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# A Framework for Multi-Agent and Acoustic Simulation for Office Design

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**ABSTRACT**
A large number of studies suggest that employees in an open-plan office are disturbed during their day-to-day work for a variety of reasons. In particular, disturbances caused by speech are difficult to estimate during the early design phase. Multi-agent models provide a way to predict the behaviour of diverse systems, including occupants. We introduce a framework combining multi-agent modelling with acoustic simulation to evaluate spatial layout at the early design phase. The framework provides results by evaluating trajectories and interactions between the agents throughout the simulation. The results are presented in the form of acoustic performance of the layout on the spatio-temporal scale along with performance matrices. The framework was assessed through a case study of an architectural office in Amsterdam.

**Author Keywords**
User behaviour simulation; multi-agent modelling; acoustics of workspaces; User-centered design

**ACM Classification Keywords**
• Applied computing~Arts and humanities~Architecture (buildings) • Computing methodologies~Modeling and simulation~Simulation types and techniques~Agent / discrete models

## 1 INTRODUCTION

Users in an office environment are impacted by various indoor environmental quality factors. One of the most important of these factors is *noise disturbance*, which leads to decreased concentration, reduced satisfaction, and sick building syndrome in some cases [1-3]. The current design process for a building relies heavily on the experience of the architect. The architect's perception of space use may not match the real use of the building. Noise disturbance is currently studied through a post-occupancy evaluation process, which means that the only choices stakeholders are left with are improving or refurbishing the building.

Acoustic simulation allows architects to analyse noise disturbance, before an indoor environment is occupied or refurbished, and produce more productive and healthy designs without relying entirely on intuition. However, existing acoustic simulation methods assume a relatively static environment with a fixed primary source of noise and fixed receiver points on the spatial layout. These simulation results tend to miss out the dynamism of a typical working day in an office where noise disturbance is caused by interactions of users, appliances and movement. Multi-agent models introduce the possibility of including user characteristics that are usually ignored in conventional acoustics simulations. Multi-agent models have been explored in the built environment in simulations including but not limited to fire evacuation, crowd simulation and user behaviour related to building energy [4-6].

This paper introduces a simulation workflow combining knowledge of architectural and environmental psychology, acoustics, and computational design to create an understanding of human behaviour in the built environment. A simulation workflow is proposed with four component layers: input, information, simulation engine and output. The input layer describes the requirements of the simulation workflow in terms of geometrical and user data. The information layer covers the concepts used for acoustic simulation, navigation and agent decision making. Previous works already showcase how the decision-making processes of a user can be modelled and incorporated into a multi-paradigm simulation system [6]. The simulation engine translates simulated human behaviour into noise within a multi-domain computational framework. The framework is developed according to a set of general modelling conventions known as the Discrete Event System Specification (DEVS) formalism [7].

The layers of the simulation framework are ultimately assembled as a step-by-step workflow which can be adapted with any acoustic simulation software, pathfinding algorithm and 3D geometry models. The evaluations performed on an open-plan office with the simulation framework are also presented in the form of performance matrices on the spatial plan. These matrices include but are not limited to sound pressure level on the floor plan, number of agents disturbed, and spaces with the highest levels of disturbance. Currently, the workflow introduces a framework for the evaluation of office acoustics using a multi-agent model. Our vision is to expand this framework to include aspects of human comfort, experience and satisfaction, which can provide a matrix for designers to evaluate design options in the early design phase.

## 2 RELEVANT STUDIES

### 2.1 Noise in offices

Studies suggest that the user in a modern office gets distracted due to different reasons [1, 2, 8]. One such reason which is highlighted and often difficult to resolve is disturbances due to speech conversations. In the past, speech and its effects in the office environment have been studied using the Changing State hypothesis [9] and the Irrelevant Speech Effect [10, 11]. Both theories highlight how speech causes disturbances to other users but from a different perspective [11]. The Irrelevant Speech Effect suggests that users get disturbed if the speech is irrelevant to the context. The Changing State hypothesis states that users get disturbed due to rhythmic changing in human speech around the office. Smith-Jackson & Klein [11] also suggested that users with different personalities perceive noise differently.

