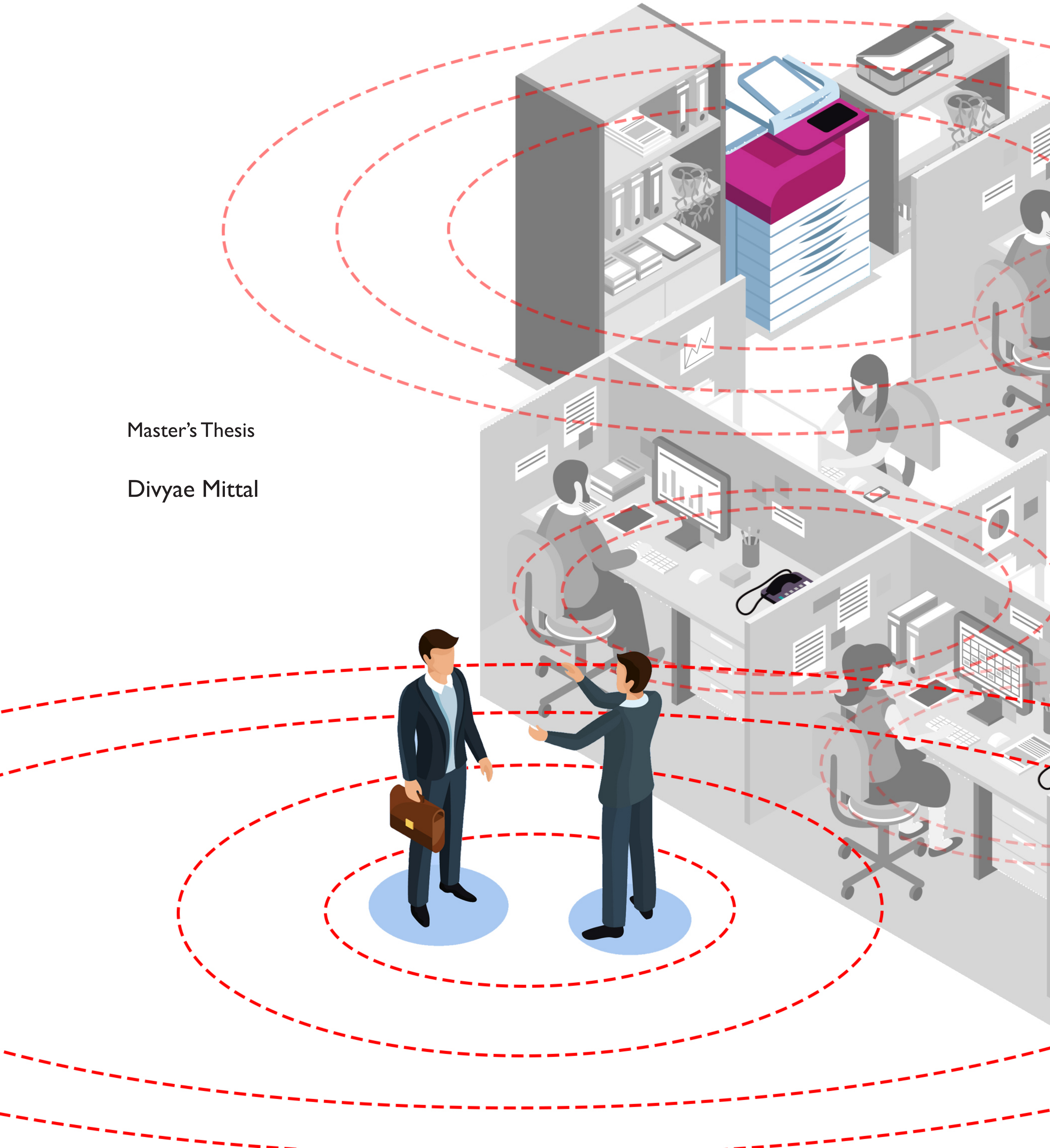
SIMULATION OF ADAPTIVE USER BEHAVIOR WITH RESPECT TO NOISES IN OFFICES



Master's Thesis

Divyae Mittal

SIMULATION OF ADAPTIVE USER BEHAVIOR WITH RESPECT TO NOISES IN OFFICES

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M.Sc. AUBS (Building Technology)

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ABBREVIATIONS

The abbreviations used in the report are as follows-

ABM - Agent-Based Models

ABW - Activity Based Working

BIM – Building Information Model

NWW – New Ways of Working

ODD - Overview, Design Concepts, and Details

SPL – Sound Pressure Level

STI – Speech Transmission Index

AI – Artificial Intelligence

ABSTRACT

In recent time, there has been a rise in the number of coworking and activity-based working spaces. This increase has brought a high return to the real-estate developers but at the same time has compromised with occupant satisfaction. It brings an additional challenge for the architects and designer to look into the user-centred design for workspaces and offices. The current design process relies heavily on the experience. There is a need to evaluate the design from a user's perspective.

It is known that user's in an office environment are impacted by various Indoor environmental quality factors. The most important of those factors is the noise disturbance which leads to decreased concentration, reduced satisfaction, and sick building syndrome in some cases. The noise disturbance is caused by speech interactions, appliances and services. These disturbances are relatively unknown to the designer in the early design phase and depend on user behaviour. This graduation project challenges the current design process by proving a digital intervention in the form of workflow. The workflow aims to help architects and designers in the early design process to evaluate spatial layout with respect to disturbances in the office.

This research combines the knowledge of design informatics, psychology and building physics to come up with a simulation workflow. It uses the knowledge of the psychology of workspaces to understand the user behaviour towards the noise disturbance. This knowledge is put to use through an agent-based model simulating the user movement and interactions through the office layout. It is made possible by combining existing methodologies of acoustic simulation, trajectory evaluation with the newly developed agent-based model that is simulating user behaviour. The results are then visualized on the spatial layout to get further insights into the design by testing with two case studies. As a result of prototyping, a simulation workflow is proposed which can be used to evaluate workspace layout in terms of user behaviour towards the noise.

Keywords – User Behavior, Agent-Based Simulation, Acoustics of workspaces, User-centred design

CONTENTS

1. BACKGROUND

Chapter Overview

The chapter introduces the topic of research by presenting the state of the art readings about the topic.The topic sheds light on the current trends of workspace environment and its demand in the recent future.

Followed by introduction, the chapter narrows down the problems faced in the above mentioned environment and current design process. The chapter concludes with the research objective formulated during the early phases of the research.

1.1 INTRODUCTION

NEW WAYS OF WORKING

According to the statistics website (statista.com), the number of co-working spaces globally has seen a tremendous rise, and this trend expects to follow, as shown in Figure. Co-working, relatively new term, is a kind of activity-based working. This trend suggests that users are now moving towards activity-based working (ABW) and adopting new ways of working (NWW). The development of digital and ICT technologies enables users to carry out work without any restriction of fixed workspace. Thus, it poses a challenge for architects, designers, and other stakeholders to create a holistic environment that can foster greater connection and efficiency. Such spaces may provide an inclusive environment to different needs, priorities, and workstyle of users. Mostly, such spaces are created using open-plan planning, with diverse zones including recreational zones like gym, cafeteria, and reading spaces. In totality, users seek optimum indoor environmental quality in such workspaces. In the context of this research, co-working spaces, activity-based working, and new ways of working are considered the same as do not differ a lot and tend to follow a similar philosophy.

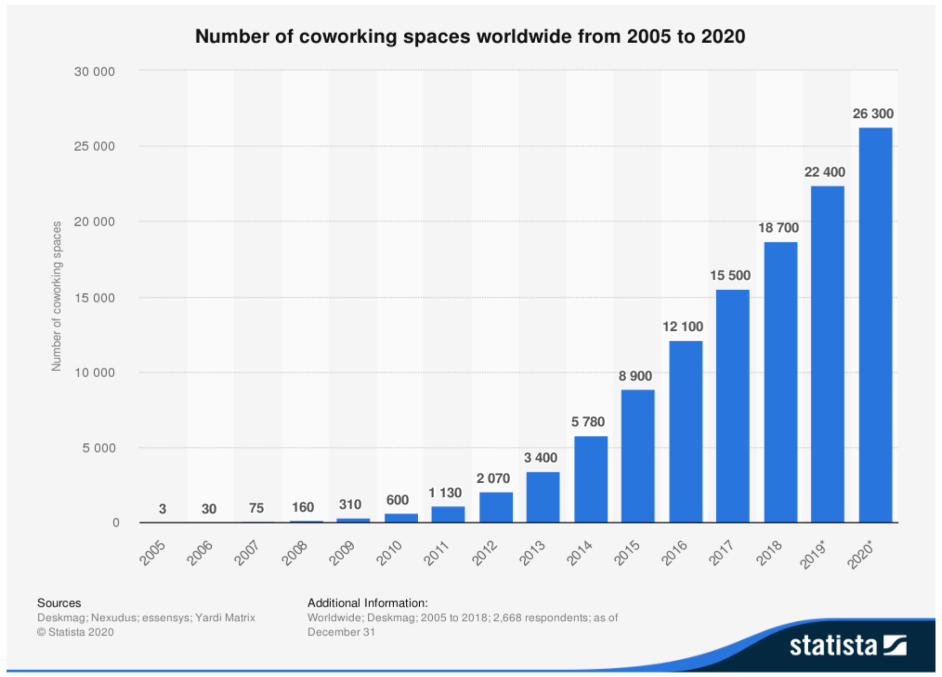

Figure 1.1 Number of co-working spaces globally. (Source - statista. com)

DISTURBANCES IN OFFICES

In the last two decades, organizations for green buildings are also stressing on the importance of higher indoor environmental quality (IEQ). Green building rating systems such as LEED, BREAM, and WELL have the specific contribution of points for the same(Altomonte et al., 2017; Lee, 2010).

Multiple pieces of research show that different types of office layout have a significant impact on occupant's satisfaction based on different IEQ factors(Altomonte et al., 2017; Lee, 2010). The satisfaction of the employees in these offices was affected by disturbances, lack of privacy, inadequate lighting, poor air quality, and other factors(Banbury & Berry, 2005; Lee, 2010).

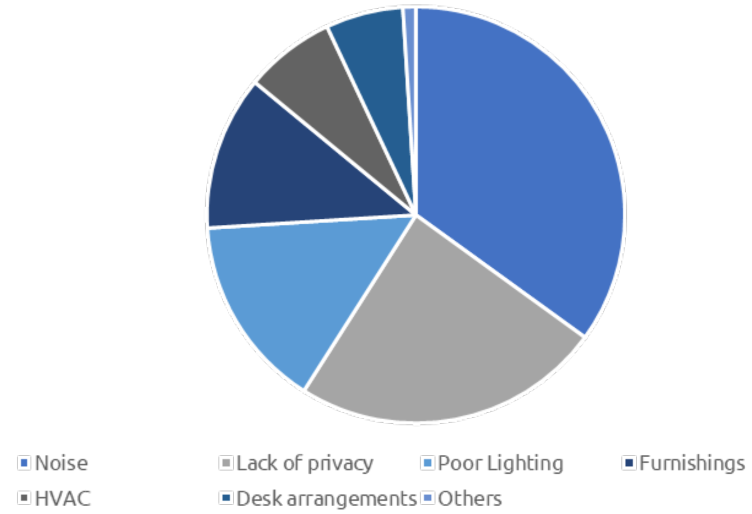

Figure 1.2 The Most disliked aspects of an office.(Banbury & Berry, 2005)

It was noticed that open-plan offices result in distraction and disturbances (Hedge, 1982). Hedge concludes that 54% of the people in this research confirmed that they were interrupted by one or the other kind of stimuli. These distractions can be due to numerous reasons ranging from visual disturbance, glare, poor lighting, sparse furniture arrangement, and noise. (Banbury & Berry, 2005).

Multiple kinds of research provide evidence of noise being the most concerning factor which affects occupants in the open plan or mixed office environment(Banbury & Berry, 2005; Klanderman, 2019).

HUMAN BEHAVIOR SIMULATION

A simulation in most general terms is defined as re-creation/imitation of the real system. The scope of human behaviour simulation can range from industrial design, social sciences, education to the financial market. Human behaviour has been studied for a long time to predict human actions towards a specific event, but now the computational model allows a better understanding of the same. For instance, the human behavioural model can be used, to predict the productivity factor in an organization(Singh et al., 2016); to create an artificial bot in the gaming environment (Silverman et al., 2006) or to train pilots using flight simulator (Boril et al., 2016).

What is human behaviour?

In architectural design domain, human behaviour simulation is studied in diverse aspects such as pedestrian dynamics (Pax & Pavón, 2016), fire evacuation strategy (Li et al., 2004), organization of work (Schaumann et al., 2016) and occupancy patterns(Gaetani et al., 2016). Based on preliminary research, human behaviour in case of architecture may be defined as

'the response of individual towards changing environmental conditions of the built environment.'

In the scope of the architectural evaluation, it can be assumed that the simulation model cannot be used to study the changes in human behaviour occurring due to non-environmental conditions such as bad mood due to mishappening or stress due to approaching deadline.

1.2 RELEVANCE

SOCIETAL

"We shape our buildings, and afterward, our buildings shape us." – Winston Churchill

A human being typically spends 90% of their time indoors throughout his lifetime and a substantial amount of that time at work. The above quote reminds the architectural designers of the responsibility of creating a

user-sensitive design. However, there are pieces of evidence that users are not satisfied inside the office designs leading to reduced productivity, increased stress, and sick building syndrome. The number of workspaces is going to grow, and thus we need more than the conventional design process to improve users' satisfaction. With this thesis, the author aims to contribute by developing a method that can help designers gain insight into the use of the building before it is built. This method is supposed to increase the users' satisfaction and productivity in the broader framework.

ACADEMIC AND PROFESSIONAL

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 with the real purpose of the building. Such evaluations are currently studied through a post-occupancy evaluation process. Which means stakeholders are left with the only choice of improvement or refurbishment of the building. Such action leads to an increase in cost as the cost of design increases with the subsequent design phase, as shown in Figure 1.3. With this thesis, the author aims to combine the knowledge of architectural psychology, climate design, and computational design to create a holistic understanding of human behaviour in the built environment. The research in this domain is still in nascent stages, with few researchers trying to simulate the user behaviour. With the advent of super-computing, this research domain is expected to contribute to the sustainability of the built environment. A few of those factors that are identified right now are users' comfort, cost efficiency, energy efficiency, and space efficiency.

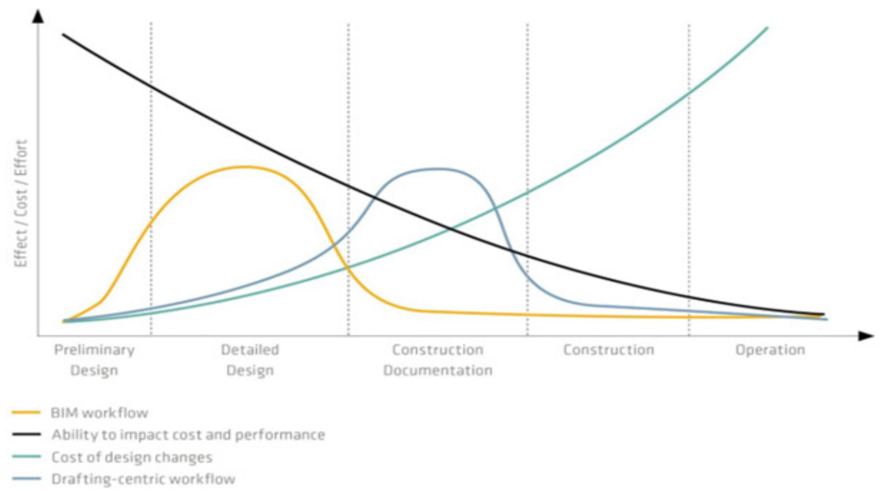

Figure 1.3. MacLeamy curve showing the cost of design changes with the design phase. (Source: https://mys.sika.com/en/documents-resources/sika-bim/benefits-of-bim.html)

1.3 PROBLEM STATEMENT

In recent times, new ways of working and a new paradigm of co-working spaces have created a shift from the traditional concept of 'office buildings.' Multiple types of research suggest that poorly designed workspaces may cause additional effort from the user to cope with it, leading to a waste of time and energy(Banbury & Berry, 2005; Veitch, 1990). While there is an increasing demand for the required number of co-working spaces, the architectural design process has been relying on old methods. Thus, the actual building efficiency and users' productivity is lower due to the gap in the prediction of users' actual behaviour (Buffoli et al., 2014).

The reason for this gap can be the lack of human behavioural insights during the early phase of design(Schaumann et al., 2019). Research that users' satisfaction is greatly affected by the design of the workspace(Frontczak et al., 2011; Lee, 2010). Additionally, factors affecting actual users' feedback are studied only in the post-occupancy evaluation process, which in turn does not help the architectural design process directly. Thus, it becomes essential to analyze users' behaviour at the early design stage as the cost of design changes increases with the phase of design development.

Many pieces of research reflect upon the fact that disturbances due to noise and lack of privacy are primary reasons for decreased user satisfaction or productivity(Altomonte et al., 2017; Banbury & Berry, 2005; Frontczak et al., 2011; Veitch, 1990). The factors that can be considered to study office disturbances range from personal behaviour, noise sensitivity, interaction to connectivity. A review study mentions that the disturbances reported due to unexpected noise are approximately ten times more in open-plan offices as compared to enclosed offices(Pierrette et al., 2015).

The study about the human response to different architectural designs can now be better studied with the abundance of data. This possibility can be attributed to the development of state-of-the-art technologies like Artificial Intelligence and Machine learning, which allows for more significant information gathering from the data. The information gathered can be useful and provide insights allowing us to simulate human responses. The event-based simulation method has been used to predict nurses' movement patterns in healthcare facilities (Schaumann et al., 2016). Research also used multi-agent systems used to predict the crowd movement for indoor location(Pax & Pavón, 2016), while the generative design has also been used to create options of spatial layouts based on

multicriteria performance matrix in an office building (Nagy et al., 2017).

Thus, the problem posed is the absence of the simulation method to evaluate or generate design proposals from the users' perspective concerning auditory disturbances. It could be helpful to both the architectural designer and the end-user if the computational process can aid in the early design phase to predict the zones of disturbance and create solutions for these disturbances arising due to various factors. The research focus is highlighted in the proposed scheme of the new architectural design process, as shown below.

1.4 RESEARCH OBJECTIVE

To develop and test computational simulation workflow that can be used to simulate users' movement in space with respect to acoustics, allowing evaluation and improvement of design proposals of office spaces at an early design stage.

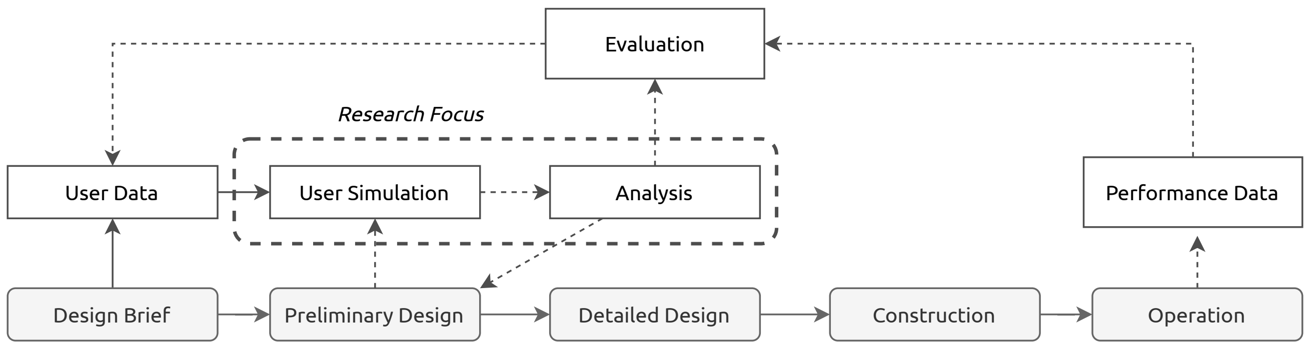

Figure 1.4. Proposed architectural design process. (Source: Author)

2. RESEARCH FRAMEWORK

Chapter Overview

This chapter presents the research methodology followed by the author. It highlights key questions posed for the effective research and how the questions were answered. It discusses the different approaches adopted for completion of the research in given time frame. The chapter also outlines the hypothesis and evaluative approach adopted by the author.

2.1 RESEARCH QUESTION

How can computational simulation methods of various users' movements support the evaluation and improvement of the spatial design quality of office space in terms of noise?

- What are the various factors which contribute to the noise disturbances in the typical workspace?
- What are the types of social user interactions or patterns that take place in an office?
- What are the factors that affect the interaction or movement patterns of users of a workspace?
- How can noise disturbances due to user interactions be predicted in a spatial layout of a workspace?
- What are the prevalent methods used to simulate building use patterns in the built environment?
- What could be the workflow for simulating user movement patterns for the selected office space with respect to the noise disturbances?
- To what extent the simulation workflow can represent the real-time scenario for the selected case study?
- What strategies can be adopted to reduce the noise disturbances in the spatial layout while maintaining the privacy and design requirements of the workspace?

2.2 HYPOTHESIS

Based on the preliminary literature study of new ways of working, noise in offices, and human behaviour in the built environment, it was noticed that there is an absence of a tool or methodology which can help architectural designers evaluate a design proposal with respect to human behaviour. It is also evident that users are disturbed in a workspace due to the noise coming from varying sources such as speech, telephones ringing, and other sources(Banbury & Berry, 2005). Researchers are parallelly trying to study human behaviour, preference, and expectation in isolated domains. Thoughtfully, a connection between these domains may be the way to solve the underlying absence of human behaviour evaluation. Thus, the following hypothesis was stated

Computational simulation techniques can be used to predict the human behaviour/movement with respect to the noise disturbance in the workspaces.

2.3 RESEARCH METHOD

The overall research was divided into three phases – Discovery, Experiment for Simulation Design, and Evaluation. These phases were collectively composed by the combination of these three different methods – exploratory, descriptive, and experimentation. These phases answer the questions, as discussed in Chapter 2.2. The first section was exploratory research, where the research questions (R1 and R5) were answered using the results of the literature study and qualitative methods such as user interviews.

The survey was followed by causal research, which was performed using statistical analysis on, collected questionnaire data (R2 and R3) and results from past researches, to understand the causal relationship of human behaviour in the workspaces. The results of exploratory research were used for the design of the experiment for simulation design (R4 and R6). This simulation model was then be validated (R7) using data collected from the experiment site.

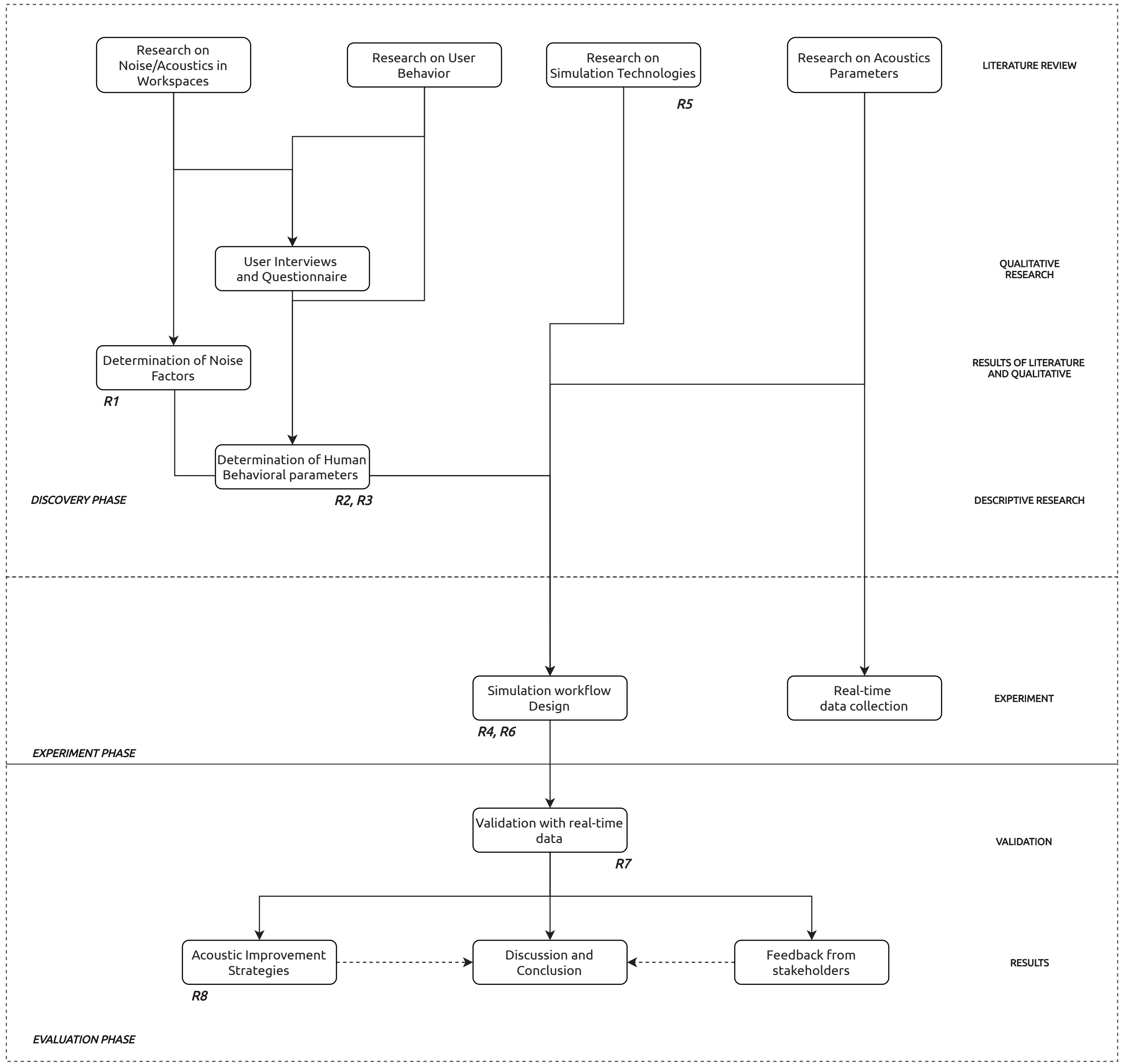

Figure 2.1. Research Overview. (Source: Author)

Simulation of adaptive user behavior with repsect to noises in offices

2.4 DISCOVERY PHASE

This research encompasses the varied scope of three fields – computational Design, acoustics, and psychology. Henceforth, the literature study was performed on the topics of 'simulation methods of human behaviour,' 'noise in workspaces,' 'acoustics of workspaces,' 'psychology of workspaces,' and 'human interaction in workspaces.' The sources considered for the literature review were journal papers, conference proceedings, journal articles, standards, theses, and textbooks. Some technical reports by reputed consultants working in the field of workspace design provided information on trends in the field.

