visitor experiences and highlighting operational issues.

The objective of the research presented here is to enable the creation of simulations that can help architectural teams achieve high operational efficiency, good comfort levels and natural wayfinding experiences in multilevel buildings. We introduce an agent simulation framework that includes a flexible approach to constructing *agent itineraries* (called *travel diaries* in urban agent-based models) with information about the use of vertical circulation elements and visits to destinations. Destination selection is constrained by a mix of programmatic and spatial conditions, while the path determination uses the origin-destination weighted agent modelling of Ferguson, Friedrich and Karimi (2012). The *agent itineraries* and *paths* enable the creation of animations of the aggregate movement and activities of all agents.

The methodology for agent modelling in Space Syntax is well developed for scenarios where either the behaviour is unprogrammed and consists of exploratory movement primarily steered by the environment (Penn and Turner 2001) or conversely when the specific number of people expected to move between each origin-destination pair is known (Ferguson, Friedrich and Karimi 2012). Our approach extends this established work by addressing the in-between situation where user behaviour is partly controlled by programmatic constraints and partly by spatial conditions (see Sailer et al., 2013, for further discussion on the related topic of hybrid strong and weak programme buildings).

Rather than just calculating paths from an origin-destination matrix Flow can accept higher-order inputs about categories of users that each represents a type of visitor (*persona*) with information about their behaviours and tasks, assumptions of transport modes and access points, percentage use of lift versus escalators etc., which are then turned into specific agent itineraries with destinations and choice of vertical circulation elements. With this approach a wider range of outputs related to the operational performances of buildings can be extracted, allowing stakeholders to ask different sorts of questions to the models, for example: which shops might be more popular according to their spatial location? Which stairs or escalators are more used? What happens if we remove one of the lifts, and which one will have a smaller impact?

The framework can be used to simulate movement and activities inside a variety of different building types from airports, railway stations, schools, and hospitals. The approach is particularly pertinent for the retail sector as the predicted footfall is an important determinator for comfort levels (Fruin 1971), wayfinding, and economic value of retail units (Carter and Vandell 2005; Joshi and Gupta 2020). Retail environments also tend to have the right combination of user behaviour that is constrained and affected both by programme and spatial conditions. Through the case study, we aim to show how understanding potential movement early in the design process can help to make better-informed decisions before a design is built. In a related paper we apply the framework to simulate passengers in an airport terminal (Uyar et al., Forthcoming).

The paper is structured by first outlining related previous work and theoretical frameworks before describing our approach to environment and behavioural modelling in general terms. A description of the framework architecture and algorithms follows including an overview of the modular, configurable approach. The case study is then presented, including results, and lastly a discussion of the strengths and limitations of the approach before ending with some conclusions.

2 THEORY

The following section gives an overview of agent-based modelling (ABM), pedestrian simulation, Space Syntax, and spatial choice modelling for destination selection and planning.

2.1 Agent-based modelling and multi-agent systems

Agent-based modelling is generally used to model complex adaptive systems where global patterns emerge from interactions between individual actors and their environment. According to Eric Bonabeau (2002) “ABM is a mindset rather than a technology”: It consists of describing a system from its constituent parts and can capture emergent phenomena, provide a natural description of a system and is flexible in terms of scaling and tuning the system.

One strand of agent-based models that is commonly referred to as multi-agent systems originated from experimental work in robotics, psychology, and computer graphics/animation. Valentino Braitenberg (1984) showed how social behaviour could emerge in robots by simple mechanisms linking sensory inputs to motor controls in robotic vehicles. Reynolds (1987) developed an approach to simulating the flocking behaviour of birds where the behaviour emerges from simple rules but with more explicit interaction and alignments between individual birds. Reynolds (1999) later expanded the approach of flocking to simulate character behaviours, where he describes that the agent’s behaviours operate on three levels: *Action selection* (strategy, goals, planning), *steering* (path determination) and *locomotion* (animation and articulation).

2.2 Pedestrian simulations

The models described in the previous section can illustrate principles and dynamic behaviour in space in response to other beings, they are not rigorous models that can be used to predict actual movement and activities. Pedestrian simulations are used to model the movement of people and crowds in and around buildings for either emergency or crowding situations or to estimate footfall performance. Some early models for pedestrian simulations were not based on agents but used mathematical equations like those used for describing the dynamic behaviour of gas and fluids (Henderson 1974), but today most pedestrian modelling approaches are based on ABM for practical purposes.

In the magnetic force model by Okazaki and Matsushita (1993) and the Social Force Model by Helbing and Molnár (1995), agents were modelled as physics-based objects or particles with a velocity. Forces were applied to steer the agents towards their destination while at the same time avoiding other agents and obstacles in the environment. By applying forces of attraction and repulsion to each agent realistic collective patterns of pedestrian behaviour emerged. An early approach by Gipps and Marksjö (1985) used a similar principle but was based on a cellular system due to limited computational resources at the time. More recent work by Moussaïd, Helbing and Theraulaz (2011) went beyond this simple repel and attract approach and focussed instead on the open visible space between other agents in the same space: “Instead of being repelled by their neighbors, as was assumed in previous particle models, individuals actively seek a free path through the crowd”, while also minimising the angular distance.

2.3 Space Syntax

The agent models used in Space Syntax research and consultancy are different from the examples described in the previous sections, in that they do not consider direct interaction between agents, but solely focus on the interaction between the agents and their environment. The agents introduced by Penn and Turner (2001) used an “exosomatic visual architecture” (their term) that builds on Visibility Graph Analysis (VGA), allowing the agents to access information about the spatial configuration by querying information in the visibility graph. In the simplest rule, an agent chooses a random visible cell within a specified field of view from their current heading direction and moves a set number of steps in the direction of the selected next cell. Penn and Turner note that this model captures customer movement in for example shopping malls well: “Results of experiments in a simulated retail environment show that a surprisingly simple ‘random next step’ based rule outperforms a more complex ‘destination based’ rule in reproducing observed human movement behaviour”. Like in the model of Moussaïd et al. the agents were looking for open space to move towards according to their heading direction, but they operated without a specific pre-programmed goal or destination and did not consider the other agents. The results tended to capture the relationship between a person and the spatial configuration in a more nuanced way than the simulations we have seen that mostly take cost functions into account and incorporate a principle that we intuitively feel is right: A wider, more open space would be chosen more often than a narrow one even if the narrower option has a slightly shorter path. Another aspect resulting from this method is that, for a large agent population, the spatial distribution of movement paths emerged through stochastic sampling. We mirror this principle (although using a different method) in the algorithm for *destination selection* (sect. 3.5).