### 2.2 Interactions and user responses in offices

A typical office working day involves numerous interactions. These interactions are governed by the spatial layout or the organisational structure of the office. Waber suggested that interactions between employees based on the organisational structure can be classified into two distinct networks [12] – cohesive networks characterised by multiple small interactions that occur in the organisation, and diverse networks implying a single interactive point. Autodesk studied the interactions in offices in relation to personal space and the social proxemics of the office environment [13].

The above studies provide clear evidence that socio-spatial transitional patterns occur in an office space during different interactions. These patterns are thus used in the simulation layer of the framework to study the nodes of speech disturbances. These patterns are the result of the movement happening around in the office. The mobility of the knowledge workers in a workspace has been widely adopted as studied by workspace consultants and researchers [14, 15].

Green and Myerson classified knowledge workers as navigator, gatherer, connecter and anchor [14]. These are linearly classified on their movement within the organisation. Similar but more apt classification for this research is given by Leesman [15], as it studies employees movement within an office. This classification encapsulates the division of the knowledge from workers sitting at the desk to those that move all around the office. Employees are categorised as 'the camper/squatter' who prefers to sit at the same desk, 'the timid traveller' and 'the intrepid explorer' who use other locations as well in the office, and finally 'the true transient' who uses multiple work settings and is rarely at their place (Figure 1).

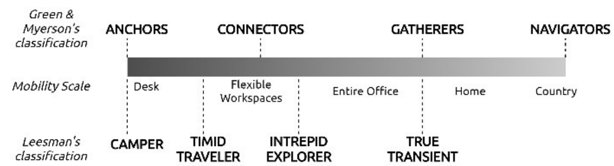


**Figure 1.** Comparison of movement personalities in an office.

While different patterns may emerge in an office, the users' response to disturbance is individualistic. This response arises as a function of a user's personality. A study in the healthcare domain concluded that the stress levels of nurses in a hospital due to noise might vary depending on personality traits [16]. There are multiple methods to classify human personality in the domain of psychology, but the one which relates to response towards noise is Rotter's Locus of Control [17]. Rotter's Locus of Control classifies people into two personalities: internally controlled and externally controlled, using a point-based evaluation of a questionnaire [18]. It was found that people with an external locus of control are less sensitive to noise disturbances as compared to people with an internal locus of control. Psychological studies also classify humans as introvert or extrovert based on their interaction with other humans [18]. It is indicated that extrovert personalities interact more frequently than their counterparts, as observed in a test case of office employees in Amsterdam (Section 3.7).

### 2.3 Pathfinding

Pathfinding is the process of evaluating a path or curve between two points in a coordinate system. There could be numerous paths to reach from one point to another, however the applications involving movement are generally concerned with the shortest path. Dijkstra's algorithm is the earliest and most basic algorithm for pathfinding [19]. The most used algorithm is A* which is basically Dijkstra's algorithm with a heuristic function [20]. A* is faster than Dijkstra's as it needs to traverse fewer nodes to search for the shortest path. Though Dijkstra's algorithm can be used when speed is not of concern [21]. Since its inception, both algorithms have found their use in games and robotics applications [22].