Based on the literature research of the noise disturbances in workspaces, extensive data were collected through the methods of user interviews and questionnaires for the selected case study. Statistical analysis, such as classification, was then performed on the collected data to identify input variables for the experiment. Additionally, during the experimental phase, real-time observational data was planned to be obtained using the sensor node to study human behaviour with respect to noise disturbances in the workspace. The real-time data required to study user's movement prediction in the spatial layout of the office is as follows –

- **User's Movement** – The location of various users measured through location sensors like RFID. The same can also be extrapolated with occupancy data of rooms/GPS data of smartphone/infrared sensors/ security cameras.

- **Acoustics –** The values of sound pressure levels to be measured at different locations and time (Spatio-temporal data) of spatial layout in an appropriate grid.

- **Spatial Layout –** The architectural layout of the floor and essential dimensions of the space along with the materialization to study sound absorption, for the location.

The validation strategy was altered due to the unexceptional circumstances of COVID-19. The additional strategies were studied and are discussed in the Chapter. 8.

2.5 EXPERIMENT FOR SIMULATION DESIGN

Different from the traditional approach, the experiment for simulation models follows a different methodology(Hunter & Naylor, 1970; Kelton & Barton, 2003). A simple simulation can be termed as a function of input parameters. Thus, it was of utmost importance that input parameters need to be studied (Kelton & Barton, 2003). It was also a matter of concern for a simulation experiment to limit the input factors so that computation can be performed in the required time. The simple four steps iterative methodology Figure 2.2, derived from the spiral model of software development (Boehm, 1986) was adopted for the simulation experiment, which is as follows –

Identification of Input Variables – Based on the literature research and statistical analysis, the input variables such as user profiles, user movement patterns, and user preferences were identified.

Defining function for Output Variable – Followed by the identification of input variables, the behaviour and interaction of users were modelled as the function of input variables. This output variable was used to calculate the performance indicator in the analytic framework step.

Simulation Prototype Testing / Debugging – An evaluative loop was set up to decide the occurrence of various functions. The evaluative loop was performed until expected observable results were obtained.

Designing of Analytical Framework – An analytical framework was set up based on the literature study and experiment results. This framework included a description and proposition of performance indicators that can be used to study the design proposal or generate the design.

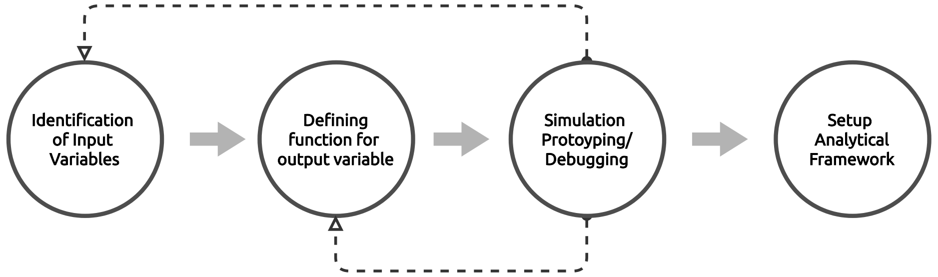

Figure 2.2. A conceptual framework for the experiment of Simulation design. (Source: Author)

Simulation of adaptive user behavior with repsect to noises in offices

2.6 EVALUATION

Followed by the final simulation prototype, the validation was performed using the real-time data collected during the experimental phase. This validation was performed using the results such as occupancy profiles, congestion areas, or noise levels at Spatio-temporal level. Further, the feedback with the stakeholders such as architects, designers was conducted to understand the holistic point of view towards this simulation workflow. Additionally, design improvements for better acoustics of the selected case study were suggested based on the literature review, real-time data collection, and simulation results.

2.7 RESEARCH SCOPE

With the primary aim to study human behaviour with respect to acoustics in a workspace, the research excludes the effects arising due to change in other indoor climate conditions such as a change in temperature, ventilation, and other parameters. The research scope is limited to single-level floor layout workspace assuming comfortable thermal conditions, but an additional double floor model was also explored. It is also noted that human responses are subject to psychological reasons, but these could not be included in the scope due to time limitations and complexity.

3. LITERATURE STUDY

Chapter Overview

This chapter covers the discussion of the literature study performed on different topics during the course of this research. It briefly introduces the concepts of acoustics and its implications in the workspace. Later, it discusses the findings of the literature research on the topic human behaviour in offices. It highlights the thoeries of social dynamics and how user behave towards the noise.

3.1 BASICS OF ACOUSTICS

Theorists have studied sound and its behaviour for years. Sound fundamentally follows wave nature, which is produced when the disturbance is created by the particles in the elastic medium(Ermann, 2015). These disturbances are heard by the human ear as sounds. Though the sound wave can propagate through any medium- solid, liquid, and gas, the literature is considered for air-borne sounds due to the context of architectural acoustics. For example, sounds produced by human speech can be heard by another human as sound propagated through the air.

The basic structure of sound propagation consists of three parts, as shown in Figure 4.1– Source, path, and the receiver. Measurement of sound at source is done by power or sound level, while intensity or sound pressure level is measured at the receiver. The loss occurred between two values describes the nature of the path.

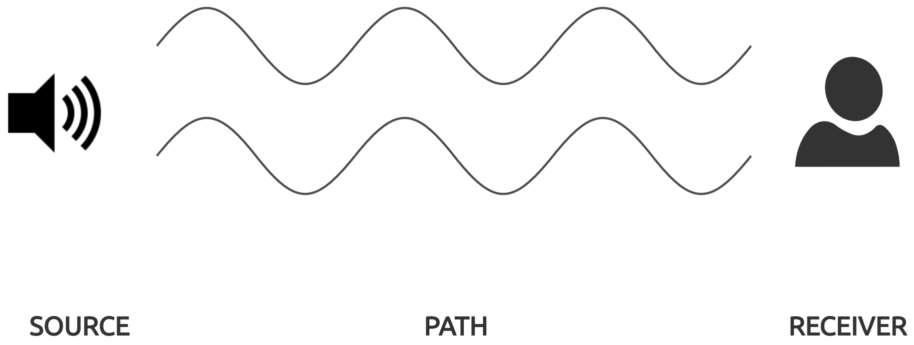

Figure 3.1. Sound propagation for air-borne sounds. (Source: Author)

The frequency of sound relates to the property of sound known as the tone. High frequency thus would create a high tone sound and vice versa. Thus, frequency becomes an important parameter in the case of human understanding, as for human speech, the frequency range is 200Hz to 5kHz(Charles, 1998). Additionally, the sound levels are measured in octave bands, where the upper limit of the octave band is twice the lower limit. In the architectural acoustics field, the centre frequency of the octave band is taken as – 63Hz, 125 Hz, 250Hz, 500Hz, 1000Hz, 2000Hz, and 4000Hz(Ermann, 2015).

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SOUND PRESSURE LEVEL (L_p)

To understand the relative effect of sound on the human ear, the term 'sound pressure level' was defined. Ginsberg explains in the textbook that; Sound pressure level is the measure of the loudness of a sound signal. In the experiment conducted in the 1920s, it was observed that humans were perceptible to the logarithmic change of pressure squared (Ginsberg, 2018). Thus, the sound pressure level is calculated by measuring sound pressure relative to the reference sound level (least perceptible sound to the human ear). It is given by the formula below

$$Lp = 10 \log \frac{p_{eff}^2}{p_o^2} \qquad [\text{dB}]$$

Where Lp = sound pressure level [dB];
p_{eff}= effective sound pressure [Pa];
p_o = reference sound pressure = 2x105 Pa

In the case of airborne sounds, doubling of sound pressure would increase 6dB of sound pressure level. While for a sound travelling with reflection, the term 'directivity' plays an important role(Ermann, 2015). The change in the sound pressure level is then calculated by measuring the change in the sound intensity. The spectrum for various human functions is shown in Figure 3.2.

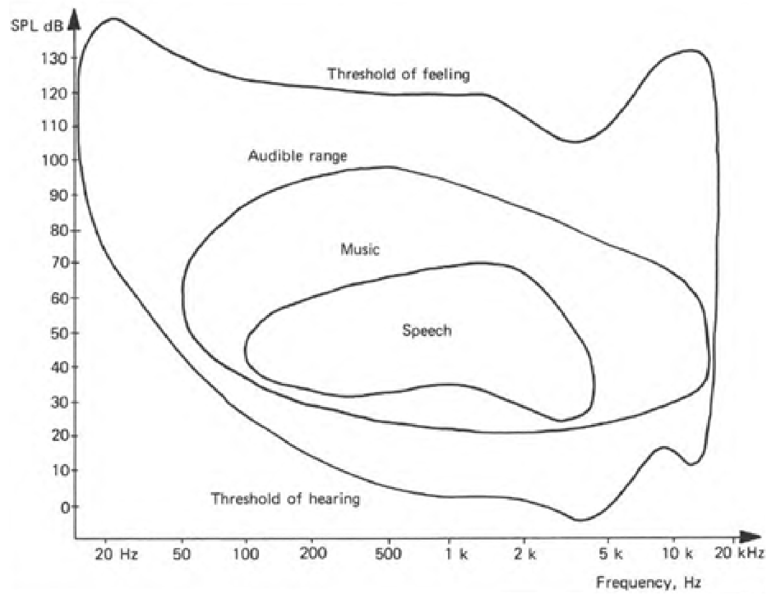


Figure 3.2. Sound pressure level vs Frequency chart for human hearing spectrum. (Ginn, 1978)

SPEECH SOUND PRESSURE LEVEL

In the context of this research, it is important to know the loudness created by the speech of humans.Various studies in the past have compiled the variation of the loudness of decibel levels for various sources, as shown in Figure 3.3. For human speech, it ranges from 45dB to 85dB at the distance of 1m, considering the case of whispering to loud speech relatively(Ermann, 2015). The same has been collected in Table 1.

A-WEIGHTED SPL (L_A)

Human hearing is susceptible to the broad range of frequency 20Hz to 20kHz. However, the variation in loudness that a human ear can perceive (threshold of hearing) in this frequency range changes a lot, as shown in Figure 3.4. For example, due to the auditory responses to sound, 90dB at 125Hz is calmer sound in comparison to 90dB at 1000Hz. Thus, a correction called A-weighted SPL was introduced to match the perception of these loudness values across the spectrum.

Voice Type	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Normal	47.0	51.2	57.2	59.8	53.5	48.8	43.8	38.8
Raised	51.0	55.5	61.5	65.6	62.4	56.8	51.3	42.5
Loud	54.0	58.0	64.0	70.3	70.7	65.9	59.9	48.9

Table 1. Sound Pressure Level of Human Speech (CATT-Acoustic, 2007)

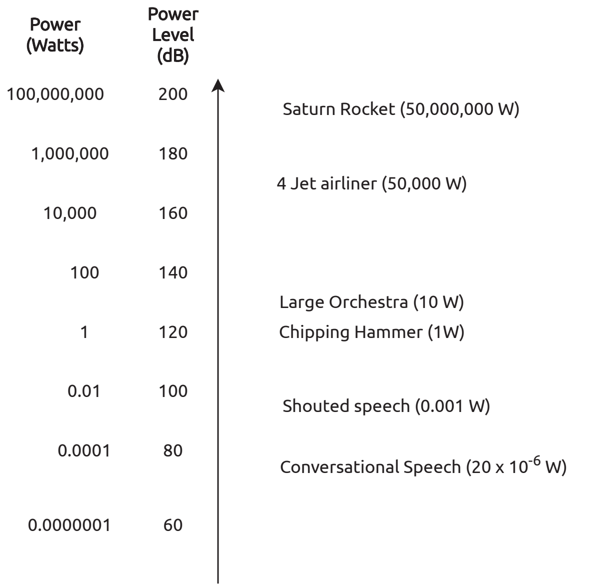


Figure 3.3. Sound pressure levels of various sources. (Ginn, 1978)

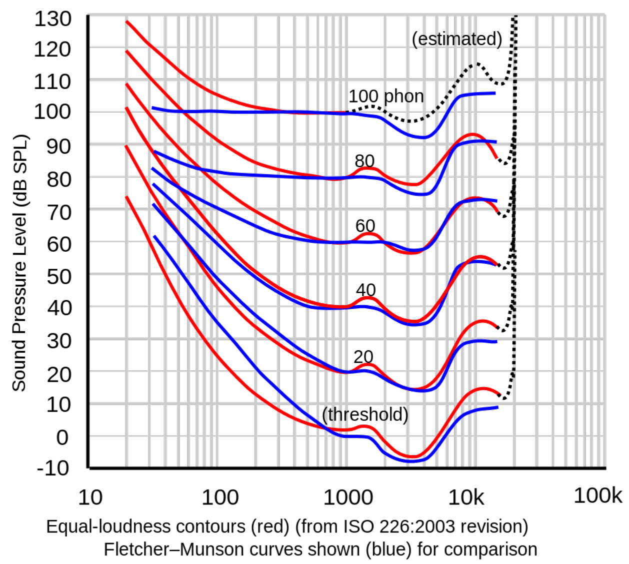


Figure 3.4. Fletcher-Munson Curve. (Source: ISO226:2003)

3.2 ACOUSTIC PARAMETERS

The evaluation of the acoustic performance of the open-plan office is performed based on the parameter as defined in ISO 3382-3:2012 International Organization for Standardization (ISO, 2012). There are other standards also which define similar parameters, but ISO 3382-3:2012 is widely adopted in Europe.

THE SPATIAL DECAY RATE OF SPEECH ($D_{2,S}$)

It is defined as the decrease in sound pressure level studied over the doubling of distance. It is derived from DL_2 as defined in ISO 14257 but considering the normal speech spectrum and A-weighted over the whole range of frequency.

SPEECH TRANSMISSION INDEX (STI)

It is the quantity that represents the quality of speech transmission with respect to intelligibility.

DISTRACTION DISTANCE (r_D)

It is the distance from the source of sound where STI is recorded less than 0.50. This distance is expressed in meters, and it is observed that privacy and concentration improve rapidly for a distance greater than distraction distance.

PRIVACY DISTANCE (r_P)

It is the distance from the source of sound where STI is recorded less than 0.20. Like distraction distance, this is also expressed in meters. For distance higher than privacy distance, privacy and concentration are perceived as separate rooms of the office.

BACKGROUND NOISE ($L_{p,B}$)

It denotes the sound pressure level in octave bands at a workstation coming from sounds that are not caused due to people. It includes sources such as ventilation, traffic noise, equipment, and masking system, etc.

REVERBERATION TIME (T_S)

It is the time elapsed till the point sound pressure level drops by 60dB after switching off the sound source. It can be calculated using Sabine's formula (Ermann, 2015) as stated below -

$$T = \frac{55.3 \times V}{c_0 \times A} \approx \frac{1}{6} \times \frac{V}{A}$$

where T = reverberation time [s]; V = volume of the room [m^3]; c_o = propagation speed of sound = 343 ms^{-1} and A = total amount of absorption [m^2 sabin]

It is one of the basic quantities which helps to evaluate the acoustics of a room; however, for open-plan offices, it is used indirectly to judge the effect on other parameters. Realistically, in the presence of background noise, the drop of 60dB is hard to achieve; thus, the decay rate for 20dB (T20) and 30dB(T30) is used and then extrapolated to 60dB. Research suggests the target value should be less than 0.8s (Rychtarikova et al., 2004) and it is advised to keep 0.5s reverberation time for furnished open-plan offices (Handboek Bouwfysische Kwaliteit Gebouwen 2018).

SPEECH PRIVACY

It can be said that perfect speech privacy is attained when speech sounds are not heard(Bradley, 2007). This is crucial in case of holding a confidential conversation to block unwanted conversation. It directly relates to STI and intelligibility. Apart from STI, the Articulation Index (AI) and speech intelligibility index (SII) is also used to evaluate speech privacy on a scale of 0 to 1 (Bradley, 2003). AI corresponds to a weighted signal-noise ratio (SNR). The table below describes the values considered to achieve speech privacy.

Target Speech Privacy	STI	SII	AI
Confidential	0-0.20	0.10	0.05
Acceptable	0.30	0.20	0.15

Table 2. Criteria to achieve speech privacy. Source: (Bradley, 2003; Ermann, 2015)

SOUND PROPAGATION IN A ROOM

In the case of an open-plan office, it is crucial to study how sounds interact with various elements of the spatial layout like furniture, partitions, and other elements. In such conditions, sound waves collide with elements, and inverse law cannot be followed. Thus, in a room sound pressure level can be calculated analytically using the formula derived from Sabine-Franklin-Jaeger's theory. Later, this formula was corrected by Barron and is as follows –

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

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 [m2 sabin]
a = average absorption coefficient [-]; V = volume of the room [m^3];
S_{tot} = total surface area in room [m2]

3.3 NOISE IN WORKSPACES

To understand the effect and solution of noise in workspaces, it is important to what noise is and what constitutes noise. Noise as perception is a collection of unwanted sounds which bothers the listener, creates an unpleasant atmosphere, distracts, or harm mentally (Cohen & Weinstein, 1981).

Disturbances due to noise have been an interest of researchers for a long time. Since the 1960s, various researches have suggested various sources that play a crucial role in these disturbances. In the 1990s, it was also suggested that noise could be the reason for sick building syndrome (SBS) in the occupants(Burt, 1996), coming from various sources. Such sources listed are but not limited to telephones ringing, computer typing, speech induced disturbances, and ventilation services. (Banbury & Berry, 2005; Cohen & Weinstein, 1981; Navai & Veitch, 2003; Veitch, 1990). Banbury and Berry, through various researches, found out that disturbance caused due to people talking, telephones conversation, and printers had a major impact on occupants' concentration level. Another research studied the effect of various noise levels in the controlled environment (Jahncke et al., 2011). The results confirmed previous claims that high noise increases tiredness while decreases the memory performance of the participants.

vSince the environment of offices has been continuously changing over time, noise due to various sources has reduced. It can be said that the development of better ventilation systems, communication technologies, and the mechanical system will help to curb noise due to sources such as electrical appliances. Thus, more attention needs to be paid to the disturbances caused by the speech factors in the office. Moreover, among the complaints from the occupants, it is the speech noises which are found dominant(Banbury & Berry, 2005; Jensen & Arens, 2005; Navai & Veitch, 2003).

The effect of speech in the office environment has been theorized using two theories – Irrelevant Speech Effect (SalamÉ & Baddeley, 1987, 1989) and Changing-state hypothesis (Jones, 1993). Both theories investigate the mechanism of disturbances caused due to speech (Smith-Jackson & Klein, 2009). Former one relates the disturbance to the meaning of irrelevant speech and how it interferes with other users' tasks, while the later translated the effect of rhythmic change of speech on users' tasks. Smith-Jackson & Klein also studied how disturbance is perceived by different users' personalities, which will be discussed in Section 3.5.

3.4 TOWARDS NEW WAYS OF WORKING

The work-life for an employee in an organization has witnessed a lot of changes over the last 50 years(Van Meel, 2011). These changes are the impact of changing technologies, culture, and work. Traditionally, the office design was mainly composed of fixed workstation, service areas, and cellular areas but are now being replaced by relatively flexible, open, and digital offices (Kingma, 2019). This replacement is termed as 'new ways of working' (NWW), where the workspaces and office environment offer flexibility in time, location, and means of working(Blok et al., 2012; Kingma, 2019; Van Meel, 2011). The rise of NWW was observed in the 1990s when furniture manufacturers and architectural consultancies spread it across the fraternity(Kingma, 2019; Van Meel, 2011). The overall effect of NWW on employees shows mixed reviews(Blok et al., 2012; Demerouti et al., 2014), but it is attributed to increased performance with respect business management and financial gains(Kingma, 2019; Ross, 2010).
NWW holds great importance in the context of this research as it offers

flexibility to the user and may impact users' movement in the workspace. This connects directly to the 'activity-based working' (ABW), which is often considered as similar to NWW in terms of flexibility(Hoendervanger et al., 2016; Kingma, 2019). A study conducted in the context of The Netherlands shows that employees do not embrace this flexibility in an activity-based working setting and tend to stay at the same place (Hoendervanger et al., 2016). Some other researches show the contrary and conclude that there may be increased satisfaction of employees in the ABW environment(Arundell et al., 2018; de Kok et al., 2016).

3.5 HUMAN BEHAVIOUR IN OFFICES

HUMAN PERCEPTION OF NOISE IN OFFICES

It has been established in the past two decades that different occupants perceive noise differently (Navai & Veitch, 2003; Smith-Jackson & Klein, 2009). In the review of the literature done by Navai & Veitch, it was noted that human response to sound depends on its predictability and controllability. The sounds which are generated in a cyclic behaviour are termed as predictable sounds, while the ones which are not repeatedly occurring are rather unpredictable. It can be understood by the example of HVAC sound, which is predictable, while sound generated due to people talking or closing of door is unpredictable. Still, if occupants think that the sound is controllable (closing window to avoid noise), they tend to get less disturbed as compared to uncontrollable sounds (conversation or telephone rings)(Veitch, 1990). Another paradigm of human perception to sound depends on its necessity. It was noted in studies that users' habituate to the sounds which they believe are necessary (such as the sound of a keyboard in the digital offices)(Graeven, 1975).

OCCUPANTS OF OFFICE

An established result from Section 3.3 is that unnecessary occupant interaction in the workspace can lead to noise disturbance to other occupants. Thus, it is vital to investigate the types or categories of people that work in an office. It would not only create a base for understanding but guide the simulation model. The literature study conducted in this section is primarily derived from the researches and findings from the field of human psychology, sociology, and workspace design.

The current workforce present in the offices globally can be categorized based on various traits such as age, gender, culture, personality. In the multi-generational workforce category, the present workforce mainly consists of Baby Boomers, Generation X, and Generation Y, as shown in (Joy & Haynes, 2011). It is of importance to notice that these generations perceive spaces differently and also prefer to work with different perspectives(Joy & Haynes, 2011). This gap between generation and their preference is attributed to the type of space or perception. But it is less understood in terms of their sound preference.

When categorizing people's behaviour based on personality, researches have investigated The Big Five personality factors in the workspaces (Wells & Thelen, 2002). These five traits are – extroversion, agreeableness, openness, conscientiousness, and neuroticism(Rothmann & Coetzer, 2003). Each of these traits is associated with a set of behaviour. For instance, extraversion relates to the sociability aspect of the occupant, which is judged as introvert or extrovert. This categorization has shown considerable results to judge the job performance of various employees(Rothmann & Coetzer, 2003). It was also suggested that neuroticism affected the relationship between the noise and subjective experience of noise(Belojevic & Jakovljevic, 2001). Smith-Jackson & Klein did find the effect of the absorptive trait(ability to focus attention) follow an expected pattern(highly focused and attentive occupant getting less disturbed), but the results were statistically insignificant (Smith-Jackson & Klein, 2009). Veitch concluded that personality varied on Rotter's Locus of Control Scale does play an essential role in sensitivity to noise (Veitch, 1990). A study conducted on nurses also noticed the stress level due to noise may vary with personality traits (Topf, 1989).

Another categorization can be done based on the 'mobility' of knowledge workers (Greene & Myerson, 2011; Leesman, 2017). Greene & Myerson categorize occupants for an organization as – anchor, connector, gatherer, and navigator(Greene & Myerson, 2011). These are ranked on the scale of sitting at a desk for work, to frequent traveller globally for the organization as shown in Figure 3.5, 'Anchors' are people who prefer to sit at their desk for work, schedule social life, and are disturbed by ambient noises. 'Connectors' are people who prefer to work at any location based on their need and mood. 'Gatherers' are much more flexible in work and can also carry their work out of the office for easiness. At the same time, 'navigators' are travellers and may work for an organization on a contract basis. Leesman's approach to categorization is also similar, but

they consider the mobility in a single office space, as shown in Figure 3.5 (Leesman, 2017). Employees are categorized as – 'the camper/squatter,' who prefers to sit at the same desk; 'the timid traveller' and 'the intrepid explorer' are people who use other locations as well in the office; and finally, 'the true transient' who use multiple work settings and are rarely at their place.

Banbury and Berry studied another way of categorization based on job profile or position in the company. They examined if the job profile correlates with any of the reasons of disturbance due to noise(Banbury & Berry, 2005). The result did not follow any significant correlation, and thus job profile cannot be considered are a way of categorization.