Ferguson, Friedrich and Karimi (2012) noted (commenting on the method above) that “the tool operates more successfully when a pedestrian's predominant activity is exploratory, such as in a museum or gallery, but works less well in a context where behaviour is more purposive such as during a daily commute”. To overcome this limitation, they proposed a method of further constraining the agent’s possible movement, to always head towards a location that is at least as close to the destination as the current location (in terms of metric distance). This ensures that the agent paths will converge towards the destination, but with the least possible restrictions in choosing the path. We adapt their method for *path determination* (section 4.4).

2.4 Spatial choice behaviour and spatial interaction models

Both spatial choice and spatial interaction models aim to model how spatial conditions (primarily different distance measures) influence the choice of destination planning. Spatial choice, according to Gärling (1999), “indicates a preference for one spatial location over another”, and he notes that both spatial and nonspatial attributes affect attractiveness and “physical distance is only one of several attributes which may determine the choice. Travel time, ease of wayfinding, or scenic quality of the route are examples of other attributes”. Spatial interaction models were developed by Wilson (1967) in urban modelling and operate at the regional scale to predict origin-destination flows between zones based on attractiveness and distances, especially looking at flows from residential areas to shopping centres. While most of the social interaction models have been applied to regional scale, Liu et al. (2019) applied and evaluated building scale social interaction models for predicting customer flows.

3 ENVIRONMENT AND BEHAVIOURAL MODELLING

This section describes our approach to representing the environment, users, and scenario in the Flow agent simulation framework. We also define attractiveness functions and a method for destination selection based on the attractiveness scores.

3.1 Environment

The environment, or spatial model, provides the spatial topology of architectural elements, as well as information about which elements are permeable and accessible for walking on, which elements obstruct vision and even information about directionality, as in the case of escalators, or more complex behaviours such as lifts. For this purpose, we have implemented a data structure and JSON schema for multistorey buildings to store and retrieve both the relevant geometry and information about the spatial topology and programme. Some of the elements making up the spatial building model schema are shown diagrammatically in Figure 1.

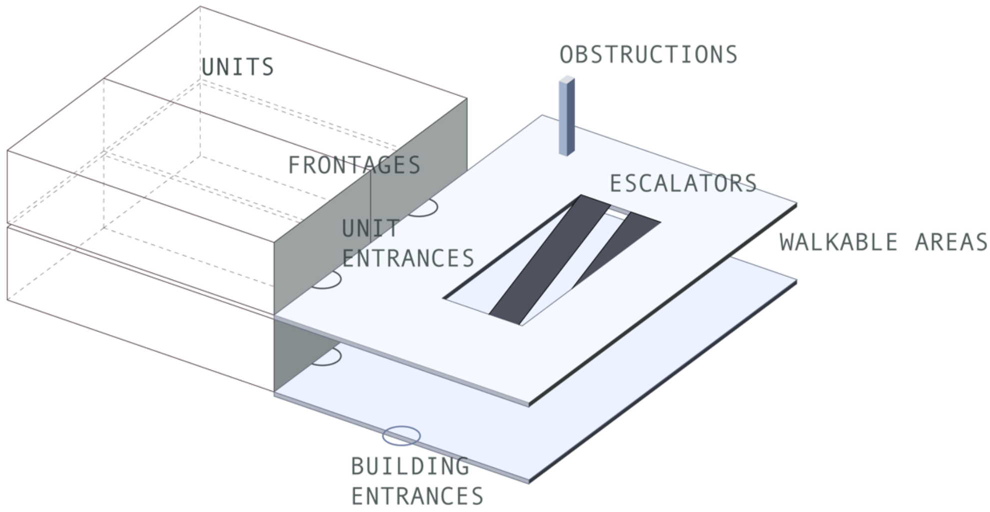

Figure 1: The representation encodes the program, geometry, and topology of spatial elements.

Algorithms were developed to extract the following structures and metrics for a model:

- Visibility graph of circulation areas (2D).
- Topological graph of the circulation areas and their connectivity through stairs, escalators, and lifts (3D), used for calculating level change between locations.
- Shortest angular and metric distances within and across floors between the spatial elements (3D).
- Visual connectivity between spatial elements (2D).
- Visual connectivity from circulation area grid to spatial elements (2D).

3.2 User

The process of creating and representing users varies between projects depending on the availability of datasets in the project and for the sector. Users are typically segmented into discrete user types (*personas*) according to shared behaviour patterns: in some cases, a set of goals or tasks to achieve in any order ("visit two shops and one restaurant"), and in other cases a specific schedule to follow such as pupils in the same class at a school following a timetable. The user-type specification is one layer of information that can be combined with data sets about transportation modes or other personal attributes independent of the type: For example, the preference or need to travel with lifts versus escalators for example is set to a fixed ratio independent of the user type.

3.3 Scenario

A scenario is made up of data and behaviour patterns of users for a specific time. For example, the difference in shopper behaviour around weekend lunch compared to a weekday morning time would have very different behavioural patterns. The main purpose of limiting and selecting the scenarios is thus 1) to direct the effort to where it matters (we avoid modelling every possible "situation"), and 2) to avoid modelling transitions between these behavioural pattern situations. If we model a morning scenario and a lunchtime scenario independently, we do not need to worry about how to transition from the first to the latter.

For each scenario, we usually distinguish between the scenario period and the read-out period. Unless the scenario being considered is such that no one is present before the start of the read-out period (for example an early morning scenario), the simulations typically need to run from an earlier point of time to capture the agents that arrive before the read-out period and are already inside the environment. The simulation period is set by estimating the maximum expected duration of a user in a building and set to the start of the simulation time offset by this amount compared to the read-out period. While the starting times vary between the simulation and read-out period, the end times always coincide as we do not need to model any activity after the end of the read-out period.