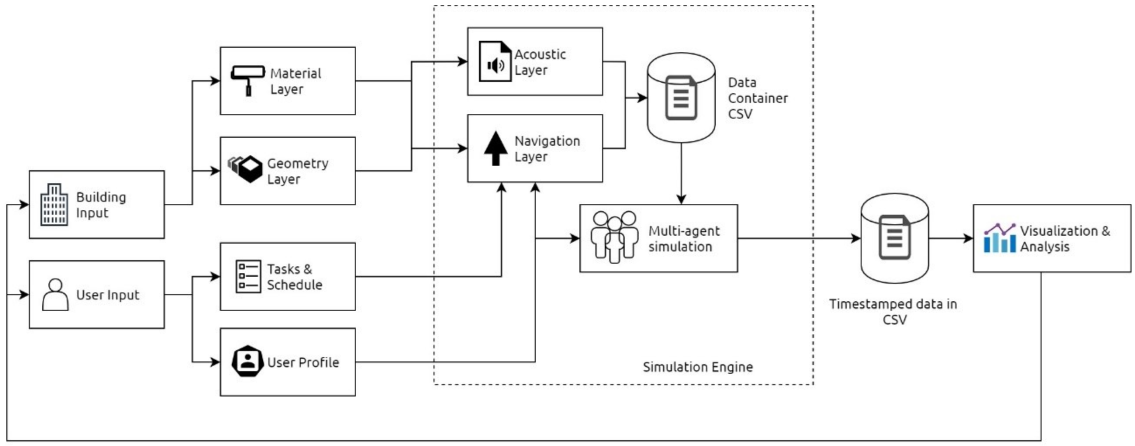


**Figure 2.** Overview of the simulation framework.

### 2.4 Acoustic simulation of offices

Acoustic evaluation of an open-plan office in Europe is governed by ISO 3382-3:2012. It defines the concept of speech privacy which is used to study the disturbance caused due to conversations [23]. The state of acceptable speech privacy is achieved when users cannot hear other's unnecessary and unwanted conversations [24]. Speech related disturbance can also be measured using STI (Speech Transmission Index), Articulation Index (AI) or Speech Intelligibility Index (SII). STI and SII are evaluated on the linear scale ranging from 0 to 1, while AI measures the weighted signal to noise ratio [24].

It is also crucial for open-plan office design to understand how different layout elements (such as furniture, partitions, artefacts) affect the sound distribution throughout space. This interaction of sound with elements prohibits the use of the inverse square law in acoustic simulation. To overcome this issue, the Sabine-Franklin-Jaeger theory, with later modifications by Barron [25] and Sato and Bradley [26], presents a way to calculate sound pressure level (SPL) throughout space analytically. SPL represents the (objective) loudness of sound and is measured in decibels (dB) or, when correcting for ear sensitivity, dB(A). The equation (1) to calculate SPL is as follows:

$$Lp = Lw + 10\log\left(\frac{Q}{4\pi r^2} + \frac{4(1-\alpha)^{\frac{r \times fb}{mfp}}}{A}\right), mfp = \frac{4V}{S_{tot}} \quad (1)$$

where $L_p$ = sound pressure level [dB]; $L_w$ = sound power level of source [dB]; r = distance from source [m]; Q = source direction factor = 1 (omnidirectional) [-]; A = total amount of absorption [$m^2$ sabin]; α = average absorption coefficient [-]; V = volume of the room [$m^3$]; $S_{tot}$ = total surface area in room [m2] ; fb = Empirical factor for scattering of sound.

### 2.5 Human behaviour modelling

Multi-agent models have been used to understand human behaviour in the built environment for various applications such as hospital planning, egress simulation and user movement [4, 5, 27, 28]. The behaviour of an individual agent is governed by a set of rules. The individual agents interact with each other, which results in the emerging behaviour of the collective population [7]. These rules may evolve out of deterministic or non-deterministic logic [7]. Thus, agent-based models provide a modular approach to system simulation, where unique characters and identities can be embedded into agent behaviour. The cognitive decision making of a normal human being can be conceptualised as behaviour in an agent-based model. The agent behaviour is translated into system understanding using state variables which represent how agents will behave in different conditions. The variable values are either adjusted to achieve a fitness goal or to adapt according to other agents.

Schaumann et al. proposed a hybrid model, where multi-agent models are combined with other system simulation techniques such as discrete-time and discrete event models [6]. Such hybrid models can represent human behaviour more accurately due to macro and micro levels of decision making [6, 27, 28]. The study by Schaumann et al. used a combination of discrete-time modelling and multi-agent modelling to study the steering of agents in space; and a combination of discrete event modelling and multi-agent modelling to evaluate agent comfort in the space [6].

A multi-agent model may be used to simulate diverse range (from simple to extremely complex) systems. Thus, the reproducibility and understandability of the model are important. To facilitate this, Grimm et al. introduced the ODD (Overview, Design Concepts and Details) protocol, allowing modellers around the world to maintain readability and validity of the respective models [29].

## 3 FRAMEWORK

### 3.1 Definition

The multi-agent framework (Figure 2) was developed following the ODD protocol so that it is easy to understand, test and replicate in different conditions. The description of the framework, according to the protocol, is as follows.

### *Purpose*

The purpose is to understand the noise disturbances caused in the open-plan office due to speech conversations between employees. The current version of the model does not take into account the noise produced by appliances.