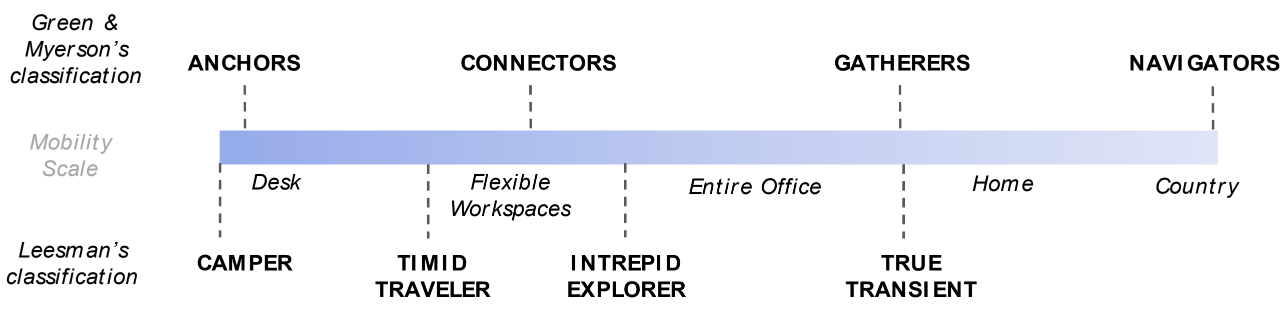


Figure 3.5. Comparison of Greene & Myerson's and Leesman's classification on mobility scale. (Source: Author)

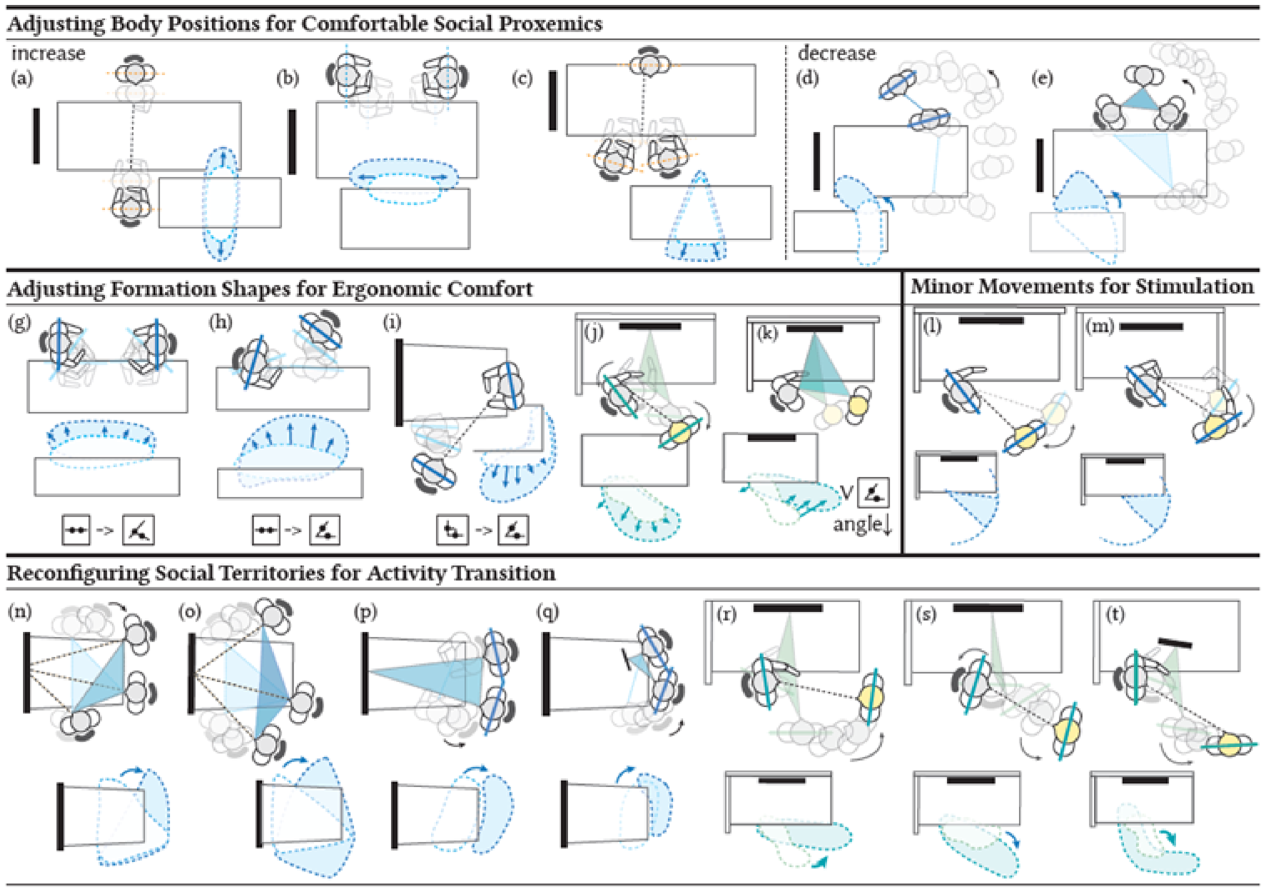


Figure 3.6 Socio-spatial transitions in the office. Source - (Lee et al., 2019)

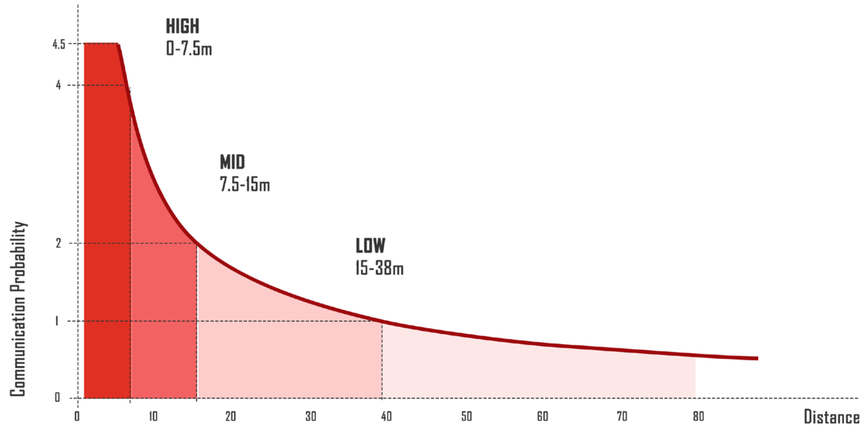


Figure 3.7. The Henn-Allen curve. Source - (Betti et al., 2019)

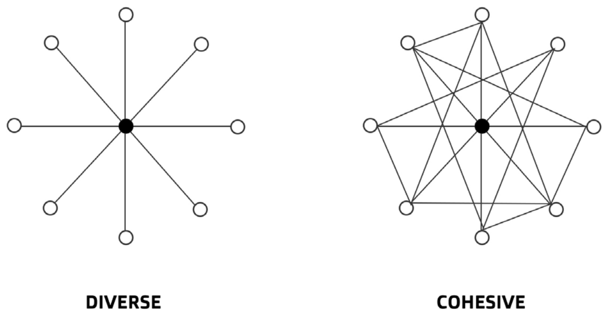


Figure 3.8. Social networks in an organization. Reconstructed from - (Waber, 2013)

Simulation of adaptive user behavior with repsect to noises in offices

3.6 SOCIAL PATTERNS IN AN OFFICE

A workspace is a place where numerous interactions take place daily. Such interactions may create some patterns, which could help understand user behaviour in the office. A study was conducted in an office by observing human behaviour (Lee et al., 2019). Lee et al. suggested that different user patterns occur per the spatial layout of the space. The study in-depth focused on understanding aspects such as social proxemics, personal space, and interactions in the office. The study suggested that four types of socio-spatial transitions occur in a space, as shown in Figure 3.6. These transitions give rise to various interactions around the space.

It was also observed in another study that the probability of social interaction between employees can be defined as a function of distance (Allen & Henn, 2007). This probability is shown by a correlation graph called the Henn-Allen curve, as shown in Figure 3.7 (Betti et al., 2019). This probability is plotted as the weekly interaction between employees as the function of the distance (Betti et al., 2019).

The social interactions in any organization can also be studied in terms of networks. It was suggested by Waber that inherently there are two types of networks for social interactions – diverse and cohesive (Waber, 2013). The diverse network suggests a single point of interaction, while a cohesive network consists of multiple interactions occurring at the same time (Waber, 2013). The simplified network diagram is shown in Figure 3.8. Another theory that is important to look into is the action theory. Action theory has been in the centre of philosophical discussion for over a century (Davidson, 2001; Friedberg & Crozier, 1980; Mele, 1997). The theory suggests that agents, employees, in this case, take action based on the rational logic of behaviour (Davidson, 2001). The agents try to achieve a state of maximum satisfaction or maximum comfort (Mele, 1997). The evaluative loop of the agents' decision making can be conceptualized, as shown in Figure 3.9. below.

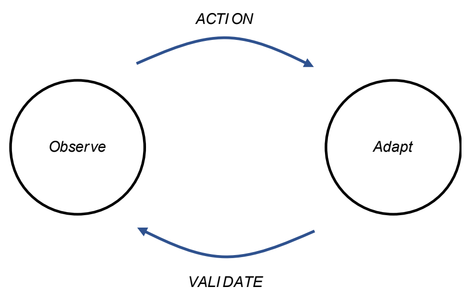


Figure 3.9. Conceptual description of action theory.

3.7 CONCLUSION

The NWW and ABW are primarily attributed to open-plan and flexible spaces. These spaces increase floor efficiency, offer better management but show mixed results in terms of employee satisfaction. Further, NWW and ABW offer mixed task zones, and clustering of activities can help create a practical layout. The ABW environment offers flexibility, thus from the literature, it can be concluded that the occupant holds the decision to change the workspace as and when required but does not follow any logic.

Occupant's decision may be derived from the idea that various workspaces provide different working conditions in ABW suitable for different tasks. In the context of this research, the different workspace will primarily differ in the acoustic environment, and its effect on users' preferences should be studied in the selected case study.

It is evident from the literature study that employees of an office have been categorized based on age, mobility patterns, and job profiles in previous researches. It is useful to categorize employees based on their mobility patterns to study employee's movement. This mobility pattern may or may not relate to the job profile but does not follow any specific relation to demographic variables (age, gender). Thus, it can be studied through a survey to establish how these mobility patterns can also be related to the interaction of different categories of employees. This relation can help in simulating employee interaction with respect to their categorization.

The literature showed that personality does affect the perception of noise, but there is no certain pattern in which it occurs. However, noise that is perceived controllable invokes a softer reaction. While uncontrollable noise would create an adaptive reaction from the users, the reaction could include hearing aid (earphones or headphones), the movement to a different workspace, stop the noise, or ignorance of noise. This adaptive reaction would change for a different context and thus need to be studied for the selected case study.

Further, the noise in the workspace can be caused due to various sources, as shown in Figure 3.10. Certain sources of noise identified (such as typewriters) were critical in past office design but are now obsolete. Thus, these noise sources can be ignored in the scope of this research.

Nevertheless, noise due to speech, communication technologies, and appliances are still cause of concern and thus needs to be considered. These noise sources were then identified through a survey in the selected case study with a primary focus on speech noises.

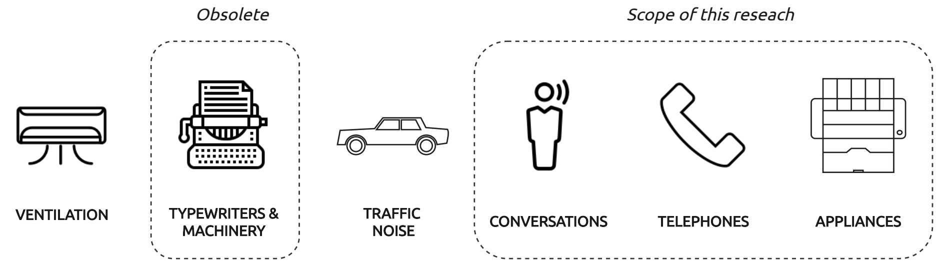


Figure 3.10. Noise sources identified in the literature and scope of this research. (Source: Author)

Based on the literature review, the following guidelines can be considered appropriate for open-plan office design –

Parameter		Target Value	Source
Noise Level	$L_{p,A,B}$	≤ 45dB	(Bradley, 2003)
Spatial Decay	$D_{2,S}$	≥ 7 dB	(ISO, 2012)
Reverberation Time	Tmax	0.5 - 0.8s	(Handboek Bouwfysische Kwaliteit Gebouwen 2018; Rychtarikova et al., 2004)
Speech Intelligibility	STI	< 0.3	(Bradley, 2003)
Absorption Coefficient	a	20-25 %	(Rychtarikova et al., 2004)
Distraction Distance	r_D	≤ 5m	(ISO, 2012)

Table 3. Target values for acoustic parameters in the open-plan office according to literature.

Office Design Parameter	Base case	Example #1	Example #2
Ceiling absorption	SAA=0.95	SAA=1.03	SAA=1.03
Screen/panel height	1.7 m	1.6 m	1.7 m
Screen/panel absorption	SAA= 0.90	SAA=0.70	SAA=0.90
Workstation size	3.0 m by 3.0 m	2.5 m by 2.5 m	2.5 m by 2.5 m
Floor absorption	SAA=0.19	SAA=0.19	SAA=0.19
Panel transmission loss	STC=21	STC=21	STC=21
Ceiling height	2.7 m	2.7 m	2.7 m
Light fixtures	None	None	Open grill
Speech source level	53.2 dBA (IOSL)	53.2 dBA (IOSL)	53.2 dBA (IOSL)
Noise level	45 dBA (Opt Mask)	45 dBA (Opt Mask)	45 dBA (Opt Mask)
SII	0.19	0.19	0.21

Table 4. Design parameters for good speech privacy. (Bradley, 2003)

4. CASE STUDY

Chapter Overview

This chapter introduces the two case study that were used for the development, testing and validation of simulation model. It also presents the findings of the survey conducted online with case study A occupants.

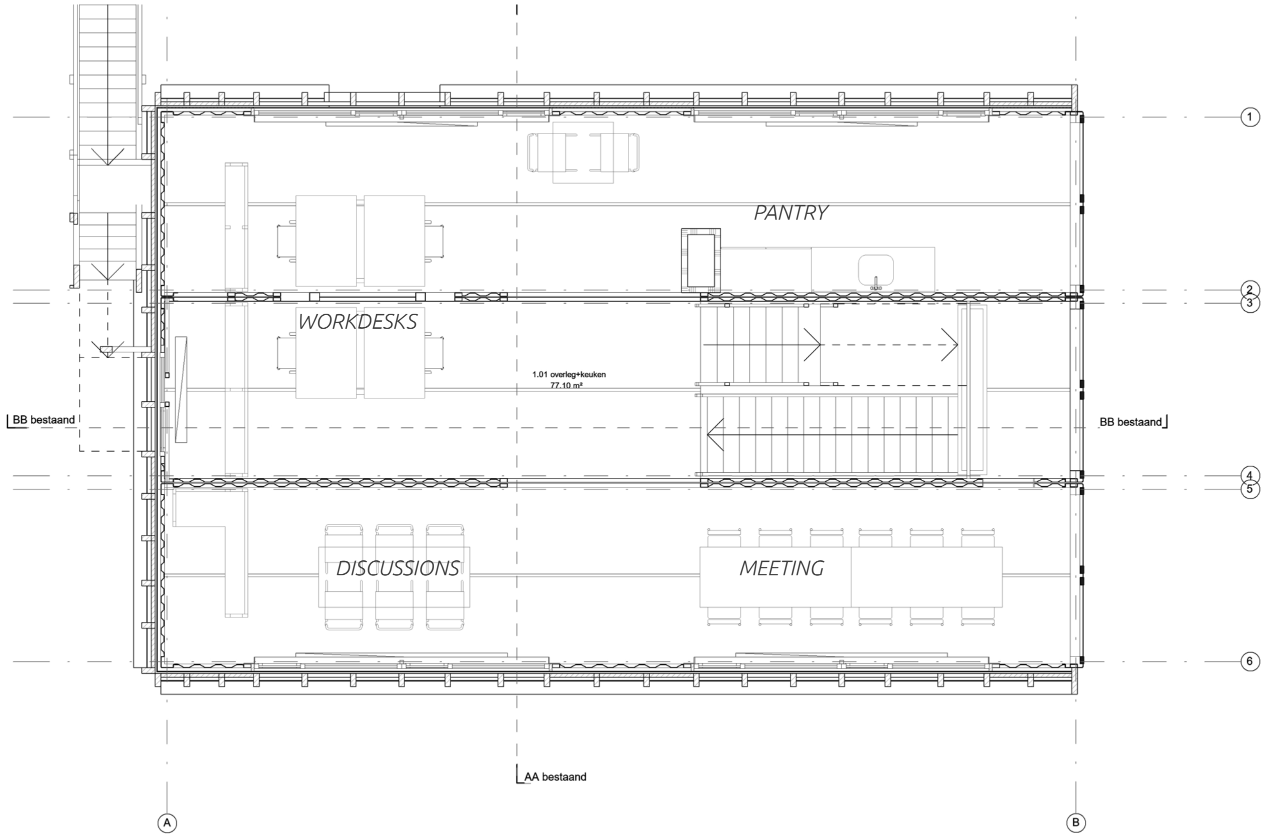


Figure 4.1. First-floor plan. (Courtesy - DOOR Architects) (Not to scale)

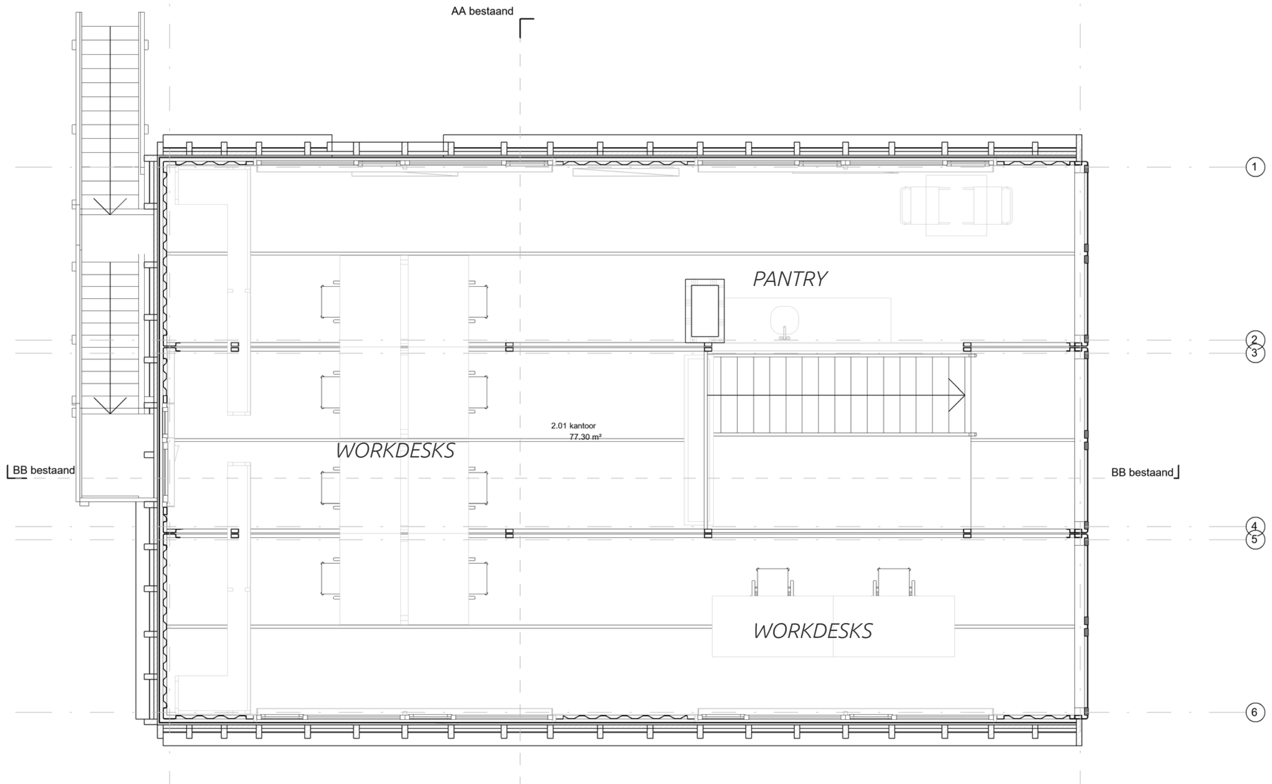


Figure 4.2. Second-floor plan.(Courtesy - DOOR Architects) (Not to scale)

The simulation model was tested using the user data and feedback from case studies. Two case studies were selected named as A and B. The case study A was used to develop initial simulation workflow and validate the model. The other case study B was used to evaluate the application of the simulation workflow with more agents and is discussed in Section 9.4.

4.1 CASE STUDY BUILDING A

The office of DOOR architects located in Amsterdam was selected for the case study. The office was selected because it was an open-plan office, and the office staff was planning on improving the acoustics of the space. The office consists of 14 fixed workspaces. The office is made of refurbished shipping containers stacked over each other, totalling to G+3 floors. The ground floor majorly acts as the storage space and toilet. The first and second floor contains the workspaces, meeting area, and pantry area, as shown in the layout. The top-level is a meeting area but used only once a week.

The office has a steel structure with wooden floors. The office is an open-plan space, comprising of internal partitions made of steel corrugated panels. The central staircase acts as the point of movement between the floors. The initial interview with employees showed that the office lacks proper acoustic treatment, and there is a lot of distraction. The same has been analyzed with more depth in Chapter 6.5.

Figure 4.3. Workspaces on the second floor.

4.2 QUESTIONNAIRE

A questionnaire was prepared for more insights and data to get the input parameters of the simulation model. It was sent online to the employees of the DOOR Architects. The questionnaire consisted of three sections – feedback about acoustics, personality tests, and their trajectories (Appendix A). It was filled by ten employees who use the office space regularly. The questionnaire was developed in a way so that the results could be used as input for the simulation. The questionnaire also aimed to provide insight into people's mindset about the space. Before the questionnaire was posted online, a small interview and tour were also conducted to get behavioural insights about the space. The results obtained from the survey further resonated concerns about the acoustics of the space. The acoustic of the space was rated on the negative side by five employees and neutral by four employees.

Further, all the employees felt disturbed often or frequently at their workspace. There was no clear distinction of where the disturbances were the most. Four employees considered their workspaces disturbing, while the pantry and meeting area was considered as the source of noise by three employees each.

The information about the actions taken by the employees when they felt disturbed was also collected, as shown in Figure 5.5. Half of the employees preferred to put headphones when they felt disturbed, while four employees preferred ignoring the disturbance. Only one employee would prefer changing place to another workplace when felt disturbed.

It was also observed that the employees frequently interacted for tasks related to work and some time for private interactions. These interactions took place in the meeting area, discussion area, and pantry area, respectively.

The questionnaire consisted of questions for three personality tests. Leesman's classification was considered for movement personality from the literature studies (Leesman, 2017). Rotter's locus of control was also evaluated as it affected the actions employees take when they feel noise (Veitch, 1990). After studying various methods of evaluating the introversion/extraversion personality tests, the questions used by Douglas Brown were used as they were clear and related to the objective of this research (Douglas & Frazier, 2001; Khatib et al., 2011).

Simulation of adaptive user behavior with repsect to noises in offices

The detailed process of calculation of personality tests has been explained in Appendix A. The results of the movement personality test revealed that a large group of employees, six out of ten, are of 'camper' personality. Three employees recognized themselves as 'intrepid explorers' while one employee is 'true transient.' Rotter's Locus of Control test resulted in two employees having an 'external' control personality while eight having an 'internal' control personality. Speaking personality test reflected that four employees possess 'introvert' personality while the remaining six belong to the 'extrovert' personality group.

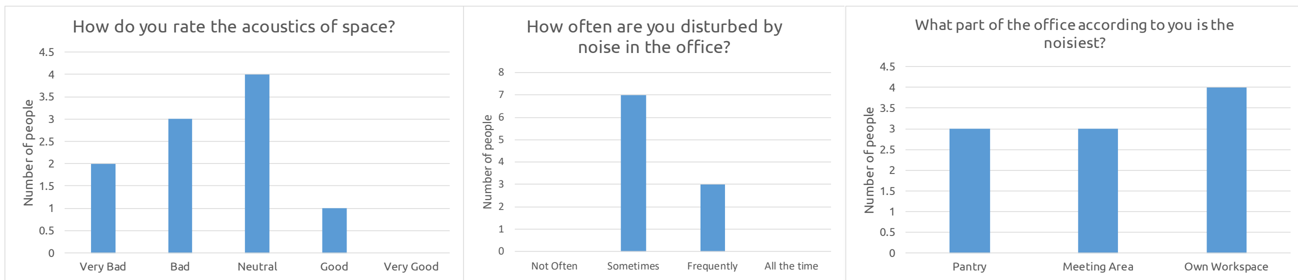


Figure 4.4. Survey results.

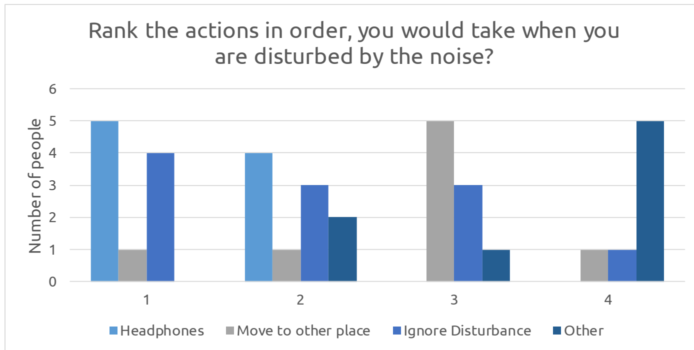


Figure 4.5. Results about actions taken by the employees.

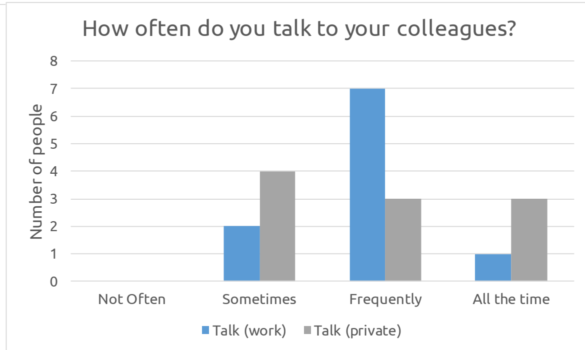


Figure 4.6. Survey results about interactions.

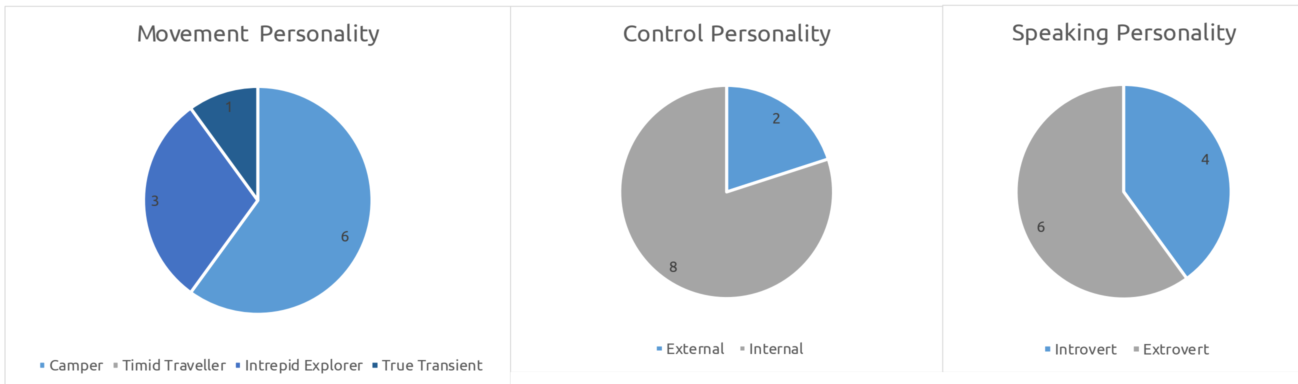


Figure 4.7. Personality test results.