3.4 Spatial attractiveness function

To construct specific itineraries each possible destination for a specific task is given a score unique to the agent's location and properties related to the candidate. For this, we propose a spatial attractiveness function (F) from an origin (agent location), i, to each candidate destination, j. We define distance attractiveness (FD) for angular distance (D^a), metric distance (D^m), and level change distance (D^l), by taking the positive part of the distance subtracted by a threshold value. Distances beyond this threshold will have 0 attractiveness for that attractiveness component, note also that setting a larger threshold makes the function less sensitive to variation of the distance value:

$$FD_{ij}^{a} = \left(D_{threshold}^{a} - D_{ij}^{a}\right)^{+}$$
$$FD_{ij}^{m} = \left(D_{threshold}^{m} - D_{ij}^{m}\right)^{+}$$
$$FD_{ij}^{l} = \left(D_{threshold}^{l} - D_{ij}^{l}\right)^{+}$$

Then with visibility between locations (V), generic visibility V^g and floor area (A) we define the attractiveness of destination j for candidates k as:

$$F_{ij} = \frac{A_j}{\sum_k A_k}\left(\frac{FD_{ij}^{a}}{\sum_k FD_{ik}^{a}} + \frac{FD_{ij}^{m}}{\sum_k FD_{ik}^{m}} + \frac{FD_{ij}^{l}}{\sum_k FD_{ik}^{l}} + \frac{V_{ij}}{\sum_k V_{ik}} + \frac{V_j^{g}}{\sum_k V_k^{g}}\right)$$

By dividing each component of the attractiveness over the sum of all other candidates k, we normalise the components according to how well they score within the group of candidates. If any of the sums are zero, we set that component to zero (otherwise a division by zero will cause an error). Each component (distances, visibility, and area) is optional, and to be included depending on what kind of user we are modelling: It is reasonable to assume that a resident or employee will know which amenity or circulation element is closer, while a visitor or tourist is inclined to follow visibility or angular distance (Turner 2000, p. 4). For some destination types, such as stairs the area is not applicable, but capacity could be used instead of floor area, under the assumption that a wider stair would attract more movement than a narrow one, ceteris paribus.

We also extend the attractiveness function for origin-destination pairs, where a strong-programmed behaviour (e.g., "go to gate") between i and d might be complemented by a more weak-programme behaviour (e.g., "grab and go") at j. The function, in that case, stays the same, but we redefine distance to be the detour to include j compared with the direct distance to the destination d.

$$FD^a_{ijd} = \left(D^a_{threshold} + D^a_{id} - D^a_{ij} - D^a_{jd}\right)^+$$

$$FD^m_{ijd} = \left(D^m_{threshold} + D^m_{id} - D^m_{ij} - D^m_{jd}\right)^+$$

$$FD^l_{ijd} = \left(D^l_{threshold} + D^l_{id} - D^l_{ij} - D^l_{jd}\right)^+$$

$$F_{ijd} = \frac{A_j}{\sum_k A_k}\left(\frac{FD^a_{ijd}}{\sum_k FD^a_{ikd}} + \frac{FD^m_{ijd}}{\sum_k FD^m_{ikd}} + \frac{FD^l_{ijd}}{\sum_k FD^l_{ikd}} + \frac{V_{ij}}{\sum_k V_{ik}} + \frac{V^g_j}{\sum_k V^g_k}\right)$$

3.5 Destination selection method

The technique used for destination selection is adapted from a method typically used in Genetic Algorithms, namely Roulette Wheel Selection introduced by Holland (1975). First, the candidates are filtered so that only destinations of a certain category matching the current task are considered. The candidate destinations are then given a score according to programmatic constraints, such as the capacity of the destination, and their spatial attractiveness considered from the origin point. This indexing thus varies depending on the location of the agent as they enter the building/environment, or as they finish another activity/visit. For stairs and lifts, we have a separate criterion which is that it should bring the agent topologically closer to the destination. The chart in Figure 2 shows the analogy with a roulette wheel: a random number from zero to one has a larger chance to fall inside one of the larger slices of the wheel.

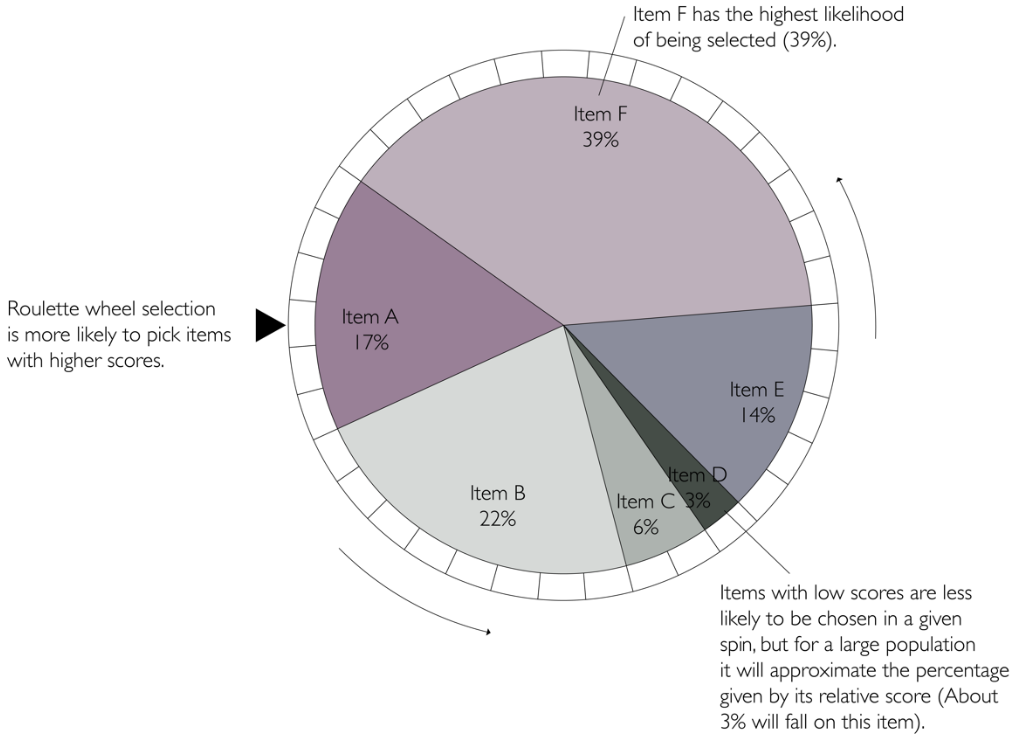

Figure 2: Roulette wheel selection was first introduced by Holland, originally for use in Genetic Algorithms.