### *State Variables and Scales*

State Variables are time-varying properties that capture the characteristics of the agents and environments [29]. The model consists of agents (office employees) with properties (state variables) of personality types, schedule, initial location, and speech levels. The three personalities are movement, control, and speaking personality. The model updates on a time step of 0.5s and can be used to simulate an entire day for an office floor.

### *Process Overview and Scheduling*

The model implements the processes of movement, interaction, hearing and adaptation by the agents. The hearing process happens on a continuous-time basis throughout the simulation, while other processes coincide with discrete events, as shown in the flowchart in Figure 3.

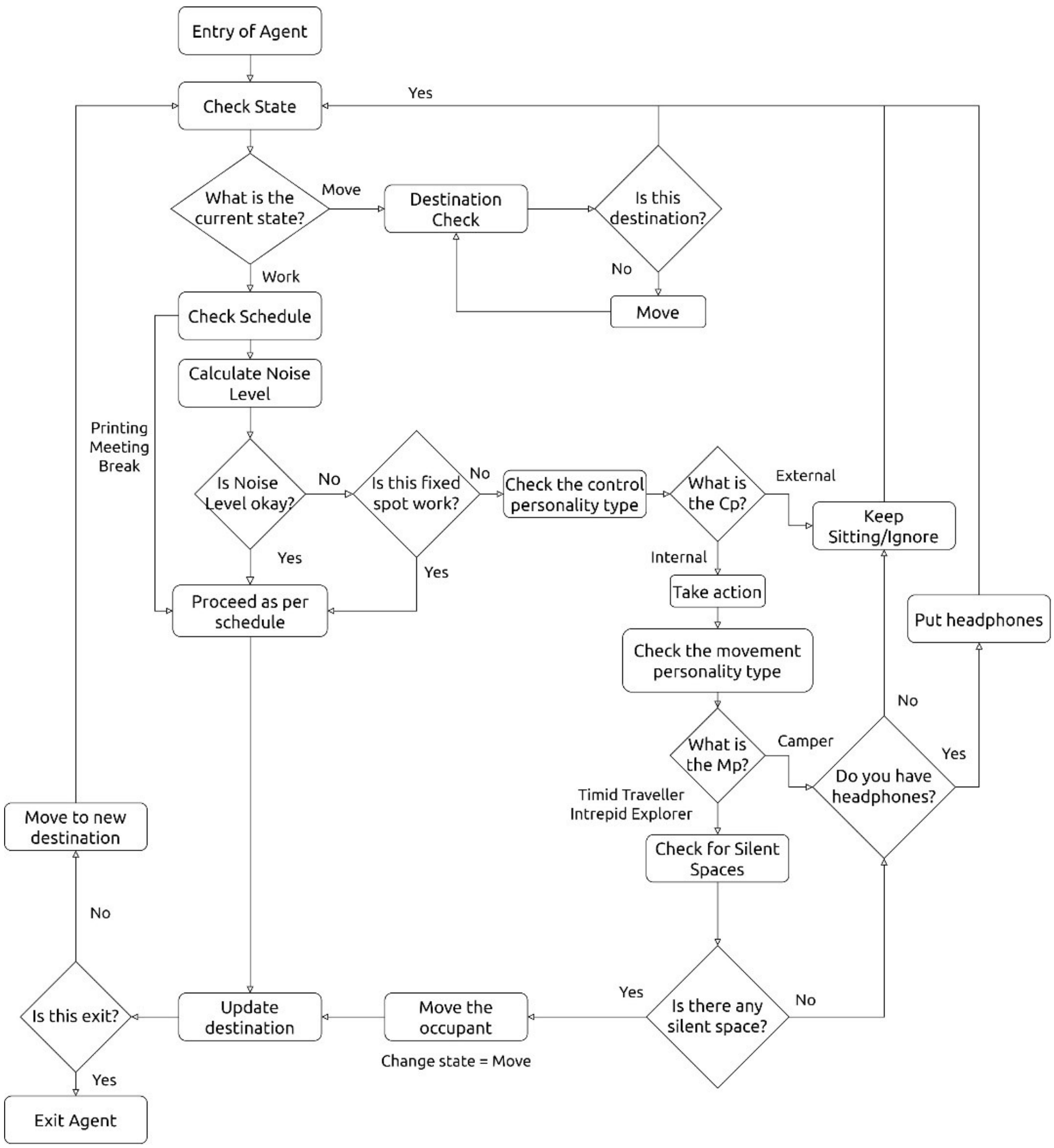


**Figure 3.** Flowchart for agent decision making.

*Design Concepts*

The model design incorporates the concepts of interaction, emergence, adaptability, sensing, and stochasticity. The agents interact for various activities such as meeting, discussion and breaks, which are planned stochastically. The agents also adapt to noise disturbances caused by other agents. This adaptation follows the goal of attaining minimum disturbance or zero disturbance. As a result of adaptation, movement patterns across the floor emerge, which are then analysed as the output of the simulation.