Figure 4.8. An impression of office of case study B. (Source: DOOR Architects)

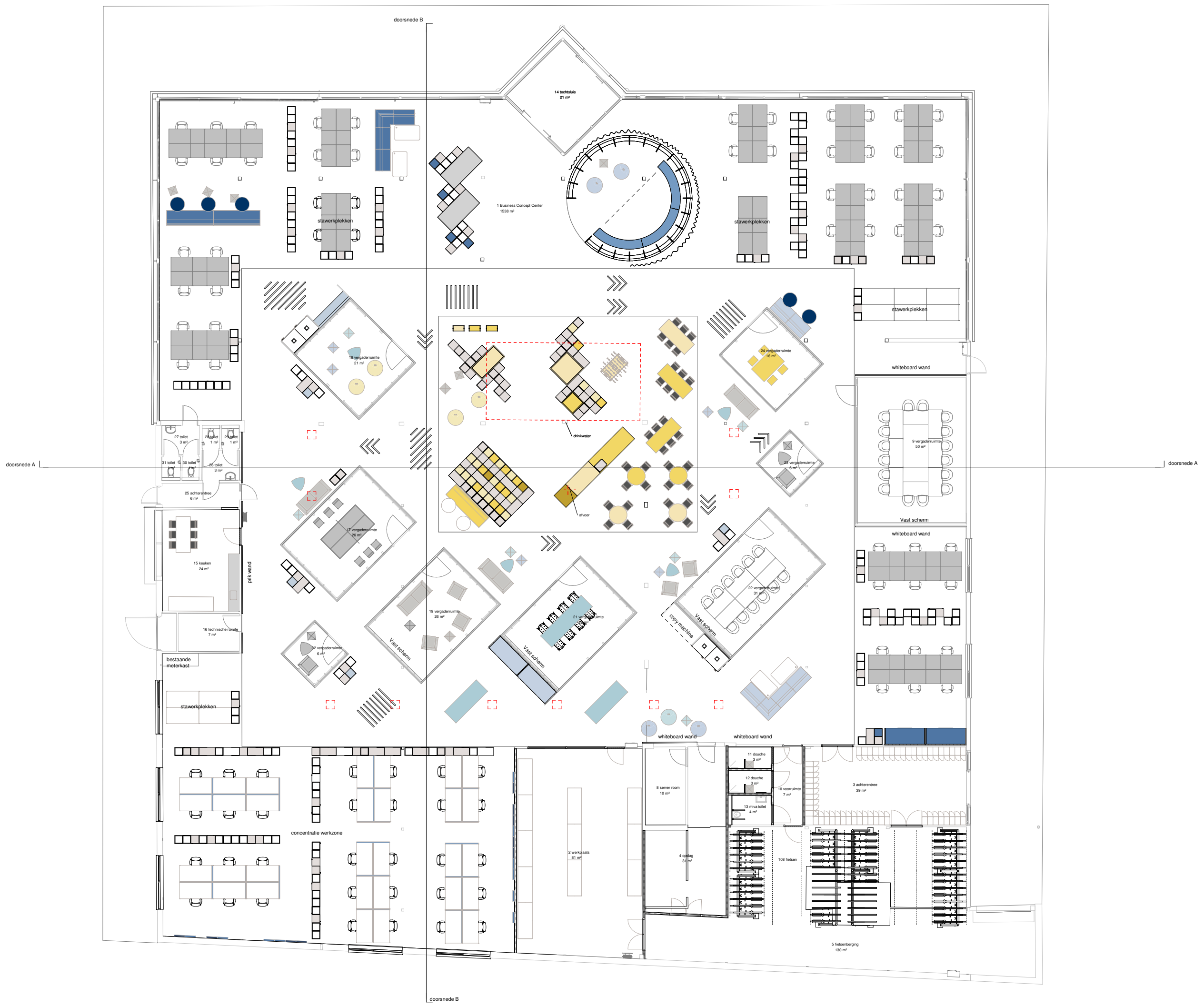


Figure 4.9. Floor plan of office for case study B. (Source: DOOR Architects) (Not to Scale)

4.3 CASE STUDY BUILDING B

The second building selected for testing of the simulation workflow is an upcoming office, to be finished by the end of 2020, for one of the construction companies. The offices are perceived to be a flexible mixed working space by the architect. The single floor office features mixed spaces such as discussion places, meeting rooms, concentration spaces and short term working spaces. The office aims to provide 58 fixed working spaces, various sizes of meeting rooms and discussion places for the employees.

The office is designed as reuse of existing shopping market which has a steel structure. The office is also planned to be acoustically designed using materials such as acoustical ceiling, plasterboard wall and glass partitions for the meeting rooms. The floor is made of wood while the front façade is a curtain wall. The detailed simulation process and its results are discussed in Section 8.4 after the finalization of the simulation workflow.

5. SIMULATION OF HUMAN BEHAVIOUR

Chapter Overview

This chapter introduces the different concepts used in the past for human behaviour simulation. It shows the comparisons of the concepts and clarifies on the selection of the method used in the later phases of the research.

5.1 SIMULATION METHODS

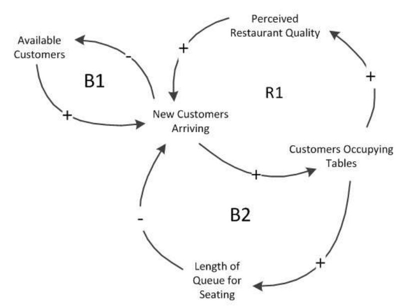
Previous researches suggest that human behaviour may be one of the factors leading to the underperformance of the buildings. The effects of the lack of knowledge of human behaviour have affected both the building and users' performance(Gaetani et al., 2016). In the information or digital age(Alberts & Papp, 1997), various methods have been tried and tested to improve factors such as cost, energy consumption, travel time for passengers at stations, fire evacuation time, and operational efficiency of the nurse in healthcare buildings(Gaetani et al., 2016; Li et al., 2004; Schaumann et al., 2016). These methods try to create 'what-if' scenarios as people behave differently in different scenarios. These behaviours can change due to numerous reasons, such as social, psychological, and cognitive effects of the built environment of the user.

Simulation methods have been in use since the 1950s (Heath et al., 2011), but the use of simulation methods to predict human behaviour has increased in the past decade. These simulation methods have been tested in various applications ranging from industrial applications such as prediction of stock flows to disaster mitigation techniques. There are numerous simulation and modelling techniques for various applications, but four primary simulation and modelling strategies that have been studied for human behaviour. (Heath et al., 2011; Schaumann et al., 2019). These are categorized and used, based on the level of complexity and abstraction(Schaumann et al., 2019). These are a) System Dynamics, b) Discrete Event, c) Discrete-Time and, d) Agent-Based

SYSTEM DYNAMICS (SD)

System Dynamics, as a method, was first conceptualized by Jay Forrester in the early 1950s (Forrester, 1961). It uses mathematical equations to represent the behaviour of large real-world systems(Heath et al., 2011). This simulation method is used to study the collective behaviour of the population and tend to miss the individual behavioural effects. It is due to the abstraction performed on the multiple components to study the outcome in a large system. This method consists of two significant aspects – qualitative and quantitative. The qualitative aspect is studied through a casual loop where the cause and effect of various factors are studied on the system, as shown in Figure 5.1.

The quantitative aspect of this method is derived using stock-flow models where the values of input and output variable determine the system nature. It can be further explained using the example of water flow through a tap, as shown in Figure 5.2. The rate of the water flow depends on the stock level of water in the tank. Since the system involves the simulation of large systems, it can be used to study human behaviour on an urban scale, where population behaviour is crucial.



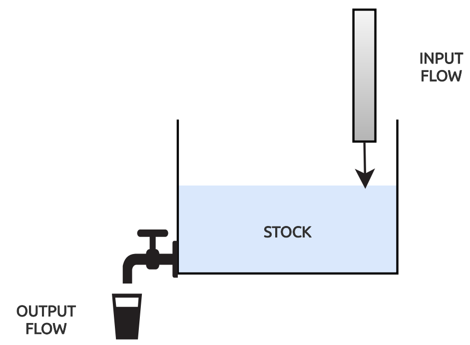


Figure 5.1. Example of causal loop diagram. (Varela-Ortega et al., 2013) (left)

Figure 5.2. Example of Stock-flow concept. (Source: Author) (right)

DISCRETE EVENT (DE)

It is a method where the results of the model are calculated at discrete event intervals using state variables. These models are stochastic and dynamic, which change at the point of time called an 'event.' Different from the other methods, DE does not consider the change of variable values over each time step. This method is described as flexible, easy to use, and a highly detailed model can be created to simulate real-time situations.

The applicability of this method is dependent on making multiple trials of simulation to achieve significant results statistically. Discrete Event method is widely used to predict the occupancy patterns of the users in a room (Gaetani et al., 2016). Commonly named as discrete-event, this method be used with two different approaches – Process-based and Event-based.

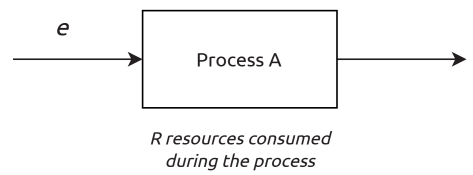


Figure 5.3. Process-resource depiction. (Heath et al., 2011)

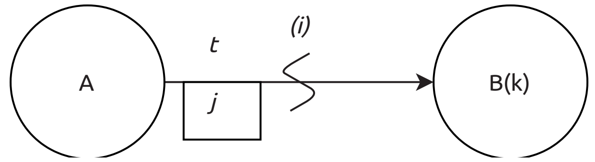


Figure 5.4. Event-graph depiction. (Heath et al., 2011)

In a process-based approach, the flow variable (called as an entity) is governed by the specific process. This process is usually stochastic, consumes resources, and thus takes a length of time, as shown in Figure 5.3. The first event would be the arrival of 'e' to process A's queue. A will then follow consuming R resources during the process. The end event would be the completion of the processing of 'e.'

In this workflow, the entities are independent of behaviour, and their flow follows specific rules made for them, which can be stochastic or conditional. This process is widely used in the industry to simulate operational simulations such as supply chains, which are governed by crucial processes (Heath et al., 2011).

More straightforward, the event-based approach consists of modelling the event itself irrespective of resources and entities. This approach defines the sequence of events and the inter-relation between those two events. This approach comprises elements that are parameters, state variables, and the graph of Events. The use of this approach has been proposed to understand the movement of entities when combined with sensors(Buss & Sanchez, 2005). This process is illustrated in Figure 5.4, uses Schruben's Event graph methodology(Schruben, 1983). During the occurrence of Event A, the state variable of A is changed. If the Boolean value of (i) is true, the Event B is scheduled to happen after time 't.' During this phase, the value of 'k' will be set as 'j.'

DISCRETE-TIME (DT)

Relatively new, the discrete-time method calculates the value of the system in repeated timesteps (Zeigler et al., 2019). This method is particularly useful for studying the dynamic system as it calculates the value at every time step. This method is the recent development of the discrete event method and is now used more commonly (Schaumann et al., 2019). The typical simulation examples, cellular automata, and finite automata are born out of the discrete-time method.

As explained in Figure 5.5, this method calculates the variable value every time step, which is represented by the mathematical time functions or previous trends. These values are then used to study the effect on other systems. In the context of human behaviour is used to simulate the hourly occupancy profiles of the user to perform energy modelling

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(Gaetani et al., 2016). Further development in this area is studied using Markov Chain models in combination with the discrete-time method.

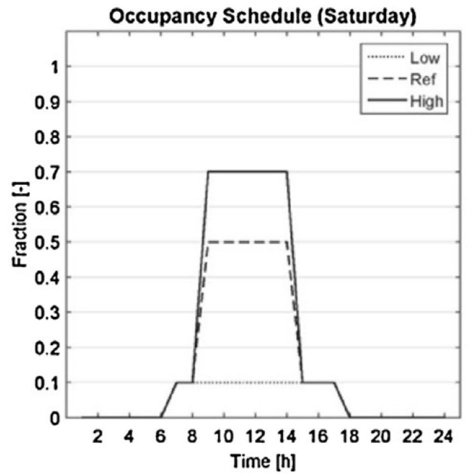

Figure 5.5. Example of application of discrete-time method where occupancy is measured in time step of hours. (Gaetani et al., 2016)

AGENT-BASED (ABM)

Agent-based modelling or simulation, comparatively new to other methods, is now used to explore human behaviour. This method allows a complex system to be modelled into 'agents' which have particular behaviour (Heath et al., 2011). These agents behave according to preset rules, which are set in conjunction with the environment and other agents. The combined behaviour of the individual agents leads to the emergence of behaviour for the entire system or population. This method is modular, where each agent has its unique character and identity. These agents can behave according to deterministic or non-deterministic logic.

Just like any other simulation methods, the agent has its state variable. These variable values represent how the agents behave in the environment. These behaviours can either be directed to achieve a goal or to adapt to the environment and other agents. As shown in Figure 5.6, the agent-based model can be created using three components –agents, a network of interactions, and the environment. Due to its highly flexible nature and ability to represent the cognitive decision-making process in the system, agent-based modelling has been widely used in diverse disciplines(Macal, 2016).

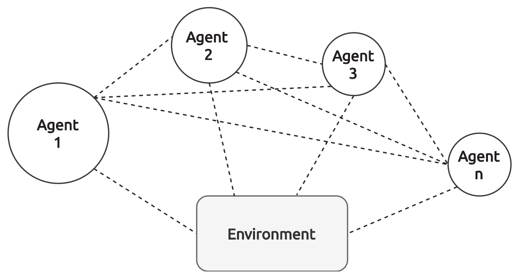

Figure 5.6 Conceptual diagram of the agent-based method. (Source: Author)

Focus Level	Discrete-Time	Discrete Event
Aggregate	Hourly Profiles Model	Survival Model
Planning	DT Markov Chain Model	DE Multiagent model
Steering	DT Crowd Simulations Model	DE Movement model

Table 5. Occupant simulation methods classification. (Schaumann et al., 2019)

Method	Nature	Complexity	Cases	Software Package
System Dynamics	Mathematical	Low	Supply-chain simulation	iThink, Netlogo, Simulink
Discrete Event	Stochastic	Medium	Fire-evacuation simulation, Peak hour load calculation for transport.	AnyLogic, DELMIA,Simcad Pro,SyDEVS
Discrete-Time	Mathematical	Medium	Occupancy estimation for energy modelling. Machine performance simulation	Simulink, MATLAB, AnyLogic
Agent-Based	Stochastic	High	Collision free simulation of cars. Bird-flock simulation.	Unity, Quelea. AnyLogic, NetLogo, Swarm

Table 6. Comparison of different simulation software from the literature study.

HYBRID METHODS

A recent comparison of various simulation methods done by (Schaumann et al., 2019) shows that hybrid methods represent human behaviour the closest, as human behaviour is subject to change in different contexts and environments. Occupant movement simulation has been addressed and researched in the last decade using a variety of hybrid methods.

A combination of the Agent-based and Discrete Event method is the most used as it may represent each agents' occurrence of event independent of system timeline. For example, the research used gamma function to create a schedule of the tasks for the occupant simulation (Goldstein et al., 2011). Zimmermann, being one of the active researchers in this domain, explored the agent-based modelling technique with diverse behaviour of agents as individual occupants (Zimmermann, 2010).

These methods are classified, as shown in Table 5, based on their use – "steering, planning and aggregate"(Schaumann et al., 2019). For an abstract level of space planning and to study how the spaces are used, the aggregate model can be used. While studying individual user behaviour, their path, and actions, the planning model can be used. And a highly detailed level of study can be performed using steering models, which includes collisions between different agents/entities and movement with precision.

5.2 CONCLUSION

Each method of simulation holds its unique place in its applicability. The comparison of methods and how these methods can be used in combination with different tools are listed below. The decision on which model to be used can be made after the assessment of user patterns specific to the case study.

However, it also possible to use two different hybrid methods in a single workflow for different focus levels (Schaumann et al., 2019). The table below shows the nature, complexity, and test case scenarios for these models. Since human behaviour is complex and driven by more than one factor, the combination of different will be chosen and tested during the experimentation phase.

6. SIMULATION DEVELOPMENT

Chapter Overview

This chapter highlights the development process of the simulation workflow. It starts with the literature study of agent-based modelling. It brings forward the concepts used extensively in agent based modelling followed by comparison of different softtware packages.

In the later stages, the chapter showcases the prototyping process in the simulation workflow. It also presents the workflow adopted, visualisation strategies proposed and pseudocode for the simulation model.

6.1 AGENT-BASED MODELS

In our daily lives, we observe various behaviour patterns occurring among us, animals, micro-organisms, birds, and so on. These behaviour patterns emerge out and can be described as complex systems (Wilensky & Rand, 2015). All these systems can be defined either as conceptual models or mathematical models. An agent-based model (ABM) provides a way to evaluate complex systems. ABM is a computational technique that allows us to define how an agent behaves.

The behaviour of the agent is encoded into simple rules which can be observed for the simulation. Thus, each agent carries specific properties that allow it to take action or change its state with respect to the change in conditions by following a behaviour. Thus it can be described below, as shown in Figure 6.1. In 2006, a protocol was proposed to keep agent-based models readable, reusable, and work properly (Grimm et al., 2006). It was then reviewed and updated with minor changes (Grimm et al., 2010). The protocol consists of seven elements grouped into three – overview, design concepts, and details (Grimm et al., 2010).

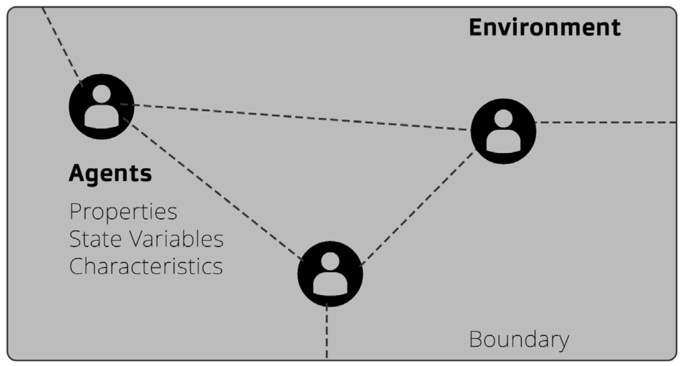

Figure 6.1. A conceptual model for the agent-based model. (Source - Author)

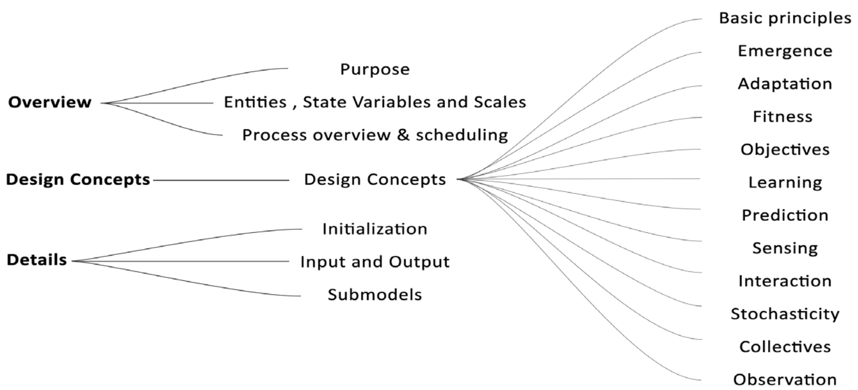

Figure 6.2. The elements of the ODD protocol. (Grimm et al., 2010)

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Purpose – The purpose of the model indicates the objective of the model. It specifies the information that was considered while making the model. It also highlights what to expect from the results of the model. It also defines the context, assumptions, and limitations of the model.

Entities, State Variables, and scales – These define the characteristics of the model. The scale describes the extent of the model, its spatial resolution, and temporal resolution, the reason for choosing the scales. The state variable is described as either low-level (individual, habitats) or high-level (population or community) depending on the extent of the model. There are aggregated or auxiliary variables that hold value, such as the number of agents or decay rate, which defines the model as a whole. Also, the value attributed to the agents is its properties, which may or may not change during the simulation.

Process overview and scheduling – Process overview gives a concise verbal description of the process. Scheduling explains the sequence of events and explaining the order in which decisions are made by the agent. It can be easily visualized or conveyed using a flowchart.

Design Concepts – These provide a background of the model for the agent-based models. Many concepts can take place in an agent-based model – emergence, adaptation, fitness, prediction, sensing, interaction, stochasticity, collectives, and observation. The clear description of the concepts and how they are used should be done in this section to make the results easy to interpret.

Initialization - It conveys the information about what happens at the beginning of the simulation. How are the agents created, and what initial values do they use?

Input – ABM model allows us to incorporate dynamic traits into the model. These traits are highlighted as input, and how do these vary over time. The model provides the output following the input values and is crucial to analyze the result of the model.

Submodels – The processes mentioned in the process overview are detailed in this section. Some models may require extensive calculations using mathematical equations using some parameters. These calculations and their relation to the parameters are highlighted in this section of the protocol.

6.2 SOFTWARE / LIBRARY PACKAGES

It was important to choose the right framework to perform the simulation of high complexity. The framework should allow easy adaptability, reproducibility, and the ability to model complex systems. The frameworks with the different basic ideas were studied to choose the best options. NetLogo, SyDEVS, and Quelea were compared for their effectiveness and criteria for the required complex modelling.

NETLOGO

NetLogo is a multi-agent modelling language developed by Northwestern University, Illinois (Tisue & Wilensky, 2004). It is developed on the pre-existing packages like Logo, StarLisp, and StarLogo (Wilensky & Rand, 2015). It is written in Java, which makes it adaptable to run on any system. It supports multi-agent modelling, where agents are commonly called turtles(Wilensky & Rand, 2015). It is known to evaluate and simulate real-world scenarios such as bird flocking, cell growth, and swarm effects.

The user interface of NetLogo provides various options for setting up the code, visualize patterns, and the results at the same time, as shown in Figure 6.3. It is considered a high-level language with applications such as supply chain management, project management, and biological treatments. The language as a whole allows interactions, concurrency, and reproducibility, but lacks the capability to integrate building model in the user interface and perform scheduled simulations.

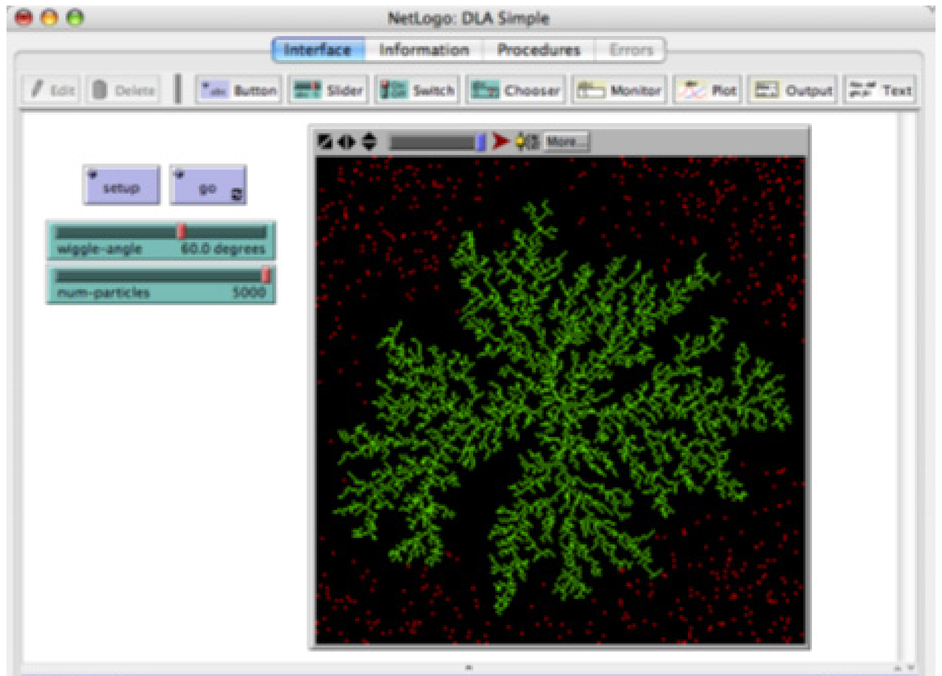

Figure 6.3. User Interface of NetLogo. (Tisue & Wilensky, 2004)

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SYDEVS

SyDEVS is an open-source C++ library developed on the Discrete Event System Specification methods (Goldstein et al., 2018). It allows the programming of data flow and agent-based modelling through its modified atomic and collection nodes. The library features a discrete event, discrete-time, and agent-based models together by using the combination of working nodes. The library consists of four nodes, as shown in Figure 6.4. Each node consists of two or more ports that are used to transfer data and sequence the flow of the program. All the ports are associated with the event handlers except in the case of the function node.