4 FRAMEWORK ARCHITECTURE AND ALGORITHMS

Flow splits the simulation process into separate "workflow steps" that each build on the outputs from the previous steps. The framework consists of five distinct steps (Figure 3): 1) *Construction of the spatial model*, 2) *Agent population generation*, 3) *Itinerary determination*, 4) *Movement path determination*, and finally 5) *Construction of maps and animations*. The version presented here is implemented in Java 11 and is run via a command-line interface (CLI) on macOS or Windows.

The simulation framework architecture is designed so that each step can be configured and run by itself as soon as the previous steps are complete (since the outputs from the previous stages are being used). As each step is reaching a satisfactory result, the next step can be repeatedly run and inspected for any mistakes or false assumptions.

Through these simulation steps, we follow a similar division of splitting up agent behaviours as Reynolds (1999), although only focussing on the former two: Reynolds's *action selection* becomes *itinerary determination* and *steering* corresponds to *path determination* in our framework, although using different methods.

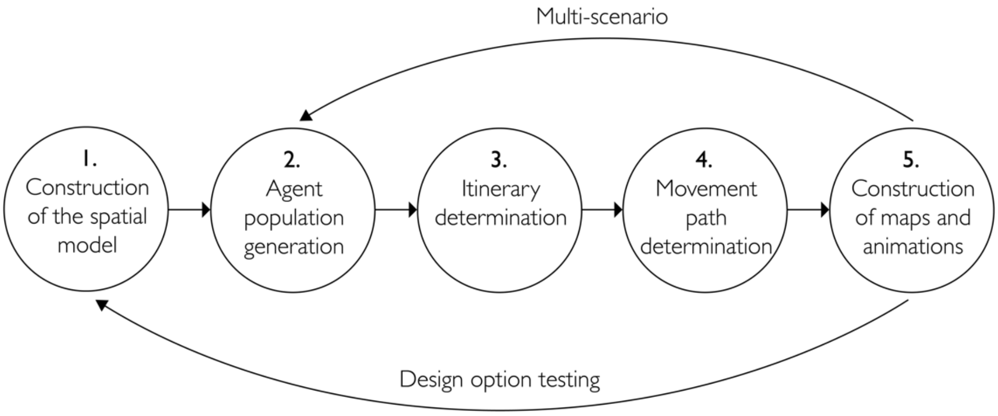

Figure 3: A simulation is built up over several steps, feeding into a design loop where changes are made in the layout to investigate the resulting performance.

The environment associated spatial metrics and attractiveness matrices can be run once, and then start from step 2 for each subsequent scenario.

4.1 Construction of the spatial model

The model is used to determine the interaction between the behaviours of the agents and spatial metrics of the environment in which they are embedded. The spatial model is constructed from AutoCAD DXF files for each level and with metadata that describe floor-to-floor heights. It produces a JSON representation of the environment as detailed in section 3.1.

The spatial building model elements form syntactic relationships: for example, a unit has entrances that connect to circulation areas, which are again linked via vertical circulation elements. Spatial predicates based on the Dimensionally Extended nine Intersection Model, DE-9IM (Strobl, 2006), as implemented in the open-source library Java Topology Suite (JTS), are used to construct topological links between elements. Unit frontages and unit entrances are either specified in the CAD file, or automatically generated, frontages are added where the unit polygon touches or is near the walkable area (circulation area), and entrances are placed at the centre of the largest straight edge of each of the frontages.

The following matrices and tables are produced:

- Generic visibility tables
    - For units: maximum visibility from the frontage, onto the circulation areas
    - For stairs: visibility of stair entrance, onto circulation area
- Visibility matrix
- Distance matrices for origins to destinations
    - Metric

    - Angular
    - Level-changes
- Attractiveness matrix from all origins to all destinations
- Metric distances to each destination on the VGA grid

Note that attractiveness matrices for stopping on the way to destinations are not pre-calculated, but when they are needed due to the number of possible combinations. Both 2D visibility and 2D distance matrices are calculated on *visibility graphs* (Turner and Penn 1999) which we construct using the fast *visibility polygon traversal algorithm* by Izaki and Derix (2013). For three-dimensional distances, we use the same algorithm for calculating visibility graphs between vertices in the walkable area and origins, destinations, stair landings etc and connected with directed edges for escalators, and undirected edges for stairs and lifts. Level change distances are calculated via a topological graph where the walkable area are vertices and vertical circulation are edges.

4.2 Agent population generation

The visitors and building users are represented as individual *agents* with specific tasks and characteristics. Each agent will have certain attributes: a gender, a preference for using the lift or escalators, an average walking speed, a means of transportation and an origin and time of entry in the simulation environment. Most importantly they are of a specific visitor type or *persona*.

Multiple visitor types are constructed to capture all the different tasks users are expected to do in the environment. Depending on the data sets and knowledge about users in the specific situation of the agent simulation the user representation is bespoke for that simulation or for a class of simulations that are very similar.

The algorithm for constructing the agent populations may vary between projects and the data sources available. One variation is to take the total number of expected visitors for a scenario and distribute their start time linearly according to the specified percentage that enters each hour with a small random variation. The agent list is then shuffled before each additional property is set based on the proportions set out in the assumptions or data set used for the given scenario: User, entry locations (based on travel mode), walking speeds, vertical travel mode preference (escalator or lift).

4.3 Itinerary determination

The agent itinerary determination method is responsible for building up the sequence of stops at destinations (with related dwell times) and vertical circulation elements as the agent journeys through the building. An itinerary is determined for each agent according to the visitor type and the specific spatial conditions and the programmatic offering in the environment.

For each agent, the itinerary determination algorithm is essentially providing the answer to this question: "Given current location A, and a list of non-completed tasks to be performed determine the next destination and, if applicable, which vertical circulation elements to use on the way". With this approach the agent simulation determines the activities and destinations with individual itineraries, walking speeds and dwell times in the building.

Since the origin-destination path determination algorithm works on a single level, the itineraries must include the selected stairs, lifts, or escalators. Our method assumes that a user would only travel to another circulation area that is topologically closer to their destination than the current circulation area. Vertical circulation elements of types that are not preferred by the agent are filtered out, for example, an agent might have a specification to always use lifts, or always prefer escalators. Then the same approach is used as with destination selection computing a score of each candidate from the attractiveness function defined in section 3.4.