*Initialisation*

The model is initialised with a fixed number of agents at their respective seating (initial location) and personality characteristics. The model also initiates a schedule of activities for each agent which replicates the day-to-day tasks that employees perform in an office.

*Input and Output*

The model takes the values of the number of agents, their properties (location, personality types), schedule and environment as input. At the end of the simulation, spatiotemporal data of agents, sound pressure levels and statistics of agent disturbances are collected as output.

*Sub-models*

The model takes information on sound pressure levels from an acoustic simulation and agent movement information from a pathfinding implementation. These sub-models and user data form the information layer of the framework.

### 3.2 User Node

The user node collects information about the users of the space. The users are categorised into different personality traits based on their movement in the office (movement personality), interaction (speaking personality) and adaptive capabilities (control personality). The node also collects secondary information such as schedule, initial location, and speech level of each agent. This information is then used by the simulation engine to simulate agent behaviour according to the decision framework presented in Figure 3. The decision framework is created using a survey of employees of an architectural office in Amsterdam; however, it can also be adapted by the designer to evaluate different office spaces.

### 3.3 Acoustic Node

The acoustic node implements the acoustic sub-model required by the simulation framework. According to a lab study by Bradley, the ideal background noise level in an open-plan office is 45dB(A) [24] whilst ISO 3382-3 gives us an example target value <48 dB(A) [23]. In this paper, any sound above 45dB(A) is treated as noise in the workspace. Thus, we use this allowed sound pressure level as a threshold for the disturbance caused by the agents in the simulation. The SPL levels of an office were simulated using Pachyderm [30], a free to use plugin for Rhinoceros 3D. The plugin is widely adopted in practice and has been verified by diverse comparisons [30, 31]. The simulation is performed by putting the material properties such as absorption and scattering coefficients of the building elements in the 3D model. The simulation is performed for three speech sound source levels — normal, raised and loud — using the settings in Table 1.

| Topic | Setting Used |
|---|---|
| **Method** | Combined Direct Sound, Image Source and Raytracing |
| **Number of Rays** | 100000 |
| **Cut off Time** | 1000ms |
| **Order of Reflections** | 1 |
| **Edge Diffraction** | False |
| **Octaves** | 62.5 to 8000 Hz (Full Octave) |
| **Background Noise** | NC-30 |

**Table 1.** Settings used for acoustic simulation in Pachyderm.

The simulation calculation is done beforehand for each source individually where interaction occurs such as meeting, discussion, break areas and corridors. The evaluation of sound parameters is performed for receiver points at work desks, meeting rooms and other seating areas. The results obtained are then collected and indexed with source position and speech level. These results are (logarithmically) added as sound pressure levels if multiple sound sources emerge during the simulation.

### 3.4 Navigation Node

The employees of the office interact for various activities throughout a day. The interaction occurs when employees move from work desks to different activity spaces [32]. The movement of employees is estimated using the SpaceAnalysis package, a tool supporting pathfinding and other grid-based floor plan analyses within the Dynamo visual programming environment. The package employs Dijkstra's algorithm with a novel path counting step that produces more direct paths [21].

The geometry data of the floor layout is used to identify obstacles and floor boundaries on the space lattice. The route component is used to calculate all the navigation paths between all possible pairs of points (work desks and activity spaces) on the floor layout. The paths were divided into a collection of points 0.7m apart in accordance with the time step of simulation (0.5s) and walking speed (1.4 m/s) of a normal person [33]. These collections of points as paths are collected to be used during the simulation by the agents. The navigation points on the paths can be increased to create smooth and realistic steering; however, the coarser-resolution is selected as the steering of agents is indicative and not the primary goal of this research.