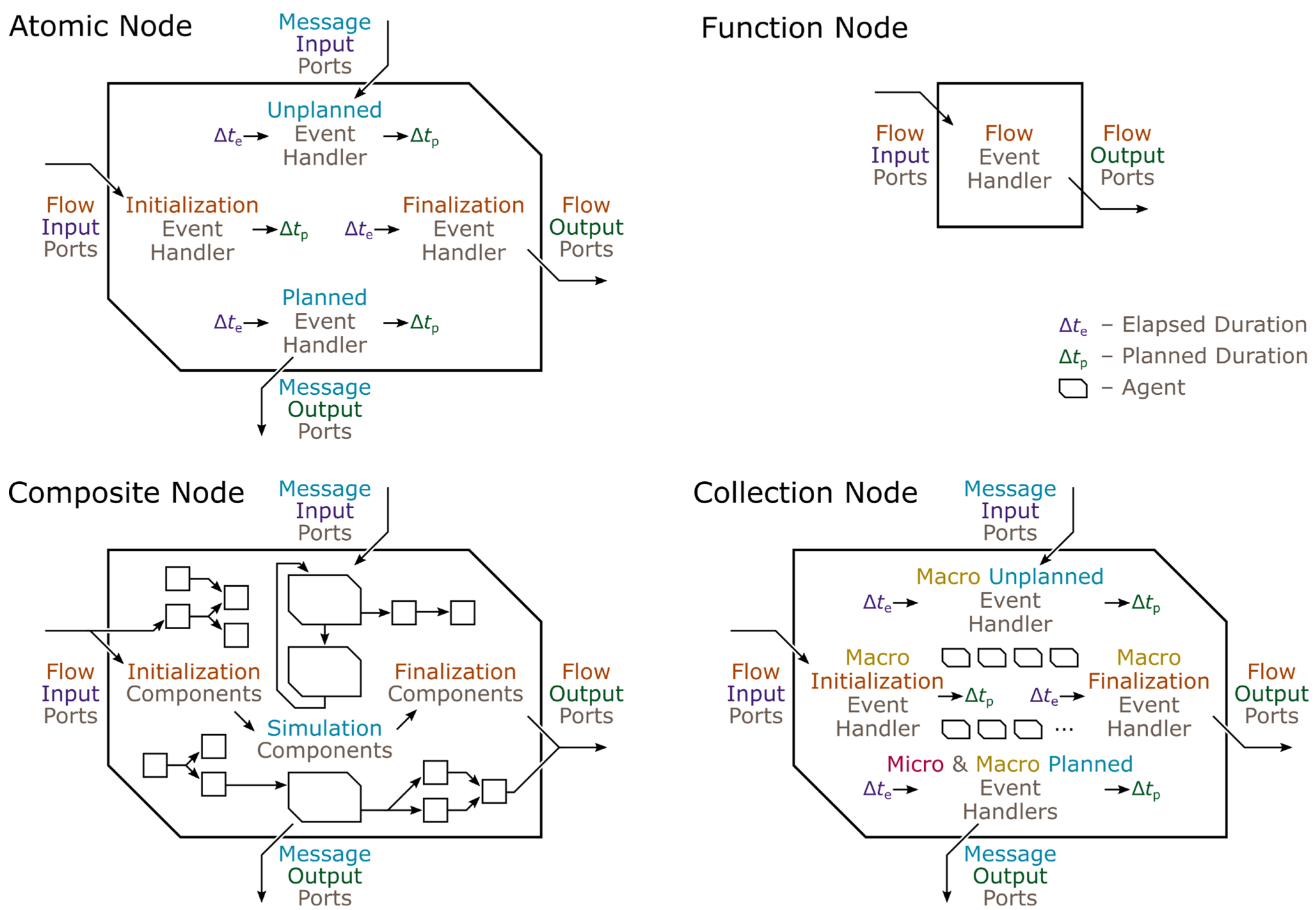

Figure 6.4. Nodes used in the SyDEVS framework. (Goldstein, 2019)

Atomic Node takes data from the input flow port once to initialize the node. It sets the occurrence of the planned event handler after the time Δ tp. The unplanned event handler is executed every time a message is received in its port and schedules the planned event again at the time, Δ tp. The finalization event handler is only executed at the end of the model to output the data of the node.

Collection Node is similar to the atomic node in its external framework but differs in its internal functioning. It allows the creation of multiple nodes inside, as the different agents. The macro event handlers function the same as an atomic node keeping data flow with external nodes. The micro event handler manages the message transfer between agent nodes. The agents are created with a unique ID and can also be removed at any point.

Composite node is the encapsulating node in which the simulation is performed. It consists of all the components as nodes that are used in the dataflow during the simulation. It initializes the nodes by sending input flow data to each node. The simulation component could be an atomic/collection node performing the simulation and data flow. The finalization component outputs the data of simulation received from simulation components.

Function Node is a dataflow node used to perform function or calculation when it receives the information input flow port to produce a result for output flow port. It is usually used in the initialization of the finalization component of the composite node.

Framework	Interactions	Concurrency	Adaptability	Geometry Data Import	DEVS
NetLogo	Possible	Possible	Not Possible	Not Possible	Possible
SyDEVS	Possible	Possible	Possible	Possible	Possible
Quelea	Possible	Possible	Not Possible	Possible	Not Possible

Table 7. Comparison of agent-based frameworks.

The SyDEVS framework has been proposed for the examples such as comfort modelling of occupants (Schaumann et al., 2019), movement of nurses in healthcare facility (Schaumann et al., 2016) and scheduling of occupants (Goldstein et al., 2010). The SyDEVS library allows reproducibility, concurrency, interactions, and scheduling. Due to its open-source environment, it can be extended, and any behavioural trait can be created in the simulation workflow.

QUELEA

It is an agent-based modelling plugin for Grasshopper, developed by Alex Fischer. The plugin uses the physical forces between the particles, in this case, agents, to create the agent environment interactions. The plugin performs well for physics-based complex models but is restricted due to its limited documentation. (Fischer, 2015). The plugin produces the capability of modelling the agents in a 3D environment of Grasshopper, but cannot code complex discrete-time/event models.

6.3 SIMULATION SETUP

Based on the results of the literature study and the initial survey of the case study, the framework for simulation design was proposed, as shown in Figure 6.5. It was noted that different users for the selected case must be categorized for better control over the simulation model. The users for the simulation model are categorized into different personality types. Each personality reacts differently to the noise, and thus rules are set based on the personality. For a basic understanding, the users will be termed as agents, and the building will be called the environment.

The rules will guide the interaction between these agents and the environment. These rules were derived from the survey/questionnaire that was conducted in the selected case study in the next phase. The environment is represented by building model where the agents interact. The environment also causes the absorption of sound and provides obstacles for the agents. This data is imported from the space layout data obtained from the BIM model of the building. The agents follow a certain pattern to start the model, which is derived from the schedule envisioned by the architect or designer.

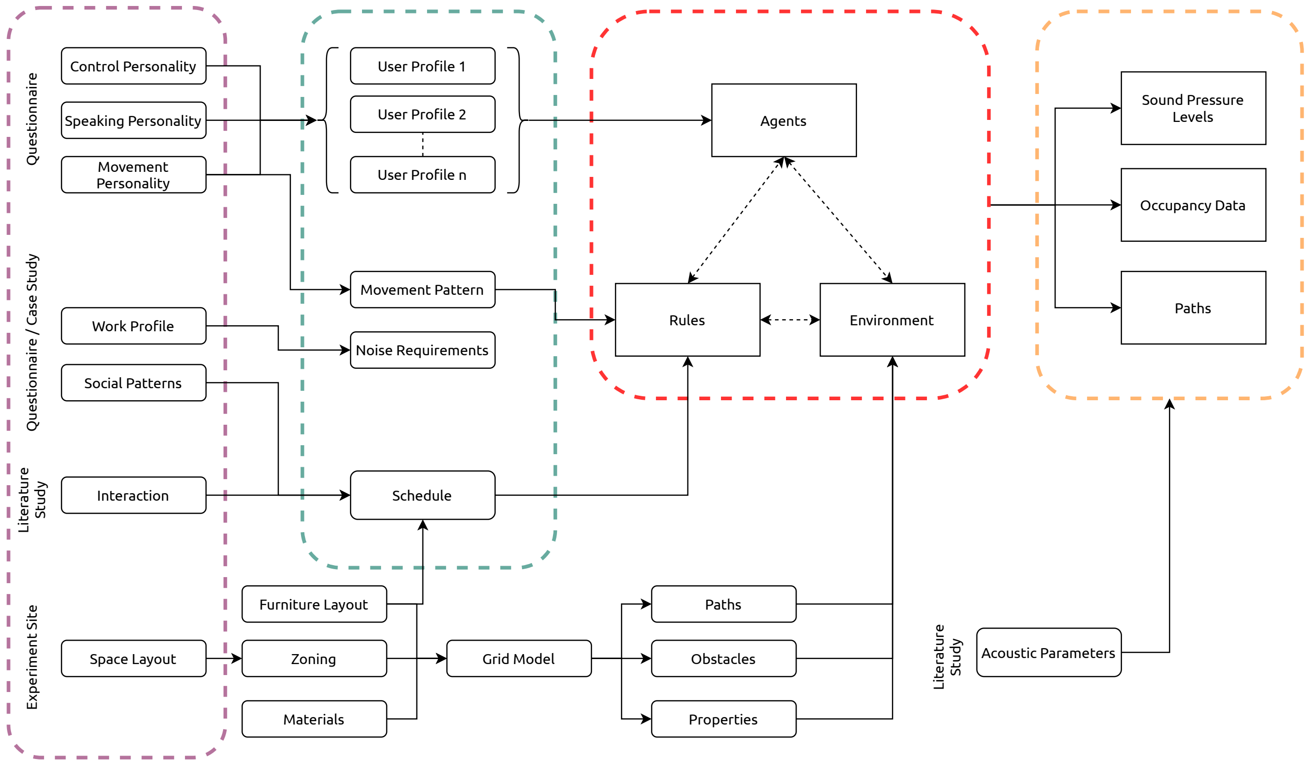

Figure 6.5. Framework for simulation design. (Source: Author)

The simulation workflow envisions the inclusion of both the discrete event and discrete-time methods at different levels. The chosen attributes are based on the case study, and these attributes can be adjusted to meet the requirements for another case study. The selected case study is an architectural office with most interactions taking place for meetings, discussions, and informal meetups. These interactions are directly dependent on the schedule of the meeting, and thus is an important attribute. It was also noted during the literature study that different work and activities have different allowed noise levels. Thus, the type of work or work profile was chosen as one of the essential criteria. For the selected case study, the work is mostly desk work.

The rules were framed in accordance with the ODD Protocol, as studied in Chapter 6.1. The rules crucial to the agent behaviour with respect to the noise were selected and put in the logical framework, as shown in Figure 6.7. It was noted in the literature study that different personality reacts differently to noise distraction (Belojevic & Jakovljevic, 2001). These reactions were put into the framework based on the conditions of the case study.

DEFINITION OF THE MODEL

Purpose - The model is defined to study adaptive human behaviour with respect to the noise in the office space selected in the case study. The model assumes that employees interact and talk in the areas of the pantry, meeting room, and discussion, thus creating disturbance for the employees. These areas are chosen based on the results of the questionnaire. The model at this stage excludes the private interactions which happen on the nearby desks. The results are aimed to provide insight into usage patterns of building together with the noise produced and disturbance caused due to speech in the office. The model ignores sound sources such as appliances and outside noise based on the initial interview and scope of the research, respectively.

Entities, State Variables, and scales – The model is composed of employees as agents, building elements (walls, floors, ceiling, and furniture) as the environment. The agents are low-level state variables with properties of personality types, schedule, initial location, and speech levels. The three personalities are movement personality, control personality, and speaking personality. These personalities can be classified, as shown in Figure 6.6.

The agents' property of speech level varies between three options – normal, raised, and loud. The properties of the agents remain constant through the simulation. The aggregate variables include the current state of the agent, the current position of the agent, the noise level of chosen points. The model works on the spatial grid of 20cm with an agent position accuracy of 0.000001m. The model is simulated at time step of half a second to study the details of the movement if needed.

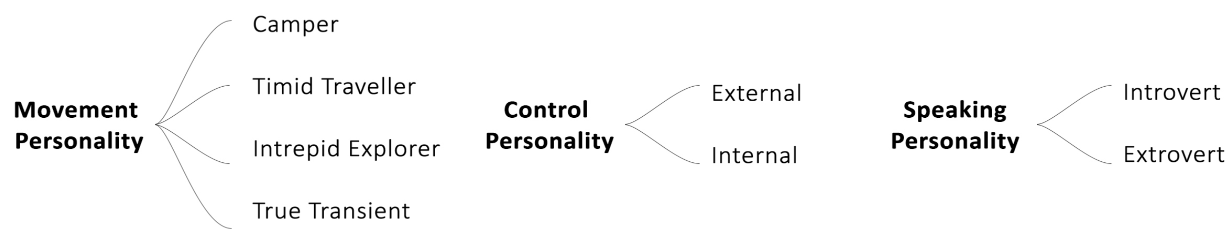

Figure 6,6. Personality traits of the agent.

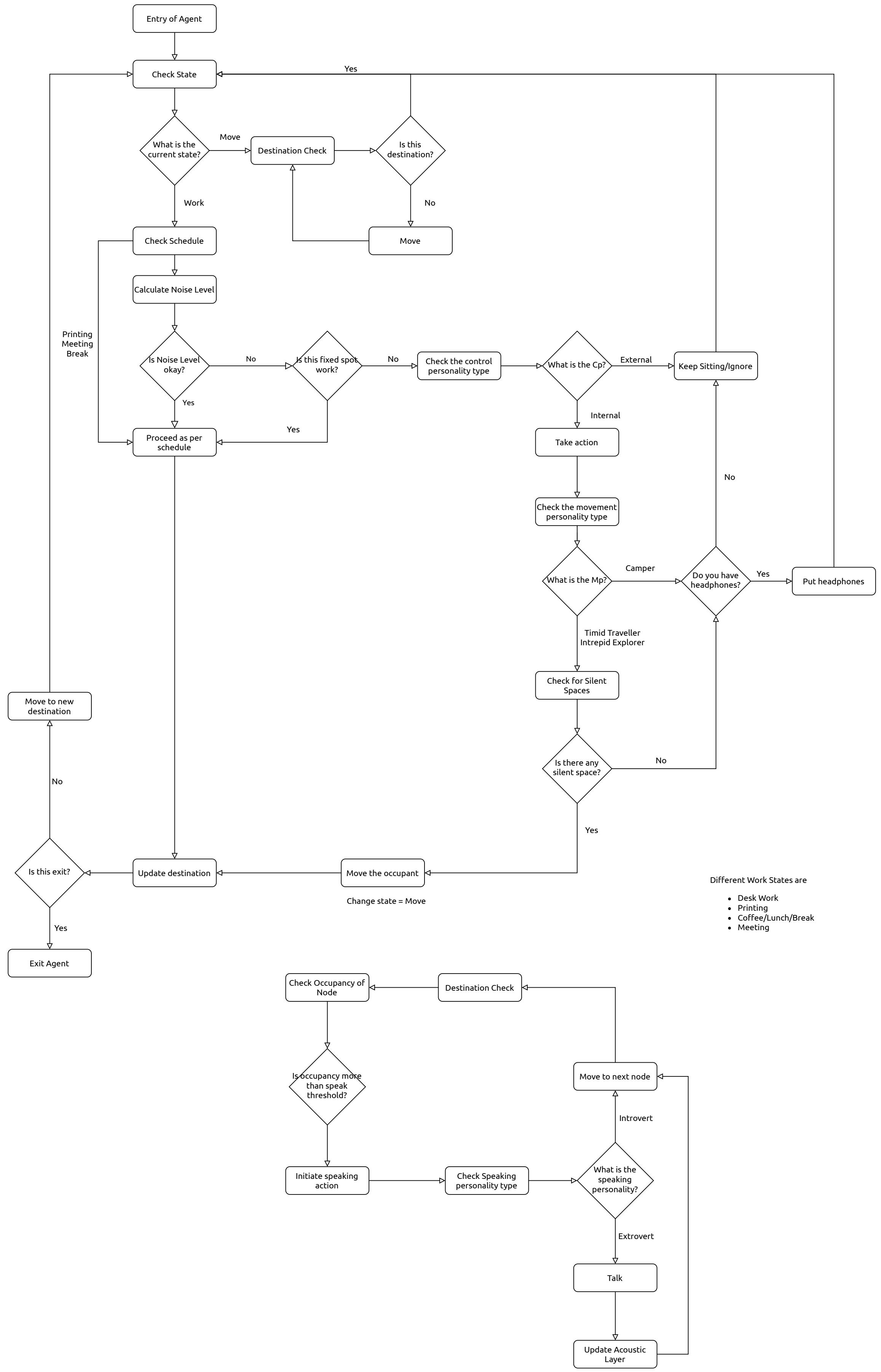

Figure 6.7. The logical framework of the agent decision making.

Process overview and scheduling – The process simulates the movement of the agents and their behaviour patterns concerning the noise in the office. The agent follows a general schedule regarding meetings, breaks, and discussions. The disturbance is initiated when an agent comes in proximity and start talking to each other. The remaining agents take action, either put headphones or ignore the disturbance, based on their personality. The simulation keeps emerging with patterns and noise values based on the decision framework, as shown in Figure 6.7.

Design Concepts – The model uses the design concepts of adaptability, emergence, interaction, stochasticity, and sensing. These concepts form the overall skeletal system of the model by being used in various events during the simulation.

- *Adaptability* – The agents adapt to the noise disturbance either by ignoring noise, putting headphones, or moving to the other place.
- *Emergence* – As the result of adaptive behaviour, the emergent patterns of the users' movement across space are expected to be analyzed as output.
- *Interaction* – The agents interact when they are together for break, meeting, or discussion. These interactions result in the generation of various sound levels across the office by selecting one of the precomputed sound fields.
- *Sensing* – The agents sense the sound levels at their location and react to it following their behavioural traits.
- *Stochasticity* – The agents' schedule involves stochasticity as the events in the daily schedule are not fixed.

Initialization - The model is initiated with each agent at its fixed initial location and personality traits. Each agent is initialized with a schedule which it follows during the course of the simulation. This schedule can be varied to get the results of different events that take place in the space. The noise level of each point is set to zero at initialization. The pre-computed paths and sound fields are also imported during the initialization.

Input and Output – The model receives the input of the state variables from the .CSV files. The inputs are taken for agent properties, schedule, precomputed movement paths, and sound fields. Similarly, the output data is collected in .CSV files for further analysis and visualization.

Submodels – The model relies on two submodels of computational simulation – path tracing and acoustic simulation. The path tracing was performed using the shortest path algorithm in the SpaceAnalysis package of Dynamo. The acoustical simulation was performed in the Pachyderm plugin of Grasshopper to get accurate results.

6.4 SIMULATION WORKFLOW

The logical framework laid down in the previous chapter was then converted to the SyDEVS simulation flow using the node connections. These nodes perform the planned events and unplanned events during the simulation process. The planned events are the usually scheduled work of the agents, while the unplanned event is triggered when an agent is disturbed by the noise. The agent in the simulation reacts when it hears sound more than the threshold noise. The agent reacts by moving to the silent place or by putting on hearing aid (such as headphones) to control the disturbance. The process of acoustic simulation and path takes in the room are computed separately using 3D interface software and then used for simulation flow in SyDEVS. The overall data flow is compiled in Figure 6.8 below.

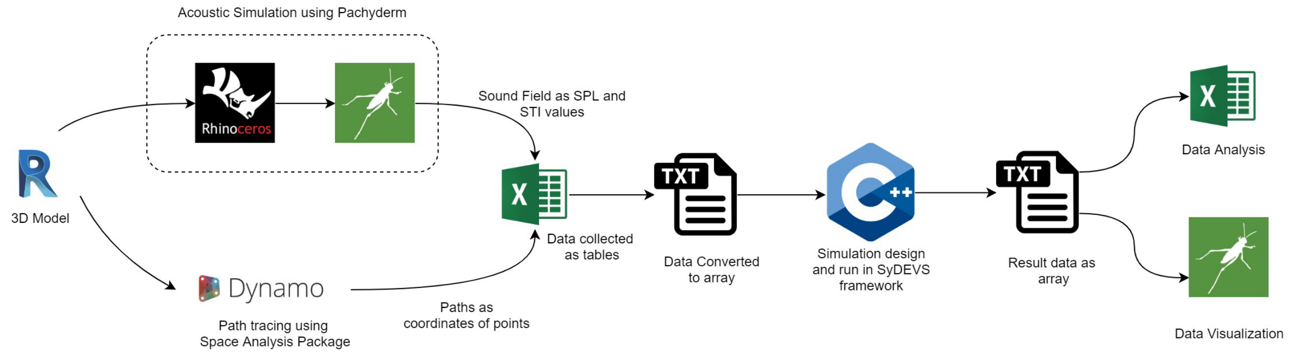

Figure 7.8. Data flow for simulation design.

COORDINATE SYSTEM

Since the simulation workflow consisted of different 3D modelling software, it was important to set up a global coordinate system to avoid any discrepancy in the results. The global origin was set up at the corner of the first floor, and a resolution grid of 20 cm was overlayed for the floor area, as shown in Figure 6.9. The fixed furniture, partitions, walls, and staircases were then highlighted as an obstacle in the grid to perform acoustic simulation and trajectory extraction in the Pachyderm and SpaceAnalysis package, respectively.

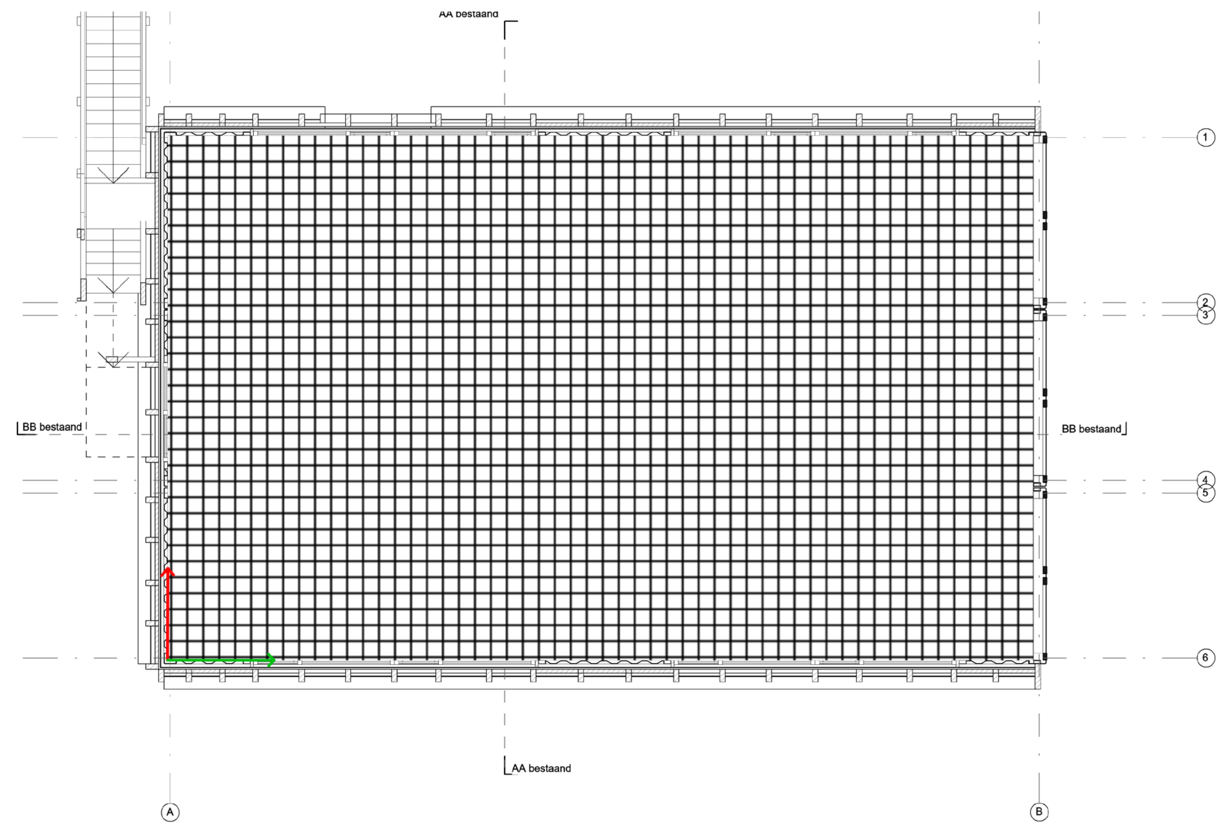

Figure 6.9. Setting the coordinate system on the floor layout with the grid of 20 cm. (Not to Scale)

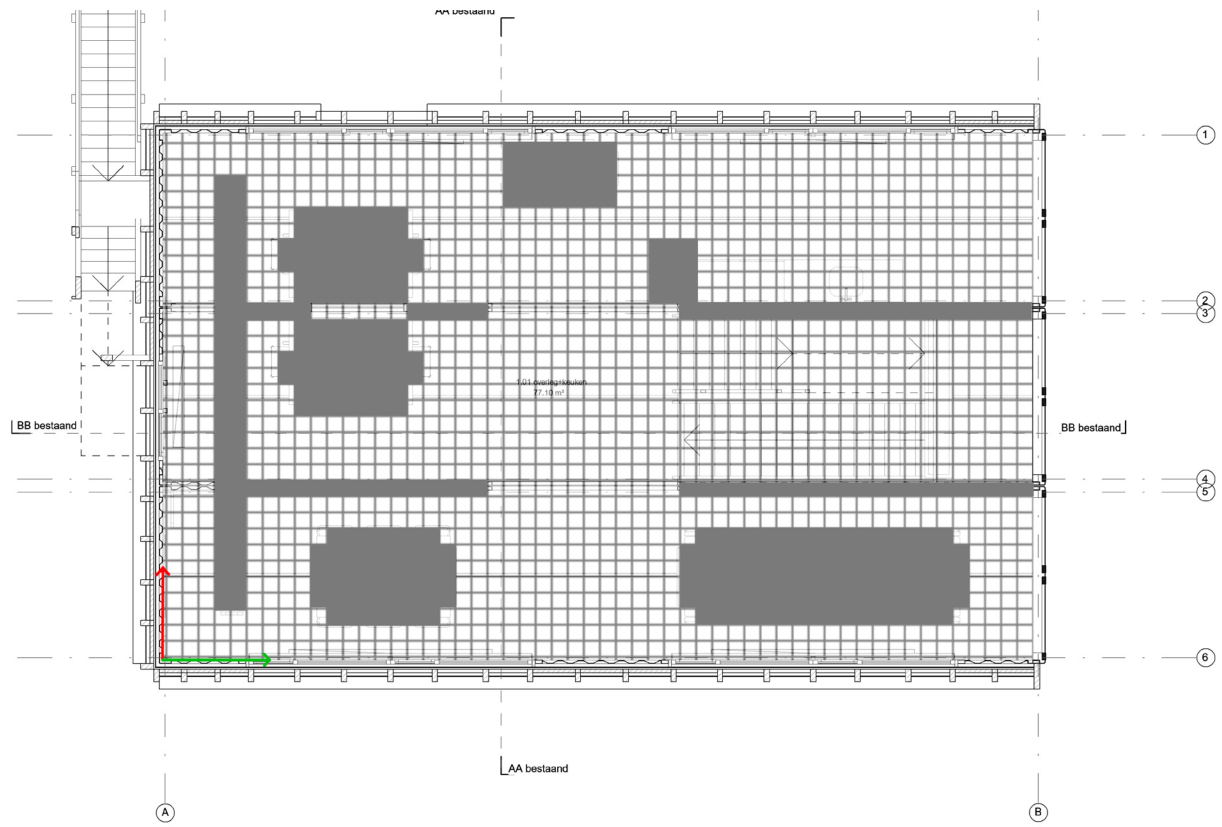

Figure 6.10. Marking grey areas for obstacle detection. (Not to Scale)

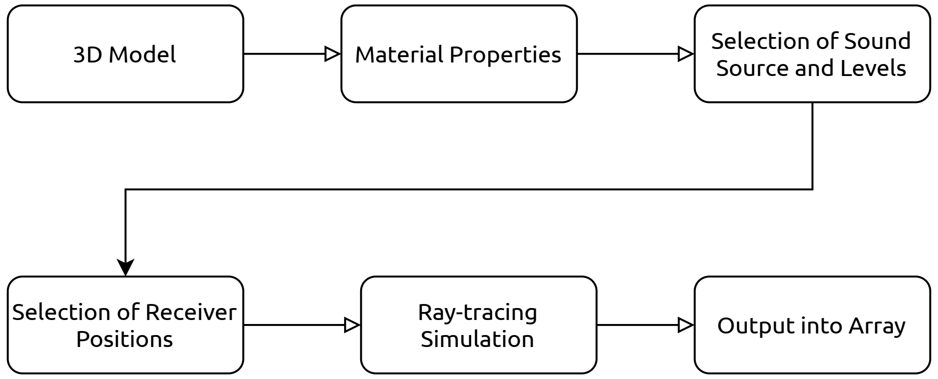

Figure 6.12. Acoustical simulation workflow.