4.4 Movement path determination

The determination of specific movement paths for each journey leg across a circulation area and adding timestamp data. The Flow framework uses the origin-destination weighted agent algorithm by Ferguson et al. (2012) to determine the paths. This stage takes each movement leg from the itineraries and determines the actual movement path through the planar walkable region from an origin to a destination. The paths sharing the destination are calculated together, for efficiency, since they use the same information: the metric distances to the destination on the VGA grid.

The agent itineraries and paths together create detailed timestamp information. This explicit timing data for each agent can be used to extract very specific gate counts at specific time windows, which is useful for comfort levels and level of service calculations, or to retrieve approximate visitor counts within shops over time.

4.5 Construction of maps and animations

For a specific scenario (with paths cropped to the specified read-out period) we construct:

- Path map: Showing all the agent paths overlaid using thin lines.
- Density map: Showing the number of agents on a coarser grid.
- Gate counts: Number of paths in each direction passing per minute and/or per minute per meter.
- Comfort levels: Typically assesses the number of agents per minute per meter according to the Transport for London standard.
- Level of Service: This metric is used for waiting for example in the lift lobbies, and needs an additional assumption about average waiting time. We can then use the gate

time, average waiting time and the area of the lobby to calculate the level of service using the Fruin standard.

- Animations: Numbered stills are constructed like the path map, but cropped to the animation frame time, showing the gradual build-up of the path map with the current location of the agents using black dots.

5 CASE STUDY

The case study presented here shows the application of the Flow framework in a design option for a shopping mall in Europe. Visitor footfall and dwelling times are key drivers of success and performance in retail spaces, and it has a good balance between constraints by programmatic and spatial conditions.

In this project, seven visitor types were created where each was assigned an individual itinerary and dwell times in at least one or more retail, Food & Beverage (F&B), cinema, culture and/or sports units. Each persona was given full autonomy to select their next destination from their decision-making points. The software was used to evaluate the proposed design to improve wayfinding, create legible circulation spaces and maximise overall user experience. Outputs included flow density, comfort levels, visitor frequency per unit to gauge commercial viability, and frontage visibility weighted by the simulated visitor paths and visitor heading directions. Recommendations were also made to identify the best locations for pop-up retail units.

5.1 Assumptions and datasets

The inputs for the case study involved a combination of information received from the client and some assumptions made in the absence of data. As the first step, we set up a scenario to identify potential congestion areas in the building. To minimise the number of test iterations, we created a potential worst-case scenario with the assumption that the building would perform well in all other scenarios if it did during the busiest peak hour.

Previous consultancy work and observed flows in similar settings have shown that weekend afternoons are the busiest periods for shopping malls and other spaces with leisure activities such as parks and museums as opposed to morning and evening rush hours in office settings. Therefore, we picked a scenario of a one-hour peak time during a Saturday afternoon where we tested movement flows. In this scenario, we assumed that one-third of the mall’s capacity would be occupied simultaneously during the one-hour peak period. Although this number seems random, previous consultancy work on similar building typology has shown that on weekend peak times, exploratory movement levels can overlap up to 30-50% during the busiest peak hour in malls compared to a weekday peak hour in an office setting which could go up to 80% of full capacity within a morning peak hour. Using this assumption, we calculated the visitor capacity of the building by multiplying the unit areas of retail, food and beverage, cinema, culture, and recreational spaces by a visitor conversion factor received from the client. These factors were respectively 0.19 for retail, culture, and sports units, 0.30 for cinema, 0.35 for Food and Beverage and 0.31 for circulation spaces. As a result, a total of 4,500 visitors were simulated during the peak hour.

The shopping mall had three floors excluding the car-park basement level and it had three separate buildings connected by a large open space on the ground floor and two bridges on the top floor. It had multiple entry points on the ground floor and three main lift cores accessed from the car park. The arrival points of visitors varied based on their mode share where most people (80%) were assumed to arrive by car as instructed by the client. We distributed the remaining 20% of visitors on ground floor entrances where 15% were assumed to arrive on foot and 5% by bus from the nearest two entrances to the bus stops When moving between floors, 90% of the visitors were assumed to take the escalators versus 10% took lifts. This percentage split was picked researching best-practice standards in similar building uses as well as transport buildings (KONE, 2009, p.15). The waiting time for the lifts from the third floor to the basement was assumed to be one minute.

To account for a variety of visitor behaviour, we created seven profiles with each unique itinerary and dwell times in different activities and destinations. Visitor surveys in international malls have shown that the average visitor dwell time in a shopping mall varies between one to two hours and in some countries this period to exceeded further (ECE Market Report, 2015). In our study, we also used a range between one and two hours of dwell time based on a unique itinerary. For example, cinema visitors stayed for around at least two hours given a standard movie length, whereas restaurant visitors stayed about one hour. Most visitors had more than one type of destination that combined different behaviour types including shopping, visiting exhibition spaces and spending time in indoor playgrounds. The assumptions used as input to the simulation are depicted in Figure 4, while Figure 5 shows the transportation mode and access point split expected for all the visitors.