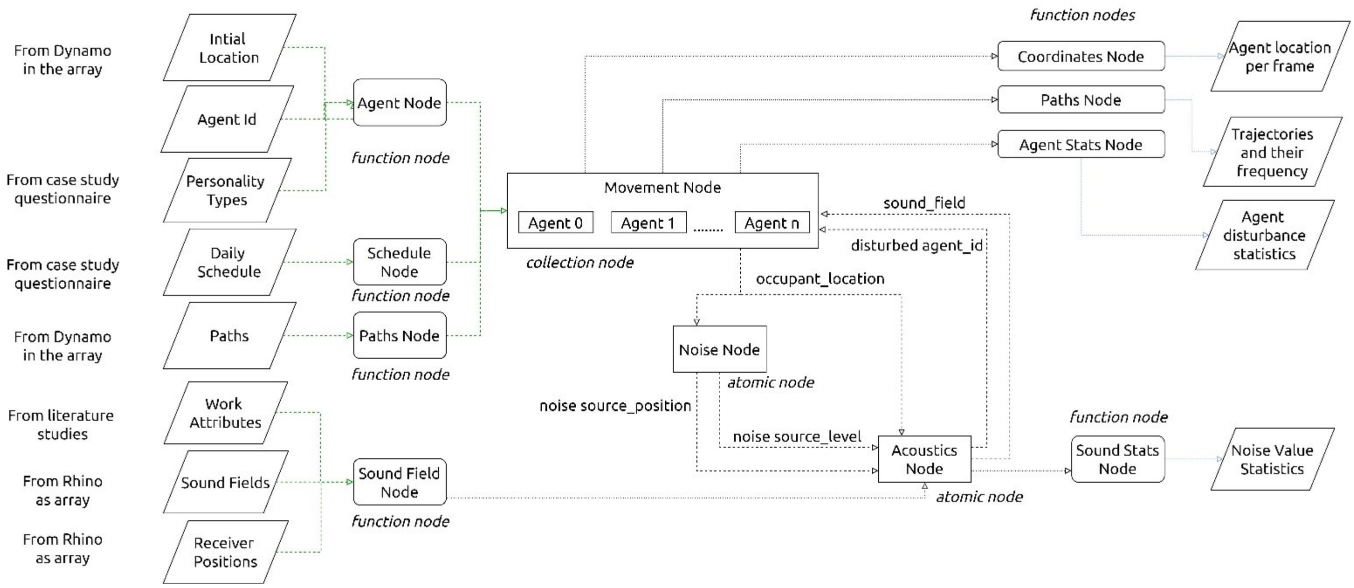


**Figure 4.** Arrangement of SyDEVS nodes for the multi-agent simulation model.

### 3.5 Multi-Agent Simulation

The simulation engine collects the information from other layers and executes the multi-agent model. The model is created using SyDEVS, an opensource C++ library [34, 35]. SyDEVS was chosen since it supports the use of different time steps and timing patterns for different aspects of the modelled system. In this case, the movement of the agents was simulated using a discrete-time step of 0.5s and noise generation was simulated using discrete events that occur when agents interact or talk.

The SyDEVS framework consists of different nodes which are connected to create systems simulation models [34]. The nodes are classified as function, atomic, composite, and collection nodes. The function nodes are containers which pass or collect information at the start or end of the simulation. The atomic node performs decision making based on the triggering of planned or unplanned events. The composite node allows macro-level processes. The multi-agent model is implemented using the collection node, which is a collection of smaller atomic nodes sharing a common definition. It is possible to reproduce the model due to its simple structure. SyDEVS can replicate the design concepts of concurrency, interaction and scheduling, which were required for this model. The present simulation model is implemented by connecting the different SyDEVS nodes which make different decision for processes and share information with other nodes.

As shown in Figure 4, agent movement is carried out in the movement node, which handles both scheduled trips and adaptive movement in response to noise disturbance. The current location of agents is passed from the movement node to the noise node where the sources of noise (interaction, meeting or discussion) are identified. This noise source information is passed to the acoustic node which identifies if any agent is disturbed (based on the personality types) and sends that information to the movement node. The movement node again creates actions of movement or adaptation based on agent properties. All these processes are repeated throughout the simulation, and information from each node is collected in a set of function nodes dedicated to preparing the final results.