Element	Material	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Floor	Wood	10	15	11	10	7	6	7	7
Ceiling	Wood	10	15	11	10	7	6	7	7
External Walls	Steel	20	30	25	20	10	10	15	10
Internal Walls	Steel	20	30	25	20	10	10	15	10
Occupied Work	Seating +Person	50	60	74	88	96	93	85	80
Unoccupied	Seating	30	35	40	45	50	55	55	50
Column	Steel	20	30	25	20	10	10	15	10

Table 8. Absorption coefficient in %. (Cox & D'antonio, 2009)

Element	Material	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Internal Walls	Steel (Trapeze Profile)	2	2	4	5	22	72	67	60
External Walls	Steel (Trapeze Profile)	2	2	4	5	22	72	67	60

Table 9. Scattering coefficient in %. (Cox & D'antonio, 2009)

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6.5 ACOUSTIC SIMULATION

The acoustic simulation was performed in the Rhinoceros 3D framework using the Pachyderm plugin in Grasshopper. The accuracy of the plugin has been established in various previous researches (Harten, 2011; Wright et al., 2016). The overall process of the entire simulation is highlighted in Figure 6.12. below. The simplified 3D model was created using the detailed BIM model for faster calculations. The model consists of floor, ceiling, external walls, internal partitions, occupied and unoccupied work desk, as shown in Figure 6.11.

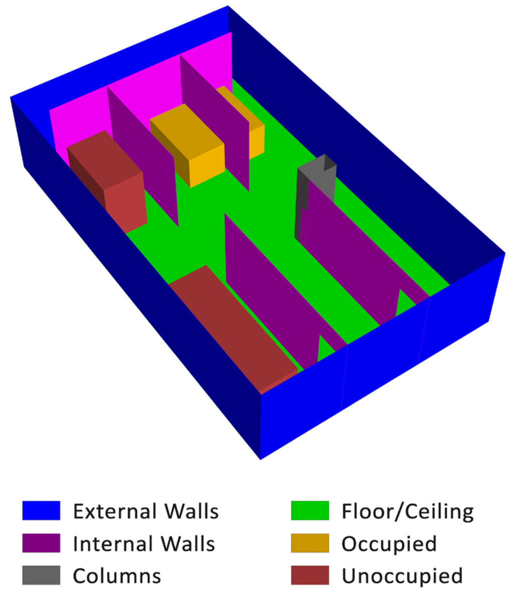

Figure 6.11. 3D model for acoustic simulation.

Based on the literature study, the absorption coefficients (Table 8) and scattering coefficients (Table 9) for the materials were collected. Since the construction of the space was done using shipping containers, the finish of the walls was of a trapeze profile.

After the selection of material properties, the location of a sound source and receiver positions were selected on the floor layout. The receiver positions were selected corresponding to each work desk, as in Figure 6.13, to study the sound levels that each occupant receives when noise is there. The source positions were selected at the pantry area, meeting area, and discussion table as these were the points of noise source according to the questionnaire. (Figure 6.13).

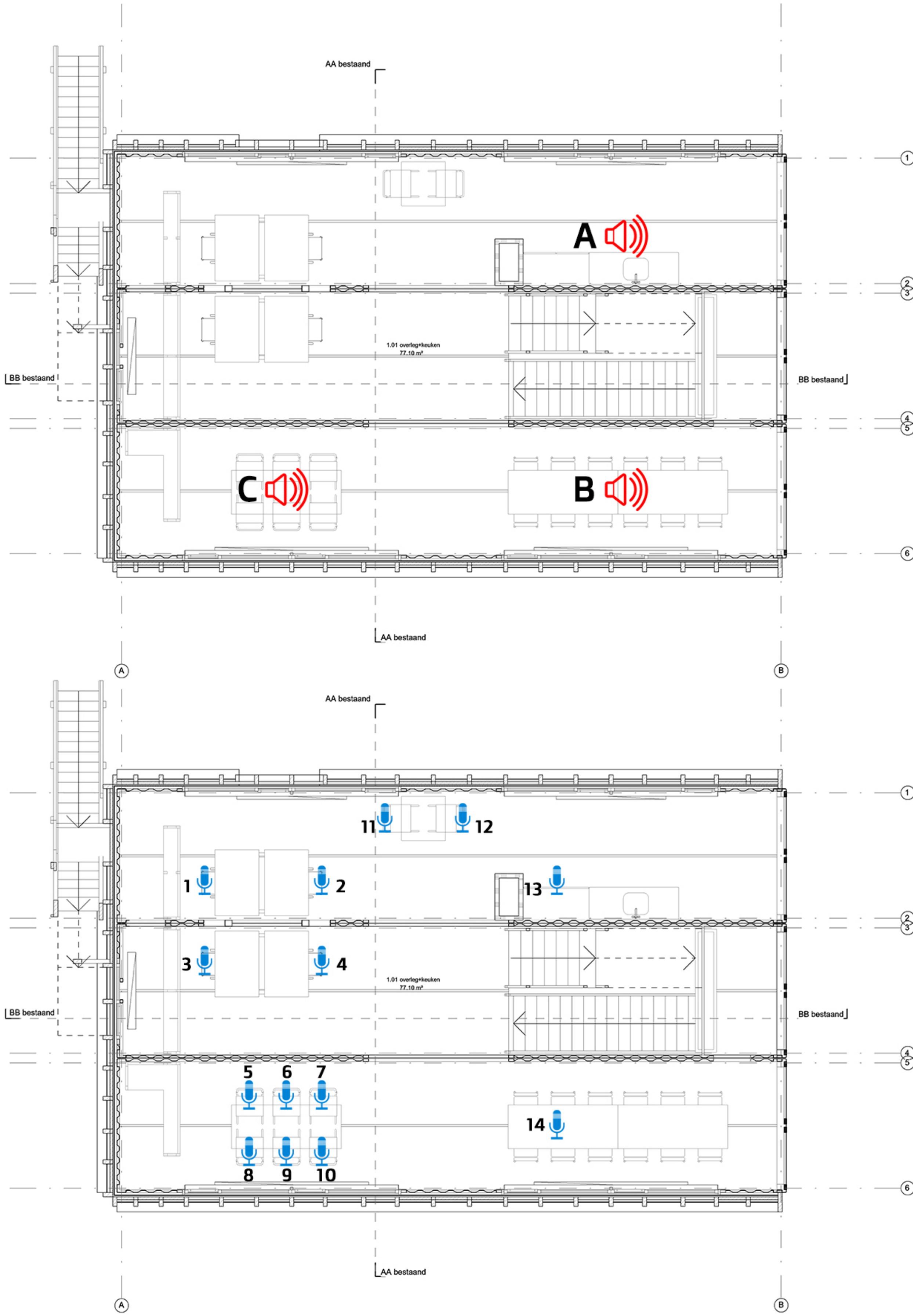

Figure 6.13. Location of source position (top) and receiver position (bottom).

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Following the selection of receiver and source positions, the ray-tracing simulation was performed using the following settings –

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

The calculation was performed with three sound pressure levels of human speech, namely – normal, raised, and loud. (CATT-Acoustic, 2007)

Voice Type	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Normal	47.0	51.2	57.2	59.8	53.5	48.8	43.8	38.8
Raised	51.0	55.5	61.5	65.6	62.4	56.8	51.3	42.5
Loud	54.0	58.0	64.0	70.3	70.7	65.9	59.9	48.9

Table 10. Sound Pressure Levels of human speech used for calculation in dB. (CATT-Acoustic, 2007)

The results obtained from the Pachyderm simulation were then exported to a .CSV file for further use in the simulation workflow. The results obtained for four receiver positions are also tabulated below. The complete results for all the receiver positions are added in Appendix D.

	Receiver Positions								
Source Position	Speech level	1	2	3	4	5	6	7	8
A	Normal	46.9	49	42	43.6	32.9	32.8	38.5	30.8
	Raised	54	56.1	49.3	50.8	40.1	40.1	45.7	38
	Loud	61.3	63.4	56.6	58.1	47.7	47.6	53	45.4
B	Normal	44.7	41.1	45.1	47.5	46	44.4	44.9	45.8
	Raised	51.7	48.2	52.1	54.6	53.2	51.6	52.1	52.9
	Loud	58.9	55.3	59.3	61.8	60.4	59	59.5	60.3
C	Normal	43.6	44.4	37.8	36.5	55.8	56.6	55.9	56.5
	Raised	50.6	51.3	45	43.5	62.8	63.7	62.9	63.6
	Loud	57.6	58.2	52.5	50.9	70.1	70.9	70.1	70.8

Table 11. Simulation results of A-weighted sound pressure level in dB.

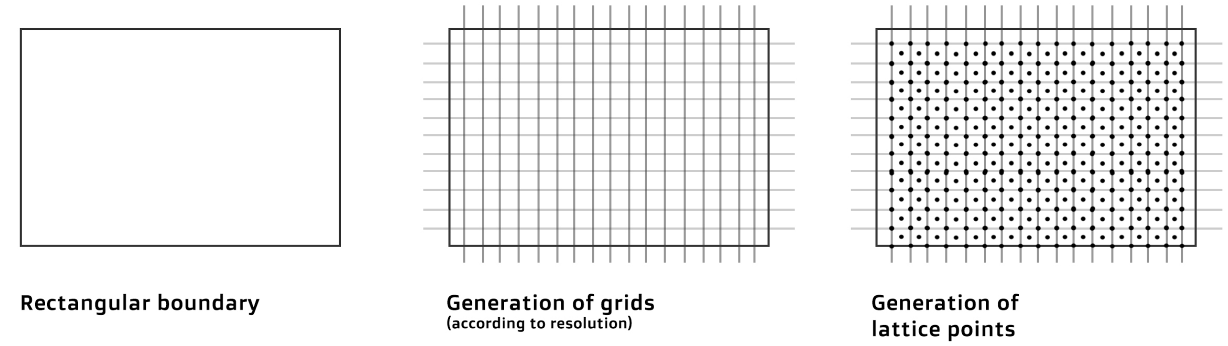


Figure 6.14. Space lattice generation. (Han, 2019)

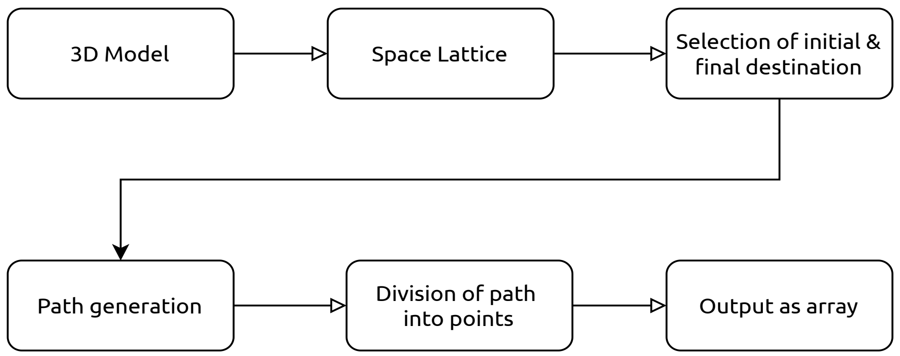


Figure 6.15. Trajectory analysis workflow.

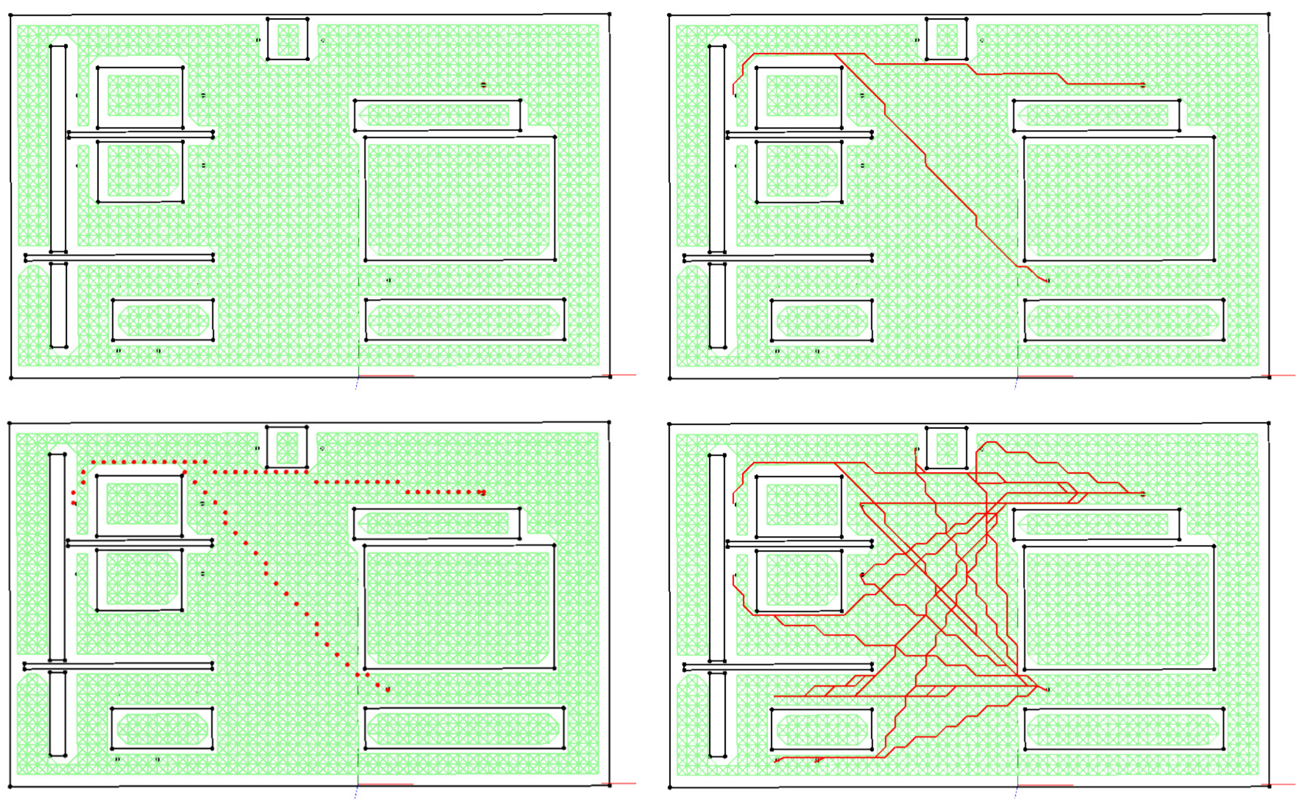


Figure 6.16. Steps are showing the generation of paths across the floor layout using SpaceAnalysis.

Simulation of adaptive user behavior with repsect to noises in offices

6.6 MOVEMENT/PATH TRACING

The possible paths that users take during their work in the office were computed using the SpaceAnalysis package in the Dynamo framework of Revit. SpaceAnalysis package uses a 2D space lattice framework, which divided the surface into the lattice of connected points (Han, 2019). These connected lattice points are also connected diagonally, which allows more iterations to take place to give accurate results (Han, 2019). Figure 6.14. below shows how space lattice is generated using rectangular boundaries.

The Route component of the SpaceAnalysis package returns the shortest path along the space lattice between two points (Han, 2019). The grid size of the lattice is a variable parameter and can be changed for better resolution. The steps involved in the entire process are highlighted below in Figure 6.15.

The outlines from the BIM model were extracted to create space lattice of the walkable area, as shown in Figure 6.16. The initial destination and final destination points are selected to generate the path along the lattice. The algorithm calculates this path through shortest path algorithms by selecting the path having the least count of Space Lattice points. A curve is then generated by connecting these points. This curve can be smoothened using resolution values for different applications.

Since the walking speed of a person is usually 1.4 m/s (Bohannon & Williams Andrews, 2011), thus the path was divided into points at 0.7m distance for 0.5s time step. The 0.5s time step was decided in conjunction with the simulation workflow. The simulation model updates the model in every 0.5s time step. This timestep was selected to create enough data to interpolate the results and animation. The data generated and simulation time is inversely proportional to the time step. This process was then repeated for all the possible paths on the floor. The coordinates of all the points of the paths were then extracted into .CSV files.

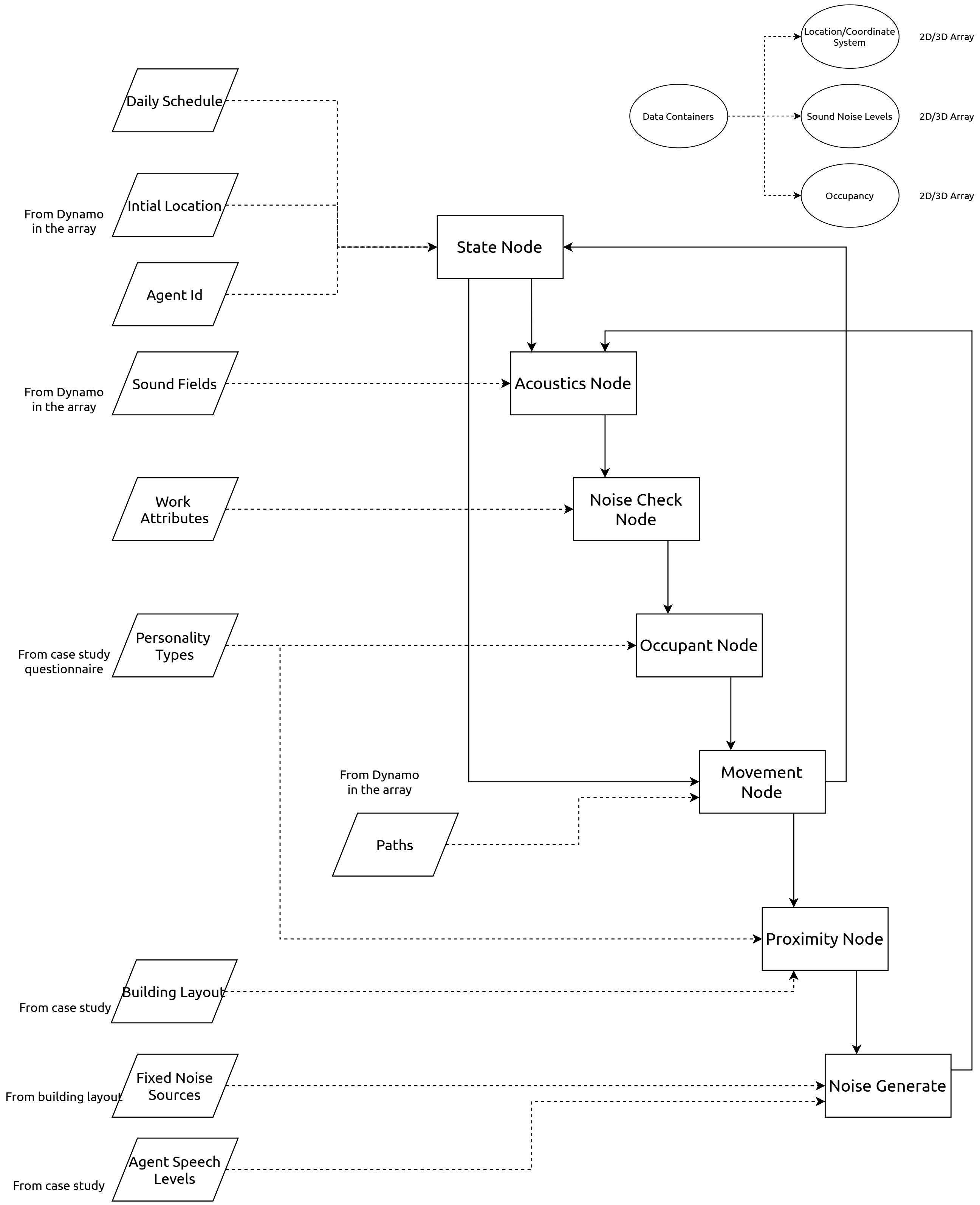


Figure 6.17. Dataflow for Prototype I of the simulation model.

6.7 PROTOTYPING

The data collected from the acoustic simulation and path tracing acts as the input for the simulation flow in SyDEVS. The prototype of simulation models was created and tested in the SyDEVS framework. The prototypes were improved with each step, making learning from the previous model. As discussed in Chapter 6.2, the simulation in SyDEVS is performed with the use of various nodes and their dataflow.

PROTOTYPE I

The first prototype was designed with seven nodes sharing data across each other at different events, as shown in Figure 6.17. These nodes make their decision based on the rules made in Section 6.3. and the information received from the input nodes. State Node would perform the check of the state of the agent following the schedule and send the message to the movement and acoustics node. The acoustics node would select an appropriate sound field from the computed sound fields when it received a message from the state or noise generate node.

The noise check node will check if an agent is disturbed according to the selected sound field. It will trigger the action for the agent who is disturbed. The occupant node, based on its personality, decided to take action by moving to another place or ignore the noise disturbance, passing on the information to proximity node to process if two agents are nearby to talk. If the two agents with a specific personality were found together, they would talk, and this action was performed in the noise node.

During the test run of the model with one agent, it was observed that the logic might be correct in the dataflow, but the time component was not ordered correctly. State Node and Movement Node were time-bound nodes, which means they are updated every time step, or they consume some time on a real scale. All the other nodes performed decision making actions taking zero time on the real scale. Thus, the two separate time-bound nodes created unexpected results and added complexity to the model. The two different nodes executed events in a difference of time step as movement node depended on state node for data information. It was observed that merging the two in a single node would be a better solution

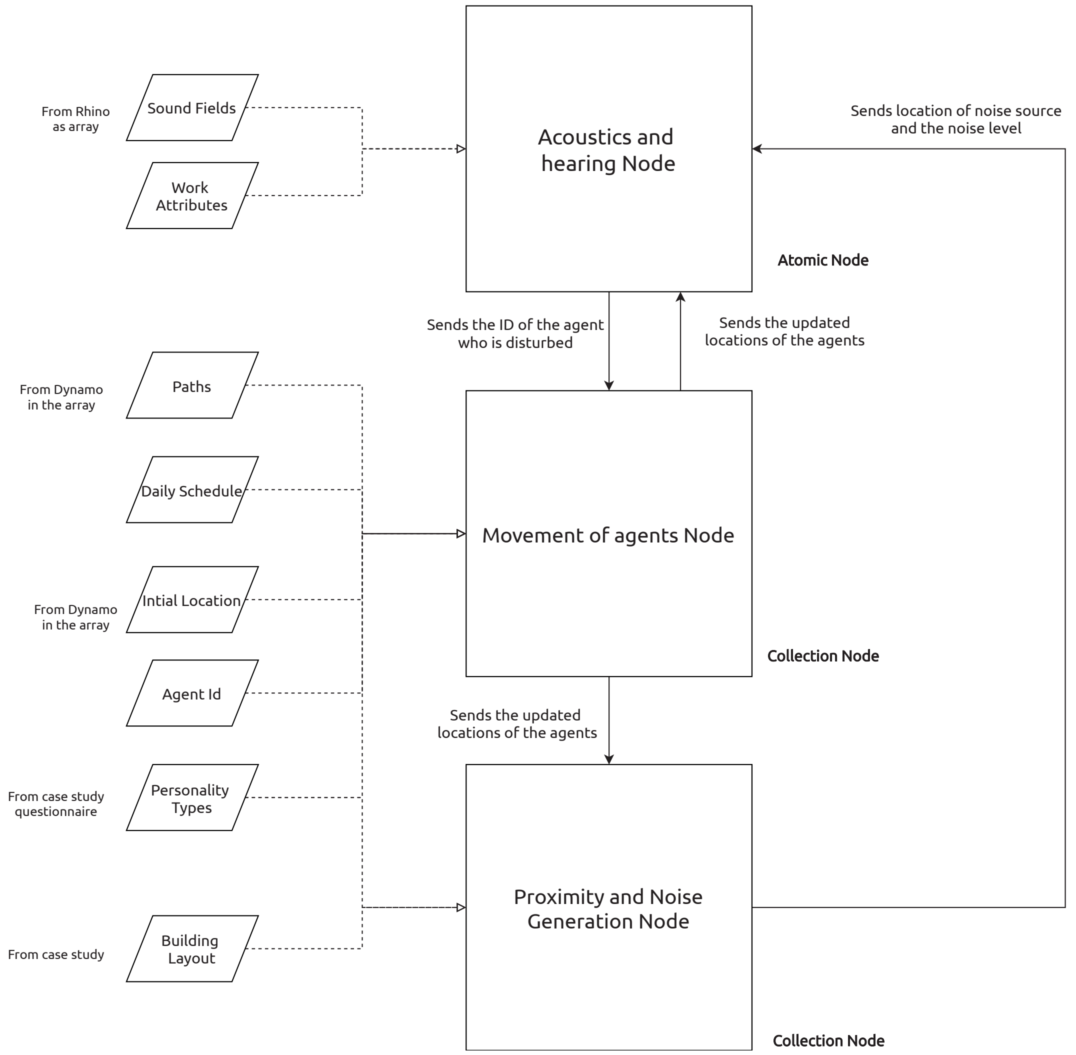


Figure 6.18 Dataflow for Prototype II of the simulation model.