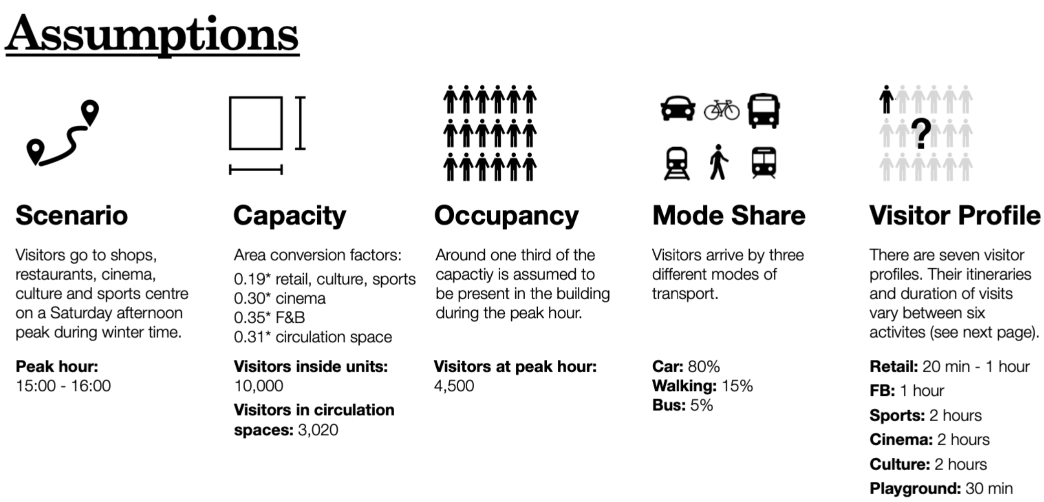

Figure 4: Scenario and assumptions

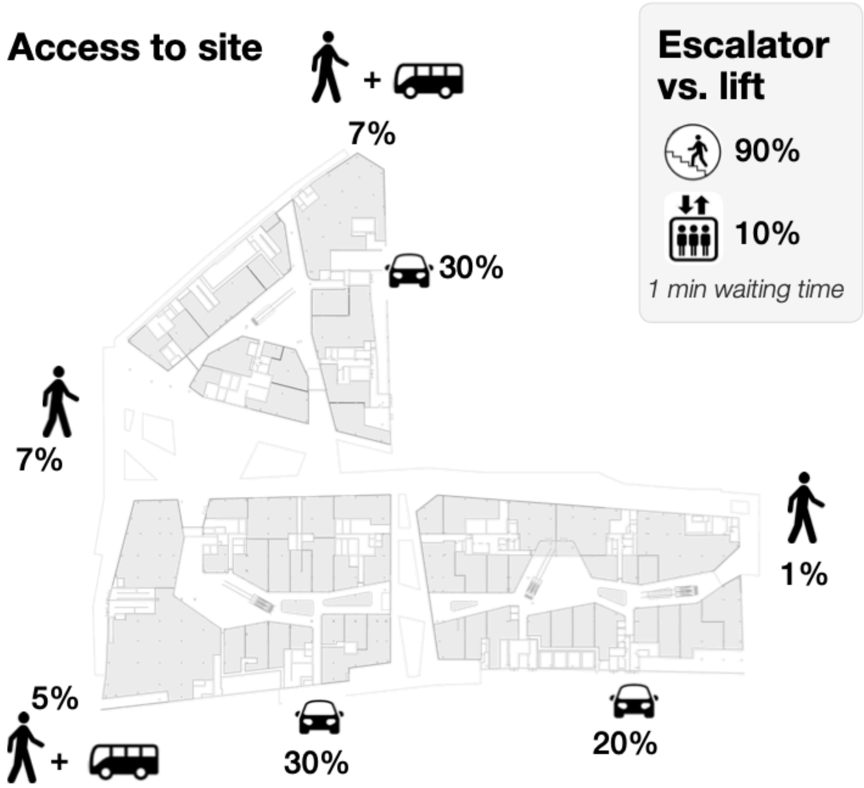

Figure 5: Access to the shopping mall

5.2 Methodology

Visitor movement between origins and destinations was set up using the Flow framework where each agent decided the next unit depending on a defined "attractiveness". The attractiveness score defined the percentage chance of a unit being chosen. Each score was normalised against all other scores of the same type (F&B, retail and culture, escalator, entrances of the same unit), and calculated across all floors.

The key decision on choosing a unit and its entrance (in the cases where a unit had multiple entrances) was based on the unit's area, its frontage visibility and angular distance from the agents' decision point. Similarly, the attractiveness of vertical cores (escalators and lifts) was defined by their general visibility from the floor as well as the angular distance from the agents' decision points.

5.3 Results

The case study identified, analysed, and described visually and numerically the predicted movement patterns of visitors. Outputs included maps of Flow Density, Flow Paths, Gate Counts and Level of Service using Fruin and Transport for London standards in selected locations. The first stage of the analysis helped understand the potential footfall outside retail and F&B units whereas, in the second stage, the study focused on circulation spaces to identify the best places to put open retail kiosks as well as assess the location of indoor playgrounds.

Flow Density (Figure 6) and Paths map (Figure 7) highlighted key desire lines, high levels of flows and their directionalities which helped identify potential movement obstruction points. The top floor had the most direct circulation paths free from obstructions where also the highest flow during the peak minute was recorded on the bridge connecting the two buildings (Figure 8). On the ground floor, we identified that one of the escalators could pose a potential issue for conflict in reverse movement flows (Figure 7). Also, the study showed that some open retail units on the second floor were located along a quiet corridor which had less potential to attract visitors compared to other retail units (Figure 7). In this area, an active retail leasing strategy was recommended to attract more visitors by enabling various stationary activities.

Comfort level outputs (Figure 9) showed that according to the TfL (Transport for London) standards, all key locations had enough width to accommodate the recommended minimum comfort level. Assessing the queuing density in the lift lobbies using Fruin standards (Figure 10), we identified a minor conflict potential in one of the three buildings where a slight increase in the corridor width was recommended.

Overall, this study formed a point of reference for leasing strategies to optimise value through all areas of the project. Additionally, through refinement of the design based on the simulation outputs, the area dedicated to circulation was reduced allowing for a more efficient commercial building footprint with higher productivity. The study has identified two areas that need attention in the next phase of development which would be addressed later in detailed planning and coordination with other project consultants. The results showed that the proposed design of the building satisfied the target for a comfortable circulation experience based on the best practice standards within an acceptable range during the peak scenario.