### 3.6 Analysis

The visualisation of the data obtained from the simulation is aimed to provide insights about the disturbances caused due to speech interactions in the floor layout. Thus, the results were studied in various combinations, and the following performance metrics were formulated to evaluate the floor layout.

*Peak Noise Level*

Peak noise level is defined as the maximum sound pressure level for each receiver point (such as work desks, and other activities areas) on the floor layout above the threshold sound pressure value.

*Average Noise Level*

The average noise level is the logarithmic average of sound pressure level that the receiver point receives throughout the simulation time.

*Congestion*

Congestion visualises the frequency of paths taken by agents on the floor plan to indicate the relative movement congestion on the floor plan. It could be useful for designers to treat the most congested area with more sound-absorbing material.

*Occupancy Density*

Occupancy Density defines the number of occupants per unit time on the floor plan aggregated throughout the simulation time. It gives information about the interaction happening at different spaces in the floor layout. Higher values mean larger numbers of agents congregate at the area during the simulation.

### 3.7 CASE STUDY

The performance metrics mentioned above were finally analysed and visualised using several case studies. One of these case studies was performed for a small architectural office in Amsterdam. The first floor was chosen for the study as four employees worked independently on this floor. The layout consists of four primary spaces: pantry, meeting area, work desks, and discussion area, as shown in Figure 5. A survey was performed to evaluate the personality types and schedule of each employee, and the data was then used to implement the simulation workflow. The survey conducted was within the checklist of standards (considered below 'minimal risk' at home institution). The simulation was tested for an entire day with a time step of 0.5s, and the timestamped data was collected for further visualisation in Grasshopper (visual programming framework for McNeel Rhinoceros 3D).

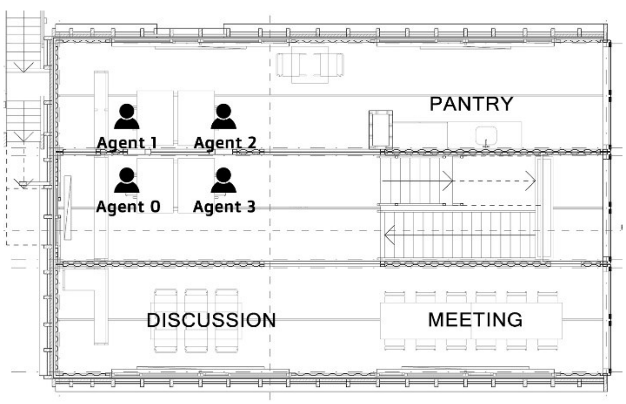


**Figure 5.** First Floor Plan of the case study.

The peak noise level value, as shown in Figure 6 indicates that all the receiver points received a sound pressure level above 50dB at least once during the simulation time. On the other hand, the average noise level suggests that work desks are relatively quieter than the discussion and pantry areas. The congestion diagram shows that high movement takes place near agent 3 and agent 4 with the pantry being the most frequently visited area, while occupancy density evaluation indicates that agent 1 and agent 4 spend large time on desks or are visited by other agents often. The pantry area is also highlighted as another area which is visited by more than one agent at the same point of time suggesting high interaction.

Additionally, the data was used to create an animation of agents on the floor layout using the Unity game engine to visualise the movement and interaction with noise generation at different points of time during the day. This animation provides intricate details about the interaction of users at different points in time. For instance, in Figure 6B, it can be observed that users gather near the pantry area during a specific time of the day, usually the coffee break. This detail is crucial in dealing with such disturbances as these are rhythmic activities and may disturb the meeting in the nearby area. As a result, it was advised to the building manager to provide either better acoustics to pantry area or to relocate it to another floor.

The framework also outputs statistical data about each agent, suggesting the number of times it got disturbed based on its personality. This result is valuable in planning a personalised spatial layout, which is one of the key aspects of designing a modern office. The model was finally tested for sensitivity and face validation with participants for the above case study. The model proved highly sensitive to different schedules and personalities, suggesting different patterns of behaviour in diverse scenarios. The simulation framework was also replicated for a larger case study with more than 50 agents to study different scenarios. Details of the larger case study are reported by Mittal [36].