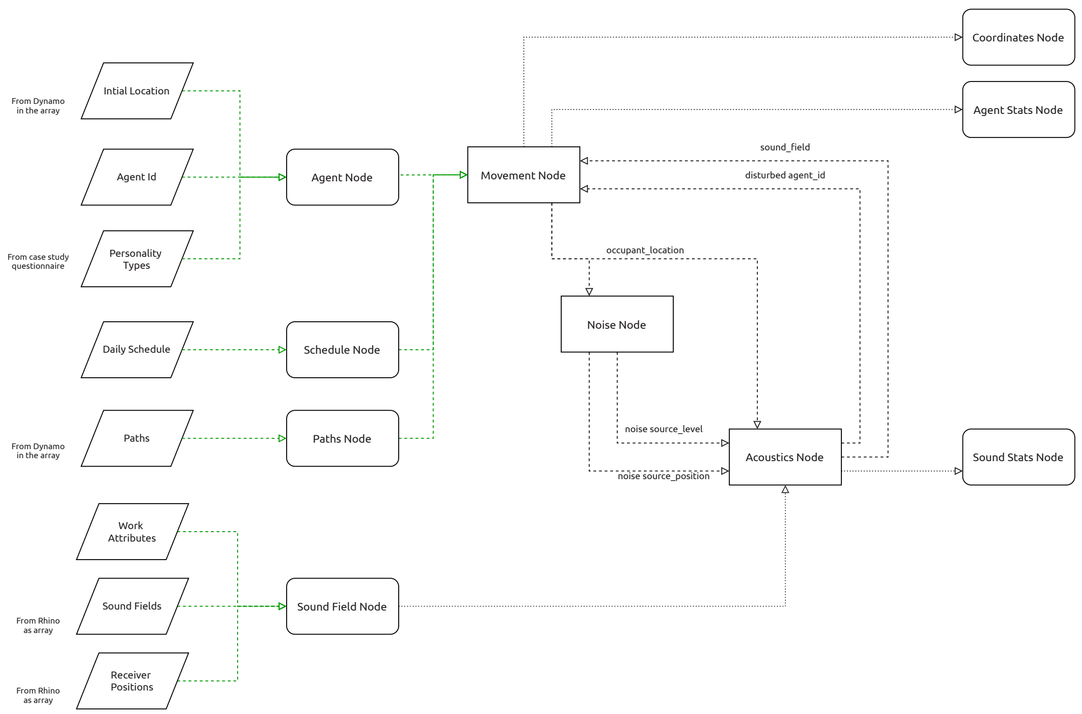


Figure 6.19. Dataflow for Prototype III of the simulation model.

Simulation of adaptive user behavior with repsect to noises in offices

PROTOTYPE II

Following the learnings from the first prototype, the improvements in the dataflow were performed. The state node, movement node, and the occupant node were merged into one to improve time-bound data decisions. The remaining nodes were also merged logically to create the simulation dataflow into three primary nodes, as shown in Figure 6.18. The improved dataflow now performed the sharing of messages in a cyclic fashion.

The test run showed that the model performed better now with movement node and noise node working with according to the expectations. The problem was noticed in the acoustics node when it simultaneously received a message back from movement and then from the noise node. This would create an overlapping situation where the acoustics node would miss one message creating the lag of one time-step in the loop. It was learned from the prototype that the order in which messages are delivered is crucial.

PROTOTYPE III

In the second improvement process, learning from the previous prototype was implemented. The order of dataflow was readjusted to create unidirectional dataflow. In the Prototype III, the transfer of event information followed top to down approach closing the loop at last, acoustic node. Also, the category of the node was improved with Movement node modelled as a collection node, while noise and acoustics node as atomic nodes. Input and Output function nodes were also added, completing the data flow, as shown in Figure 6.19.

The test run of this prototype yielded expected results on observation and was thus then selected for the final simulation of 8 hours of office day. The final simulation was conducted by importing the data about the case study, occupants, sound fields, and trajectories through additional function node. The input node received the information from .CSV files exported from sound simulation computed paths and agent information. The output node gave the results in the form of raw data saved as .CSV file. This data was then taken into Excel and Grasshopper for data analysis and visualization.

FINAL PROTOTYPE

Following the test run of Prototype III, the minor bugs were fixed, and multiple agents were added in the final prototype by converting movement node to a type of collection node. The final dataflow consists of one collection node, two atomic nodes, and eight function nodes, as shown in Figure 6.20.

The following table shows the pseudocode/logic used for each node. The unplanned event is triggered when the node receives an incoming message from the other node. The planned event is triggered after the unplanned event every time.

The pseudocode explains the main logic behind the simulation nodes. The detailed code and the working files can be found on the repository on the link –
https://gitlab.com/divyae.iitr/acoustic-simulation-in-offices

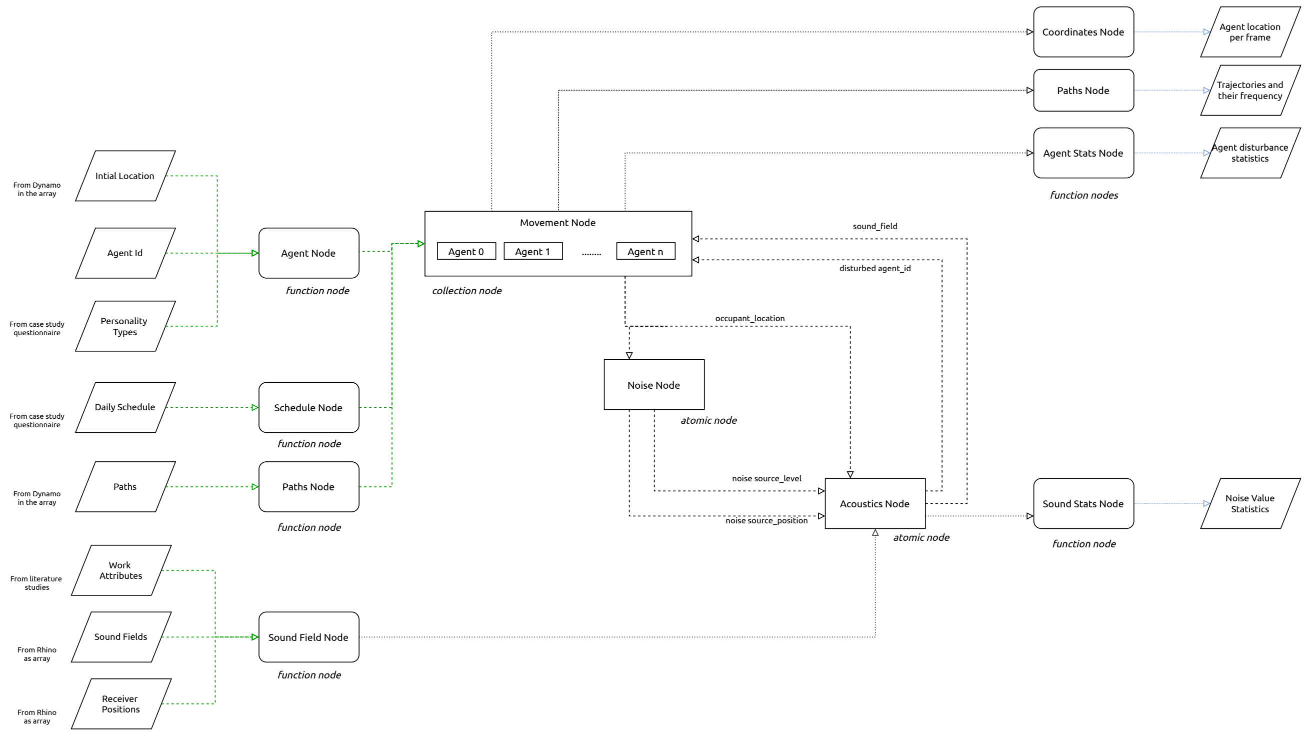


Figure 6.20. Dataflow for the final simulation model.

Simulation of adaptive user behavior with repsect to noises in offices

Acoustics Node
Unplanned Event - (updates the current sound field with mentioned noise)
source position = input.sourceposition
source level = input.sourcelevel
for index = 0
if index = source level
if index = source position
SF = CF [index]
Planned Event - (checks if the noise level is above threshold)
FOR EACH AGENT
curr_pos = input.currpos
for i = 0
if noise_pos [i] = curr_pos
return i
if SF [i] > threshold
return agentid

Noise Node
Unplanned Event – (checks the location of the sound source)
check curr_pos
if curr_pos = pantry
add n_pantry
if curr_pos = meeting
add n_meeting
if curr_pos = discussion
add n_discussion
if n_pantry > 1 select source = pantry
if n_meeting > 0 select source = meeting
if n_discussion > 0 select source = discussion
Planned Event – (sends messages to other nodes)
output.sourceposition
output.sourcenoise

Movement Node/Agent Node – It is repeated inside the collection for each agent.

Unplanned Event – (Checks the action of the agent)

```
if (cp = external)
  ignore ++
else if (cp = internal)
{
    if (mp = camper)
        headphone++
    else if (mp = traveller)
        dest_pos = call silentspace()
            if (dest_pos = curr_post)
                headphone++
            else
                call move()
}
```

Planned Event – (performs actions according to the state)

```
FOR EACH AGENT
if state = work
    if (curr_pos = init_loc)
        dest_pos = curr_pos
    else
        dest_pos = init_loc
        call move()
if state = meeting
    if (curr_pos = meeting room)
        dest_pos = curr_pos
    else
        dest_pos = meeting room
        call move()
if state = break
    if (curr_pos = pantry)
        dest_pos = curr_pos
    else
        check(n_break)
        if n_break < limit
          dest_pos = pantry
          call move()
if state = move
    if (curr_pos = dest_pos)
           end move()
    else
           next_pos = path[i]
           curr_pos = next_pos
           i++
```

Helper Functions

```
move(dest_pos, curr_pos, final state)
{
    select path[] // array of points
    return path
    i=1;
}
silent space (work, curr_pos, SF)
{
     for SF[i]
          if (sound_level) < req
               if vacant() = true
                    return pos[i] // pos at i index of sound field
               else
                    return curr_pos
}
```


6.8 VISUALIZATION

The simulation model is capable of yielding numerous data, and thus it is vital to know how to analyze the data. Data visualization helps the users of the simulation model and data analysts to analyze the results effectively with a better understanding (Friendly, 2008; Ward et al., 2010).

The final step of the simulation workflow consists of the visualization of the output results from the simulation. The output results collected were the coordinate position of agents at each time step, disturbance time of agent in time steps, and noise levels at different time steps at various points. The data collected from the simulation in the previous step was analyzed using visual representations on the 3D floor layout. Three primary data visualizations were proposed to explain the results adequately.

Trajectories - It was done using the Grasshopper plugin, where the usage of trajectories was produced using a gradient map. The frequency of each trajectory used was calculated and then mapped with gradient colours and line thickness.

Occupancy – The data collected as the coordinates of each agent were then visualized on the floor plan with dots visualization. The radius of the dot and colour convey the duration of the occupancy of the respective location.

Noise – The distribution of the noise levels over the floor layout was done for the respective receiver positions. The radius of the dot and the colour represented the number of average noise levels received at the point. In addition to the spatial visualizations, statistical visualizations and analysis were also performed and are discussed in Section 7.2.

Movement Animation – The timestamped data of coordinate positions of the agents was collected from the simulation. The coordinate data was then taken to the 3D game engine, Unity 3D to visualize the movement with varying speeds. The animation could help architects understand the patterns and congestion in the space when multiple users move through space at the same time. The results of the animation for case study A are discussed in the Section 7.2.

7. SIMULATION RESULTS

Chapter Overview

After the prototyping phase, the simulation was tested using the case study. This chapter presents the results obtained from the simulation model. It also presents the analysis methods used and inferences that were observed from the results. The chapter first discusses the results of two model of case study A followed by the sensitivity tests.

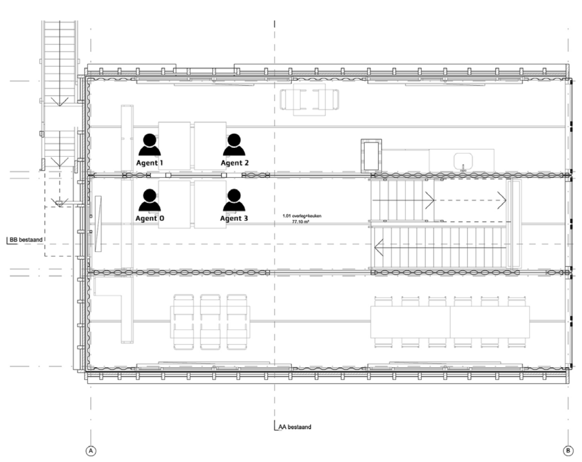


Figure 7.1. Agent positions on the first floor.

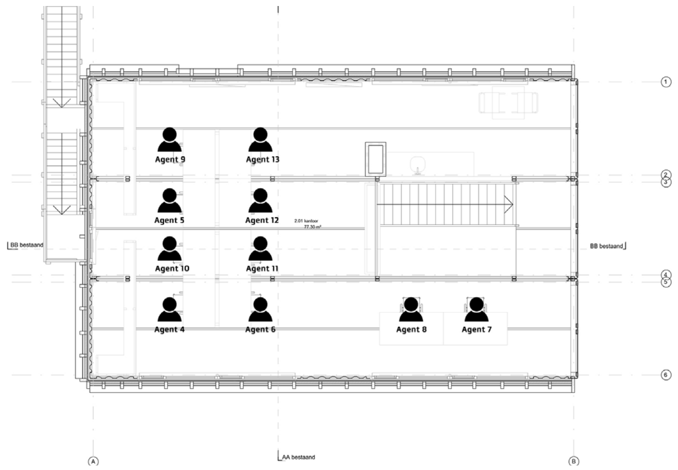


Figure 7.2. Agent positions on the second floor.

Agent ID	Movement Personality	Control Personality	Speaking Personality	Speech Level
Agent 0	Intrepid Explorer	Internal	Introvert	Raised
Agent 1	Camper	Internal	Extrovert	Raised
Agent 2	Camper	Internal	Extrovert	Raised
Agent 3	Intrepid Explorer	External	Extrovert	Raised

Table 12. Personality traits used for simulation of single floor model.

Agent ID	Movement Personality	Control Personality	Speaking Personality	Speech Level
Agent 4	Intrepid Explorer	Internal	Extrovert	Raised
Agent 5	Camper	Internal	Extrovert	Raised
Agent 6	Camper	Internal	Introvert	Raised
Agent 7	True Transient	Internal	Introvert	Raised
Agent 8	Camper	Internal	Introvert	Normal
Agent 9	Camper	External	Extrovert	Normal
Agent 10	Intrepid Explorer	Internal	Introvert	Raised
Agent 11	Camper	Internal	Extrovert	Raised
Agent 12	Camper	Internal	Introvert	Raised
Agent 13	Intrepid Explorer	Internal	Introvert	Raised

Table 13. Personality traits used for simulation of double floor model.

Simulation of adaptive user behavior with repsect to noises in offices

7.1 SIMULATION TESTS

During the last phase, the final prototype was tested with two strategies – a single floor model and a two-floor model. Both the models study the disturbance caused on the floor layout when agents interact during the break, meeting, and discussion. It is noted that there could be more interactions that take place between employees but are excluded in the scope of this model due to the limited number of agents and unavailability of real-time measurements.

SINGLE FLOOR MODEL

The single floor model was tested for the first floor of the case study office, with four agents working there. The single floor model was also tested for sensitivity analysis by creating variation in input parameters. The agent input properties were considered from the result of the questionnaire, as discussed in Section 4.2 and are also highlighted in Table 12 below. The input parameter, schedule of the agents, was also prepared using the insights from the questionnaire.

The sound field and path trajectories were imported from the.CSV data, as shown in Figure 7.1. The schedule of the agents was planned in accordance with the responses to the questionnaire. The threshold value for disturbance was considered at 45dB in accordance with the architectural standards, as discussed in Table 3. It is noted that threshold value can be more or less depending on the type of office, type of work and preferences. For the development and verification of the model, the threshold value considered was 45dB.

DOUBLE FLOOR MODEL

The double floor model was tested with 14 agents, four on the first floor, the same as a single floor model, and the remaining sitting on the second floor, as shown in Figure 7.2.

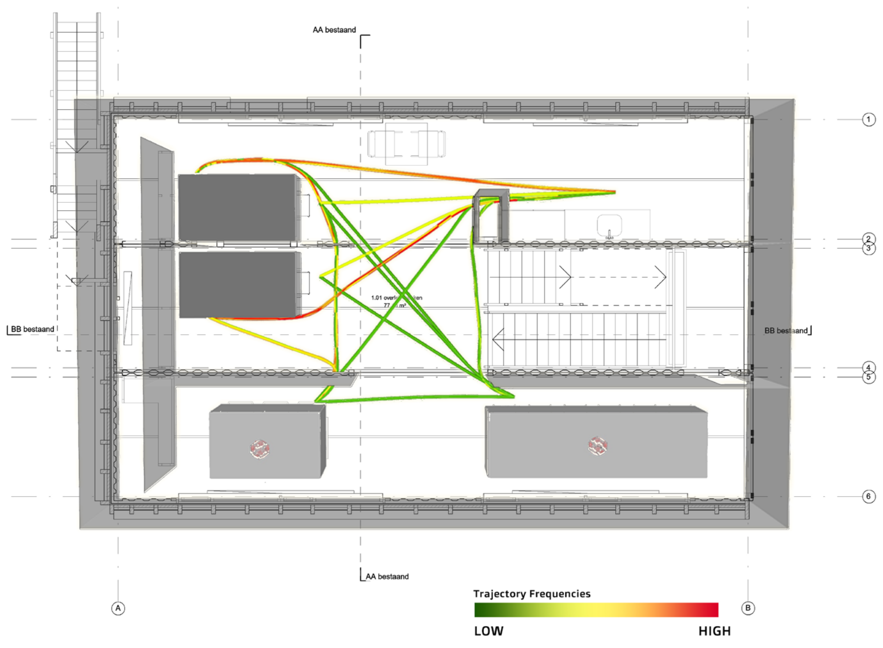


Figure 7.4. Trajectory results in visualization.

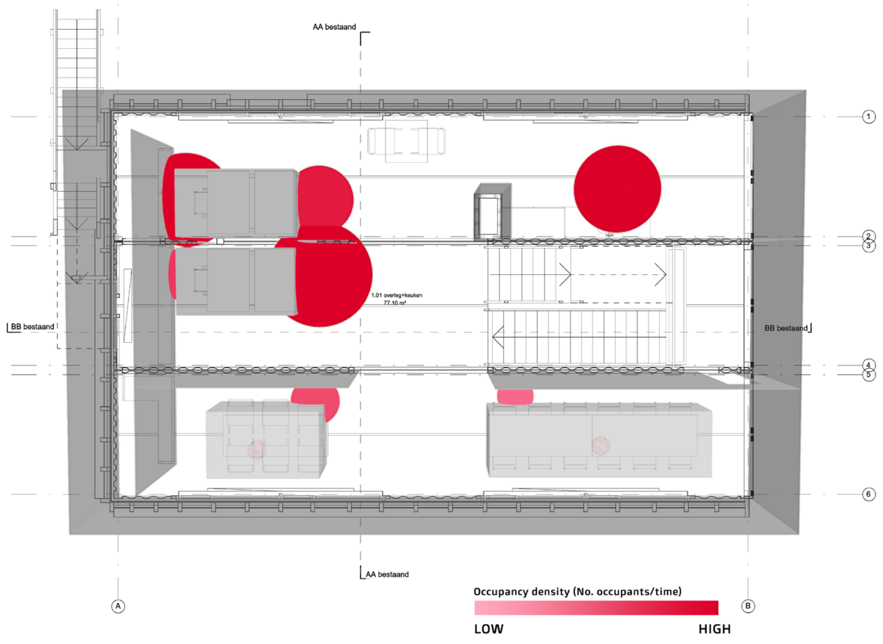


Figure 7.5. Occupancy density results.

7.2 ANALYSIS AND VISUALISATION

SINGLE FLOOR MODEL

The results of the simulation showed that the agent with ID = 0, was disturbed the least with 44.8 minutes at its work desk. The agent with ID = 1, was most disturbed for 133.6 minutes.

The remaining agents with ID = 3 and ID = 4 were disturbed for 119.7 and 89.6 minutes, respectively. In accordance with control personality, an agent with ID = 3, ignored the disturbance while other agents preferred to put headphones the entire time.

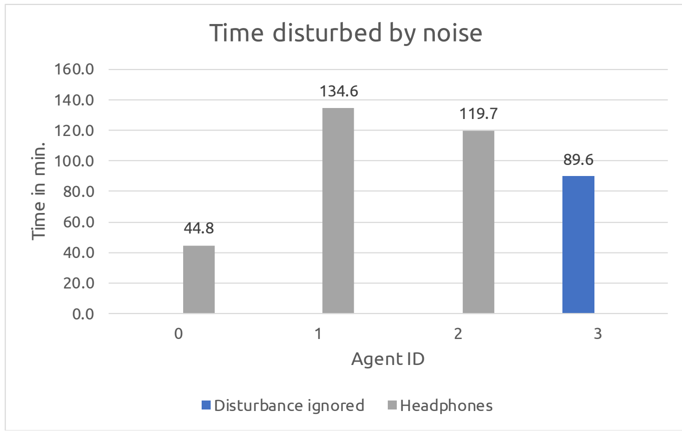


Figure 7.3. Noise disturbance time results.

The trajectory analysis shows that a high amount of movement happens in the middle part near the work desks, as highlighted in Figure 7.4. As expected, the agent with ID = 0 moved a lot from the workspace to the pantry for breaks, which is also verified by the 'intrepid explorer' personality. The agent with ID = 1, also moved a lot to the pantry as the preference was to grab a coffee before the meeting.

The simulation result also showed occupancy density, as shown in Figure 7.5. in the pantry area higher than meeting room or work desks, suggesting that more people gathered near the pantry area. Occupancy Density here is measured by the cumulative presence of agents at that location. It was also noted that agent with ID = 3 spent a large amount on the desk with fewer meetings, as suggested in response to the questionnaire.

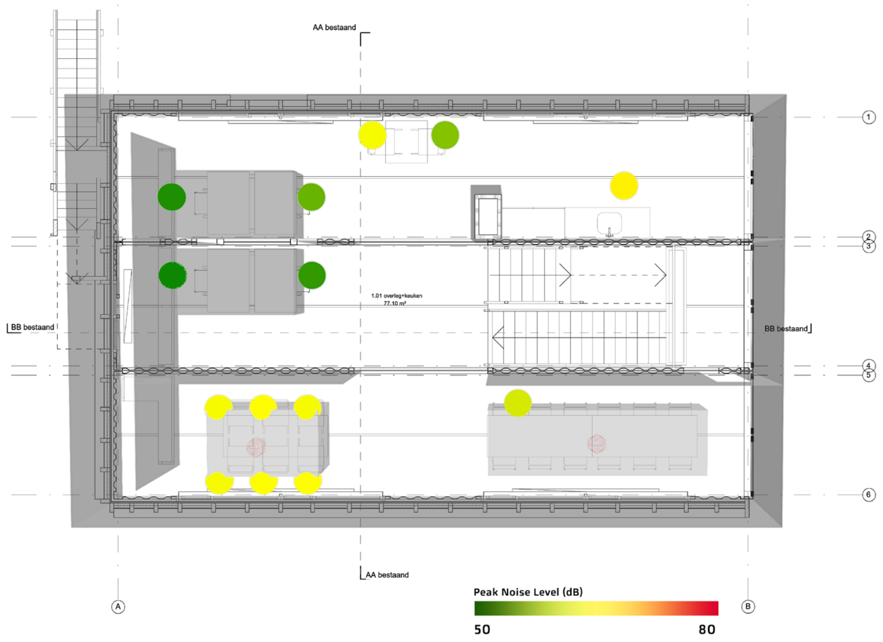


Figure 7.6.a. Peak noise values.

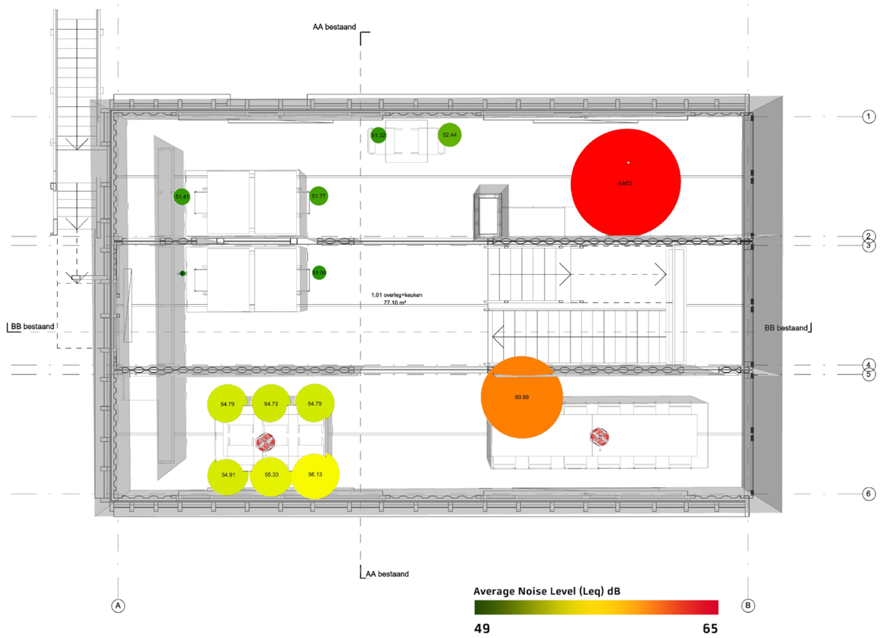


Figure 7.6.b. Average noise values.

The maximum noise for each receiver point was also plotted, as in Figure 7.6.a. It was noted that the work desk received peak noise in the range of 50-55 dB while meeting area, discussion area, and pantry area had peak noise values in the range of 65-70 dB. The peak noise results show the maximum noise the receiver point received for the entire day simulation. It can be concluded that the agent got disturbed at least once if the peak noise value is above the threshold value.

The output of the model also resulted in data about noise variation over time at a particular receiver point in the office. It was observed at agent 0's position that there was increased noise disturbance at the beginning of the day, followed by high noise during lunchtime and evening discussions.

The final output data was then sent for the movement visualisation. The visualisation shows how the users moved in the space and their trailing path. The snapshots show the instances of agents movement and generation of noise during different times of the day. The snapshots of visualisations are shown on the next page.