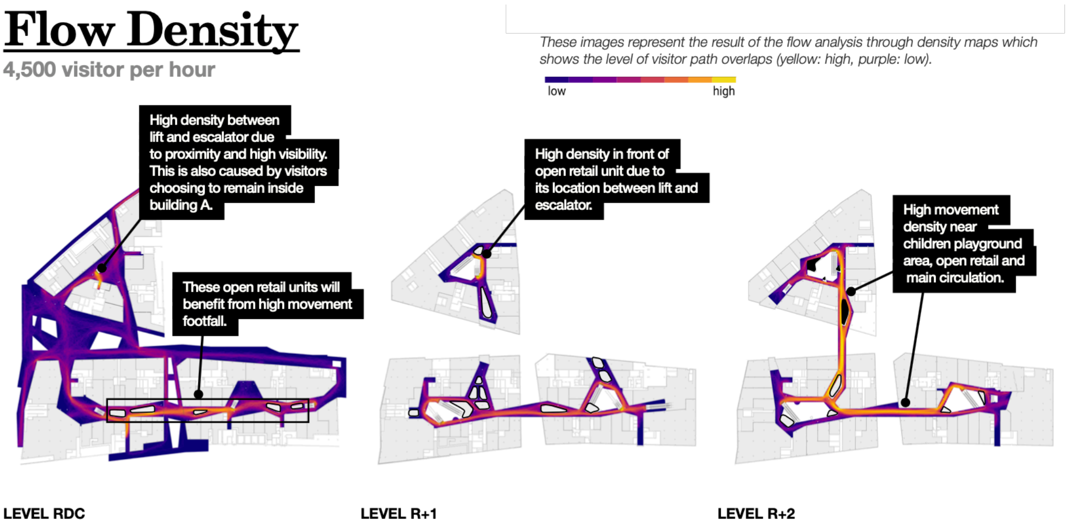

Figure 6: Flow density

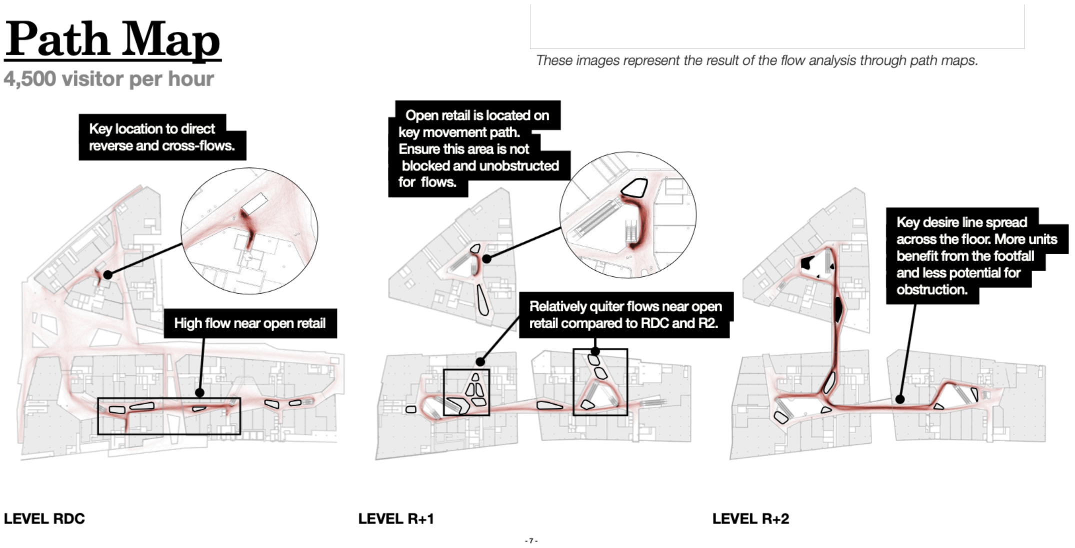

Figure 7: Path map

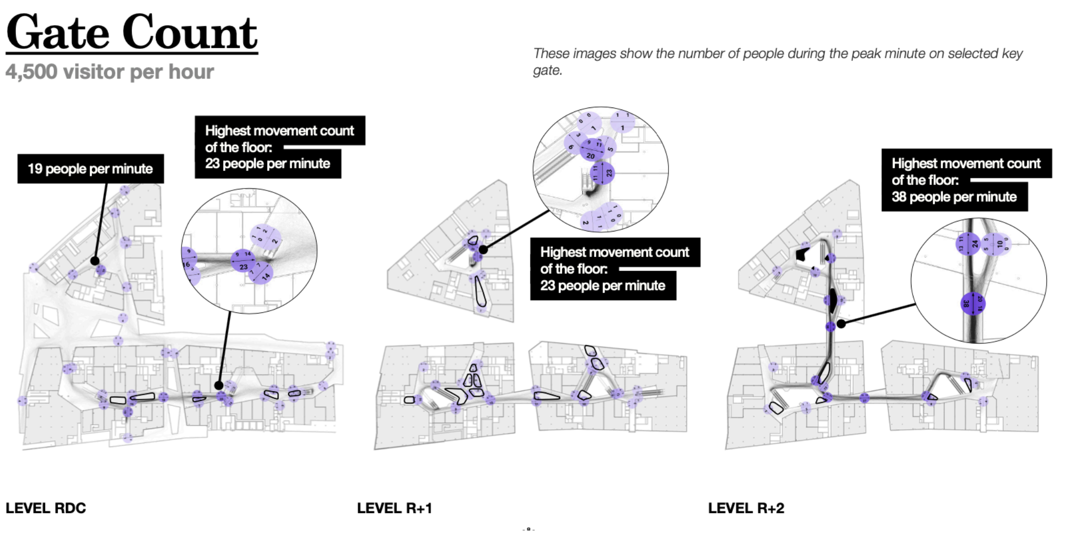

Figure 8: Gate count

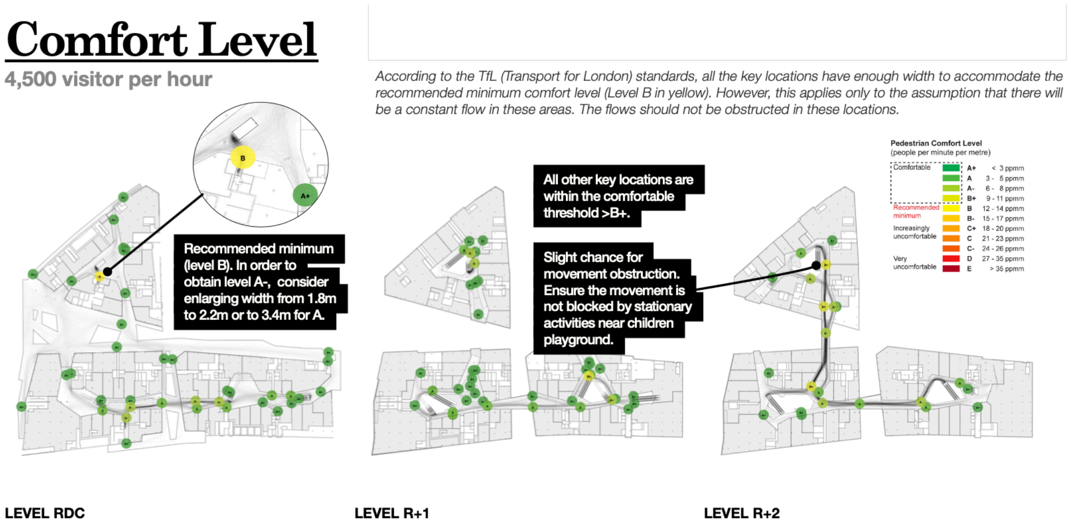

Figure 9: Comfort level and Level of Service

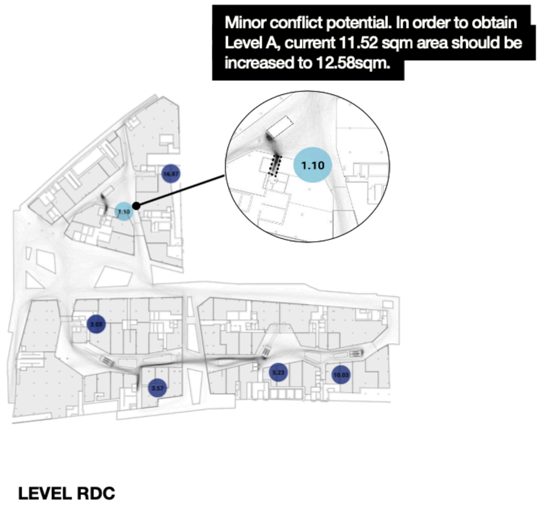

Figure 10: Comfort level and Level of Service

6 DISCUSSIONS

Origin-destination flows are typically assumed to be known or provided as an input in pedestrian simulations and agent models. In the framework presented here the agents' decisions and itineraries are generated based on both spatial and programmatic attributes. This allows for higher-level data inputs than other simulation methods, and the specific origins and destination flows emerge by letting the inputs of the simulation play out in the spatial model. This process generates not only aggregate origin-destination flows but detailed and persistent movement and activity data for each agent which is needed for creating animations. Analysis and recommendations that are coming out of the simulations are primarily based on static maps, animations tend to help in communicating the process and giving more transparency regarding the working of the simulation to a lay audience.

Although care and effort need to be taken when setting up a new project, either adapting an existing simulation model or developing a new bespoke model that is fitted to the specifics of that building, we have found that it's comparatively easier to run several design options (variations) or to test what happens under different assumptions. As more simulations of similar scenarios and building types are performed, we expect to reuse more of the code and reduce the initial set-up time.

Through the development of a case study simulation, we observed that the results produced using the framework provided useful feedback to the architectural team by indicating comfort levels and guided the wayfinding and signage strategy. The results show areas where more dense movement can be expected and conversely whether any secluded areas are expected to lack visitor activation. One important issue to the architectural team was the question of how to orient the escalators, and if there were enough space provided in front of them where people tend to "flow" out into the circulation areas.

Through a modular approach, where the simulation process is split into distinct stages, we remove some of the complexity and can access intermediate results for further study of the relationship between the inputs, methods, and outputs. This gives in our view a more transparent process and predictable results than an integrated agent model. The logic within the different simulation steps can be swapped out without breaking the other parts, granted that they follow the expected interface of inputs and outputs. For example, the step for simulating the agent movement between origin-destination pairs could be replaced with another method depending on the scale, concerns to be investigated and the time and computational resources available. The trade-off is that this approach cannot capture emergent behaviour, related for example to subjects' decisions based on capacity and waiting, such as avoiding visiting a restaurant that is full or taking a less crowded stair or escalator, i.e., the type of decisions Gärling (1995) has shown to affect the choice and order of visiting stores.