## 4 CONCLUSION

The simulation framework discussed in this paper is a result of exploration for methods to evaluate user-dependent changes in the indoor quality of built environments. The framework contributes to the current architectural design process by providing a way to study hidden nuances of building use before occupation. The current model is specific to the evaluation of office spaces; however, it can be extended to other types of buildings. The strength of the model lies in generating large amounts of output data which can be used to study the floor layout from a user's perspective and come up with adaptive solutions. One such example was noted during the case study, where one solution to overcome noise disturbance in meeting rooms could be the installation of acoustic curtains. It is also crucial to note that further validation of the framework with real-time data was halted due to the COVID-19 pandemic situation. However, the multi-agent model can be considered as a 'minimal model' according to the validation scheme suggested by Klügl [37].

This minimal model can be used in the current design process with the minimal user data that is usually available during the initial stages of design evaluation. In the later design phase, depending on the user data, the model can be adopted to make detailed acoustic design decisions. For instance, for another case study, the model was used with diverse personality scenarios to evaluate multiple design options.

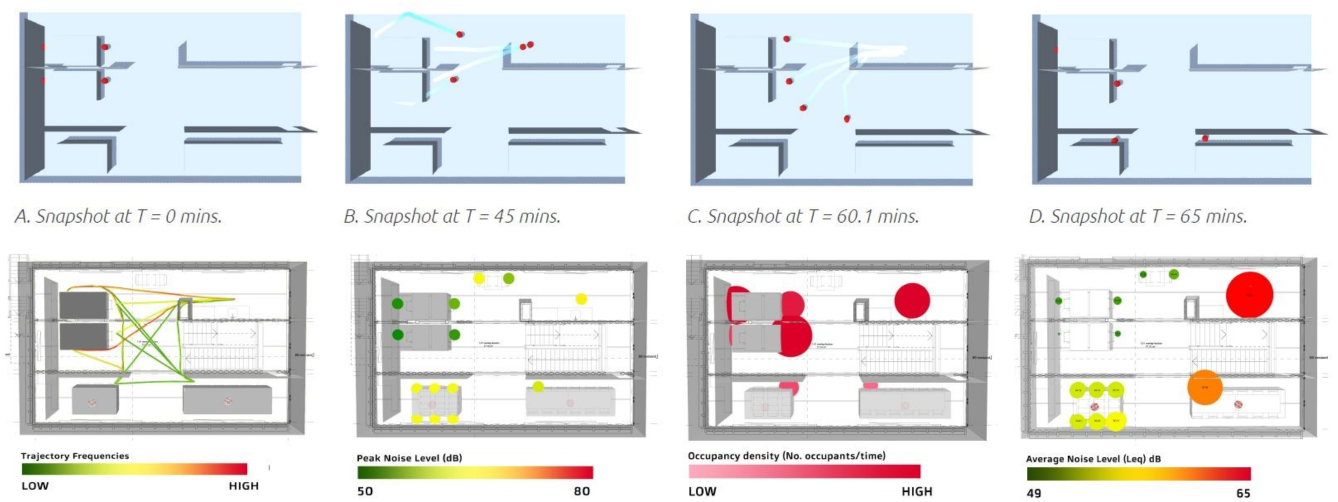


**Figure 6.** Visualisation of simulation results for the case study in the Amsterdam office.

It is also believed that with further research in the domain of human behaviour towards acoustics, user profiles to be used with the model can be standardized as in the case of energy simulation and modelling.

The current framework aims to approximate rather than accurately model the nuances of unplanned private interactions which may occur in the day to day workspace activities. Further, the framework now uses the shortest path algorithm for navigation simulation, but this approach could be supplemented with advanced algorithms that account for multiple factors influencing the movement of people in the workspace. Finally, since simulation time increases with the number of agents, further development is needed to reduce the time complexity of the framework for scenarios involving many occupants.

## 5 FURTHER RESEARCH

As a part of future research, we plan to further validate the framework with real-time occupancy and acoustics data to achieve the state of 'deployable model' as suggested by Klügl [37]. It is understood that with current pandemic scenario, the social interactions will change, and social distancing norms would be crucial. However, the proposed framework is adaptive and such scenarios can be added based on the results of the above-mentioned validation strategy. Additionally, when things get back to normal, we aim to validate normal work day scenario as well.

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