It could be argued that the approach presented here, as well as previous work in Space Syntax, are not true agent-based models in the strictest sense of the word since the agents do not interact with each other. One point that Bonabeau (2002) raises is: "Simulating the behavior of all of the units can be extremely computation intensive and therefore time consuming", this is an important point to note since long processing times can limit the use of the simulation in fast-paced iterative design work. While agent-agent interaction is essential for modelling crowding and queueing behaviour, this is not the main purpose of the simulations made with this framework and can instead be produced by existing software such as MassMotion and Legion Studio.

The research by Gath-Morad et al. (2021) indicated that visibility is a better indicator than the shortest metric path for wayfinding in the absence of familiarity or signage and that a purely distance-based method is not ideal for modelling vertical movement within a building. This supports our approach of introducing visibility into the spatial attractiveness function. We suggest that research should be undertaken to extend the three-dimensional aspects further: For example, the visibility calculations are currently limited to 2D and constrained to the same level, but visibility between floors can guide wayfinding. A related point is that the path determination algorithm could be extended to manifold meshes that connect levels, which would mean that stairs could be modelled directly through the agent paths rather than being constructed with the itinerary.

For the case study, as the project was still in the design stage, there is no observational data, and thus we could not calibrate the model or validate the results. Future studies are needed that use observational data for validation of the whole process. Additional data about retail sales and traffic would also be needed to use the model to predict economic performance. The simulations could then become a stronger point of reference for leasing strategies to optimise the value through all areas of the project. Specific care needs to be taken then to model economic performance versus the comfort levels and user experience since the latter might need to take a longer time interval into account, and not just simulate the peak hours which is sufficient for assessing comfort.

7 CONCLUSIONS

The Flow agent simulation framework is suited to create agent simulations where both programmatic and spatial attributes influence the agents' decisions in multilevel buildings. Space Syntax agent models tend to consider movement on a single level, and vertical circulation needs to be resolved outside the model and converted to origin-destination flows. The Flow framework allows for higher-order inputs and assumptions rather than working from predefined origin-destination matrix input from the user. It enables the creation of animations showing persistent movement across destinations and floors which can help in communicating the methodology and results to the architectural team, client, and other stakeholders.

Through the modular and flexible architecture of the framework, experts can incorporate project- and sector-specific knowledge and data in the simulations. We estimate that a somewhat longer time is used for developing and setting up new projects initially, but then reduced the time and effort of running repeated simulations with different assumptions, design option testing and scenarios. Over time we believe that typologies and classes of similar simulations will emerge, with less effort needed for bespoke additions for each project, and that these can be turned into reusable tools to be used without requiring the same degree of expert involvement.

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