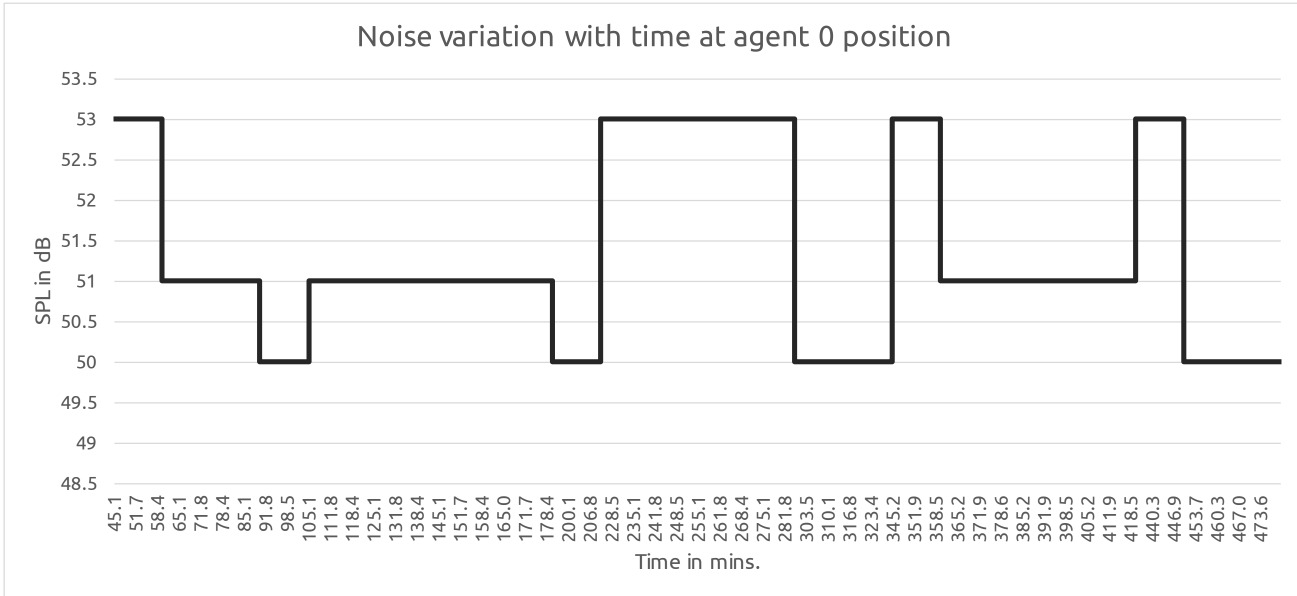
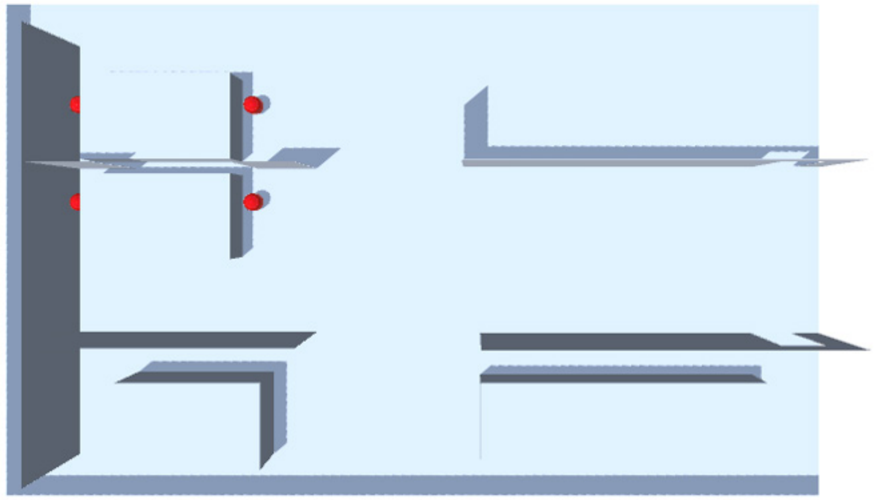
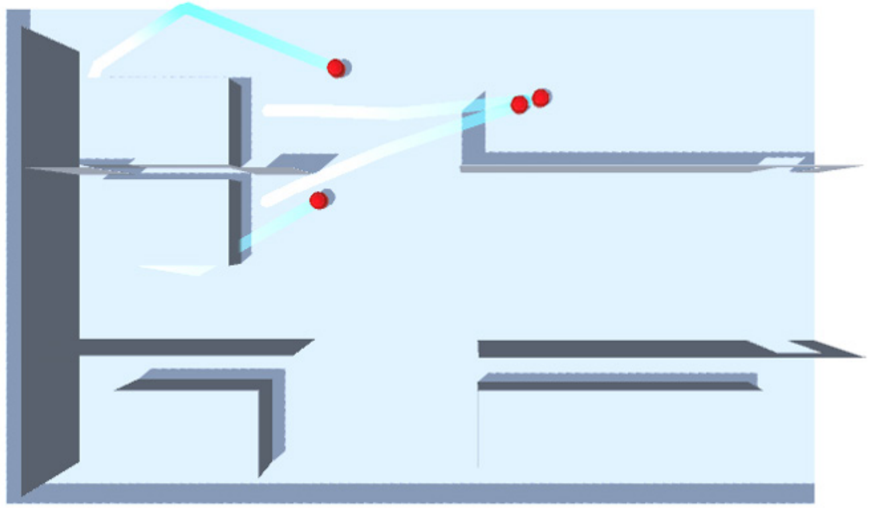


Figure 7.7. Variation of noise levels with time.

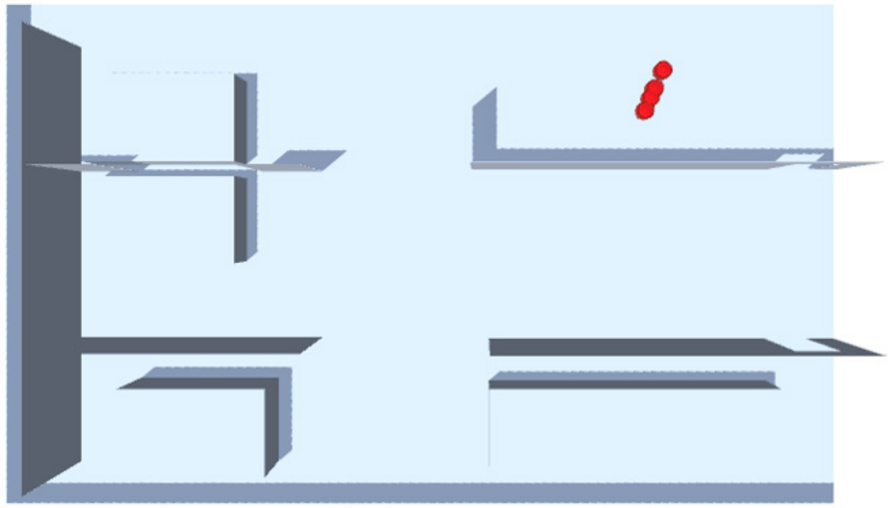
Simulation of adaptive user behavior with repsect to noises in offices



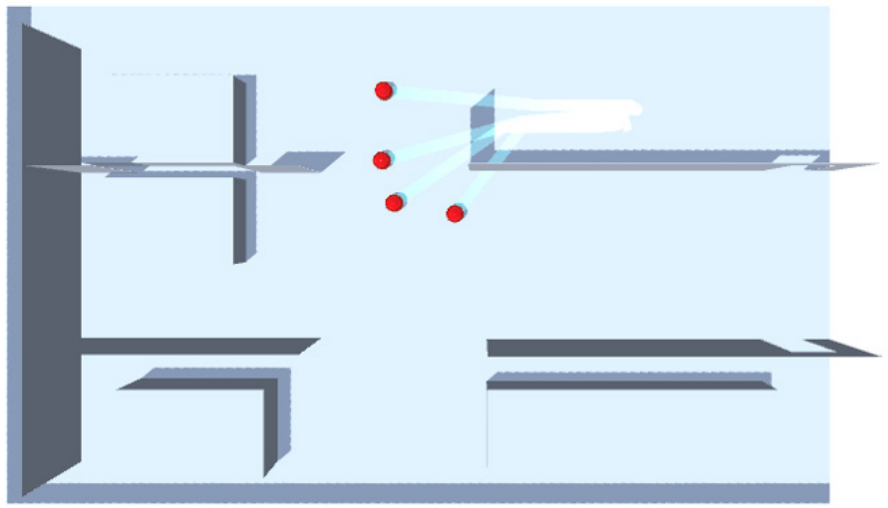
A. Snapshot at T = 0 mins.



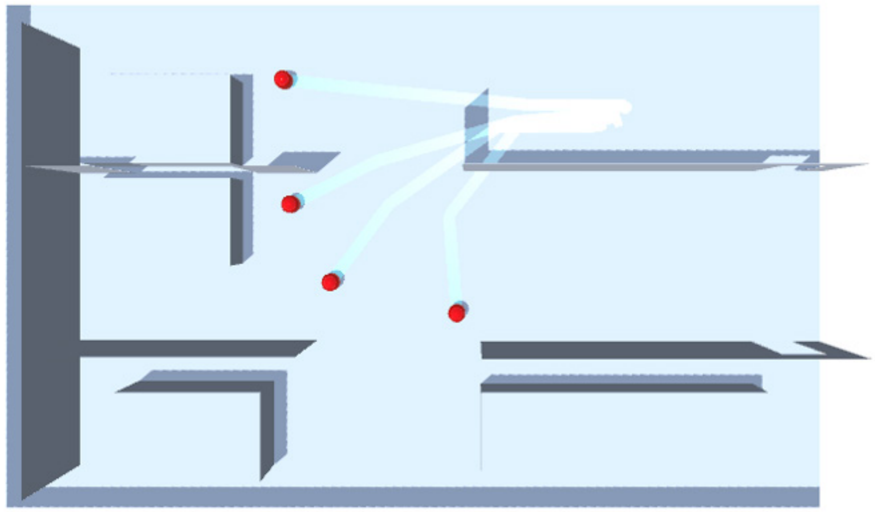
B. Snapshot at T = 45 mins.



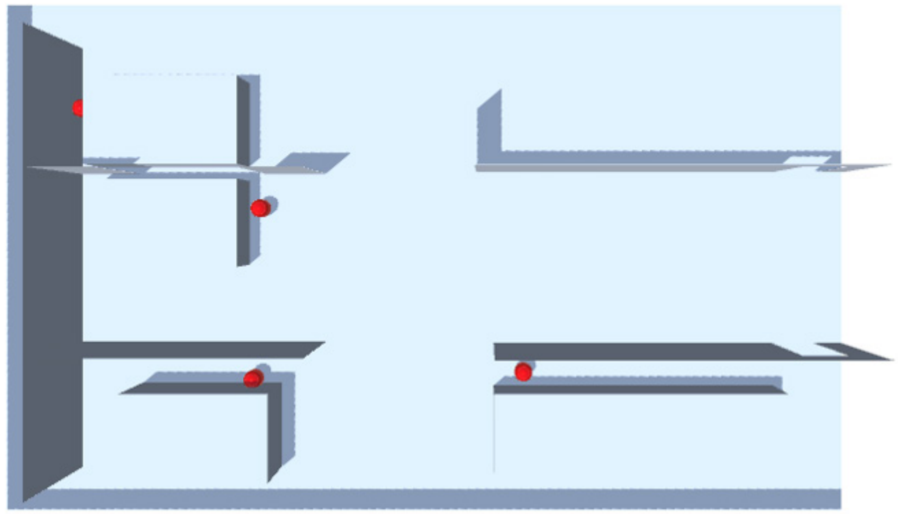
C. Snapshot at T = 45.1 mins.



D. Snapshot at T = 60 mins.



E. Snapshot at T = 60.1 mins.



F. Snapshot at T = 65 mins.

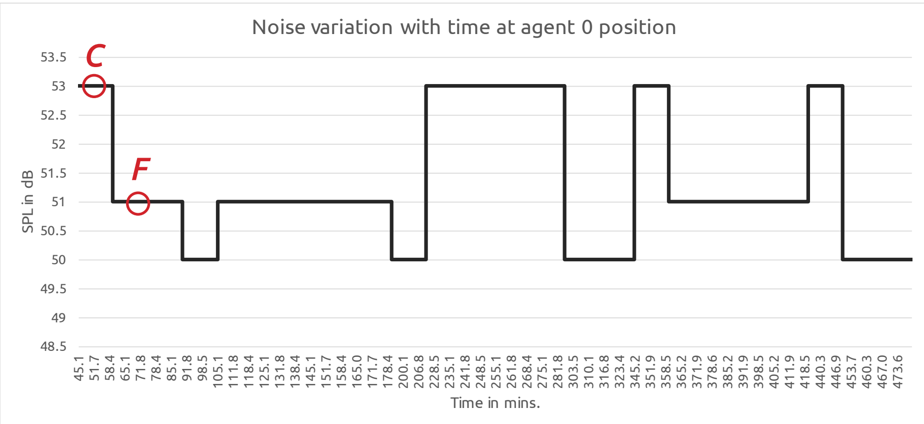
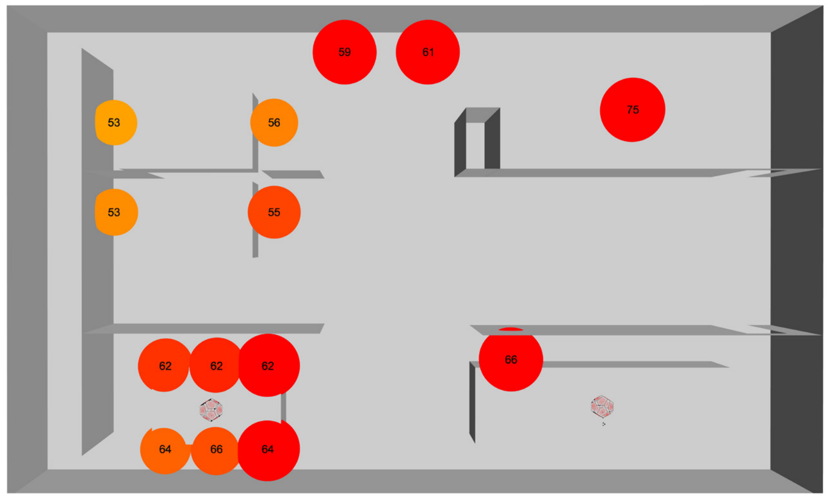


Figure 7.7. Variation of noise levels with time.



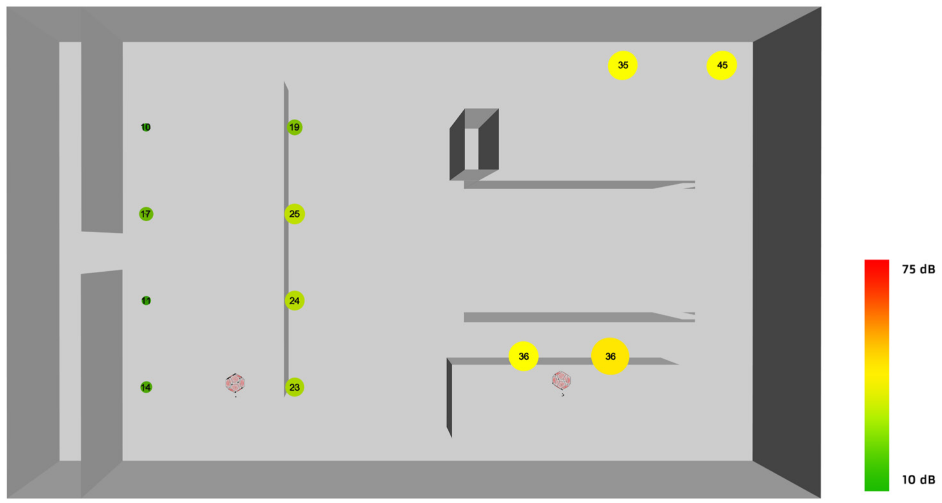


Figure 7.9. Peak noise values for the double floor simulation.

Simulation of adaptive user behavior with repsect to noises in offices

DOUBLE FLOOR MODEL

The results of the double floor model showed that agents on the first floor got disturbed by the noise in the range of 45 minutes to 150 minutes. The agents on the second floor were not disturbed as the activities under study break, meeting and discussion were taking place on the first floor. This was also suggested by the responses of the employees to the questionnaire as they held a meeting on the first floor or grabbed coffee downstairs. (Appendix D)

The peak noise results also showed that the peak noise level for the top floor stayed below 45dB. This value was set as the threshold for the disturbance. This means for lower threshold value; the disturbance would be felt on the upper floor as well. It was also noted that peak noise level reached 75dB in the pantry, suggesting it to be the noisiest area in the office.

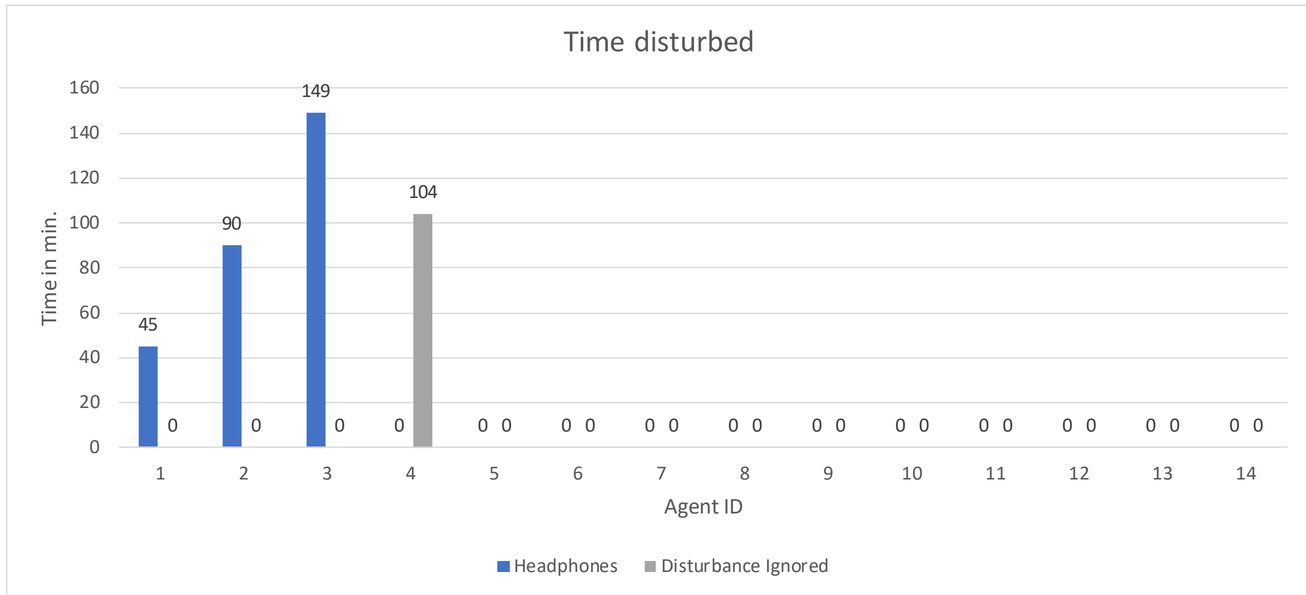


Figure 7.8. Results of time of disturbance of the double floor model.

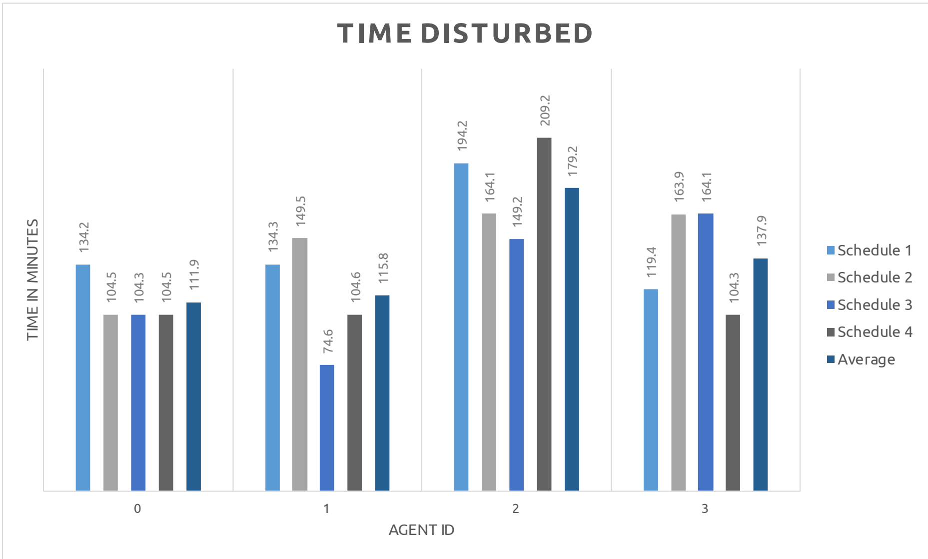


Figure 7.10. Comparison of time, the agents got disturbed for a random schedule.

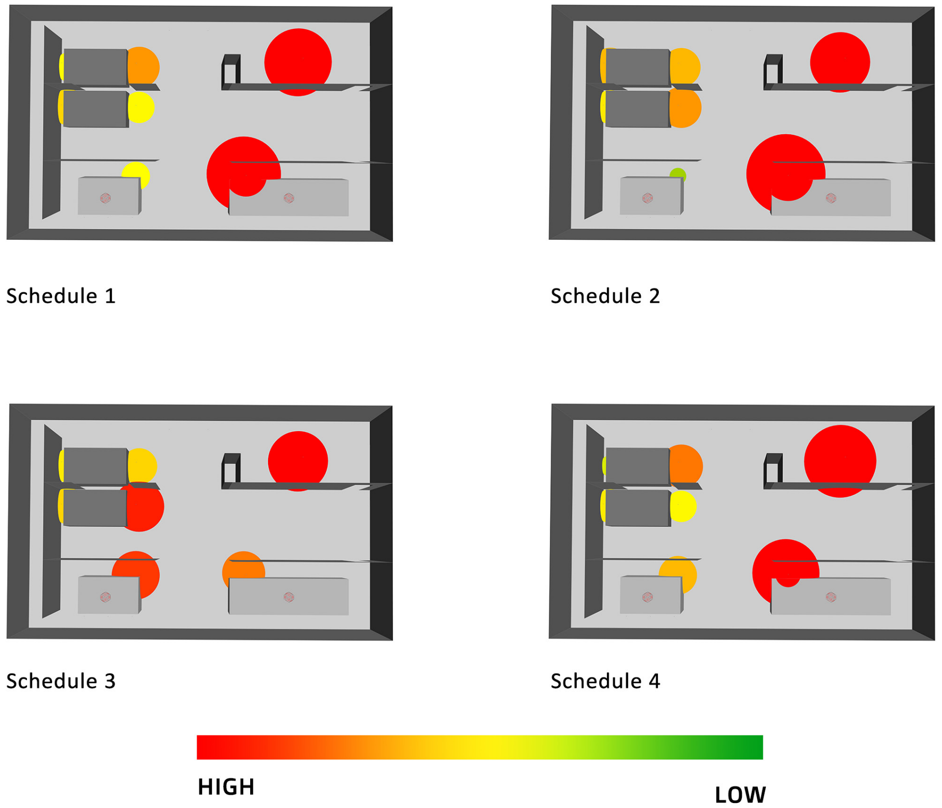


Figure 7.11. Occupancy density comparison for random schedules.

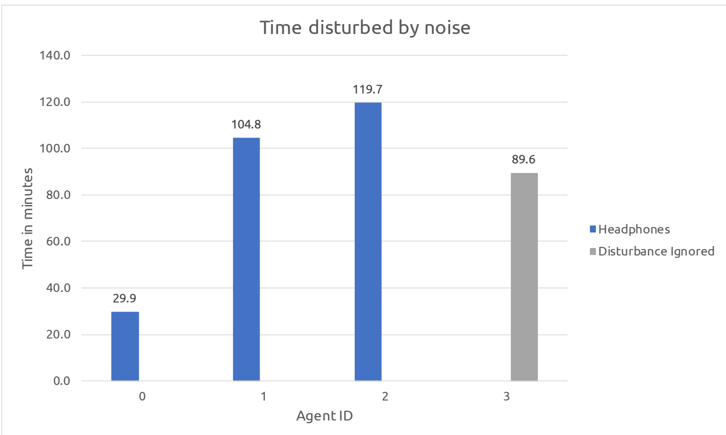


Figure 7.12. Noise disturbance time results for introvert personalities.

7.3 SENSITIVITY ANALYSIS

Multiple types of research suggest that agent-based models should undergo sensitivity analysis (Klügl, 2008; Rand & Rust, 2011; Wilensky & Rand, 2015). Sensitivity analysis is performed by changing the values of the input parameters to study the change produced in the output of the model (Rand & Rust, 2011). The sensitivity analysis projects the robustness of the model (Rand & Rust, 2011). It is done by changing the input parameter understudy while keeping other input parameters constant (Rand & Rust, 2011). The observation of results shows us how sensitive the model is to a particular parameter.

The sensitivity analysis for the single floor model was performed by using four random schedules and studying the output results. The results for the disturbance time of agents showed that the values range between 1-3 hrs of disturbance—the values for each agent varied by a maximum of 1.5 times standard deviation leaving zero outliers. Since the values didn't exhibit any outliers, it can be concluded that the model is not very sensitive to the schedule input.

The occupancy density results for the random schedule suggest high occupancy for the pantry consistently. The results also highlighted that the meeting area is also highly occupied in all the cases except for Schedule 3. The occupancy of discussion varied from low to high between schedule 2 and schedule 3. It can be attributed to the irregular distribution of discussion times between the agents during the creation of random schedules. Additionally, the model consistently predicted medium occupancy density for workspaces. Thus, it can be concluded that the occupancy results of the model also follow low sensitivity for the schedule parameter.

The sensitivity analysis was performed for speaking personality as it affects the noise generated during the interactions. All agents were set to introvert personality to study the sensitivity of the simulation model towards speaking personality. The results showed that the time the agent 0 and agent 1 got disturbed decreased. This change is attributed to the decrease in interaction between agents at the pantry. The comparison of the results is shown in Figure 7.12. Thus, it can be concluded that the model is sensitive to personality types.

8. VALIDATION AND TESTING

Chapter Overview

This chapter provide a step by step description of the validation strategy adopted in the last phase of the project. It presents the tests that were performed, their results and key learnings. It also presents the results of application testing which was performed in form of second case study.

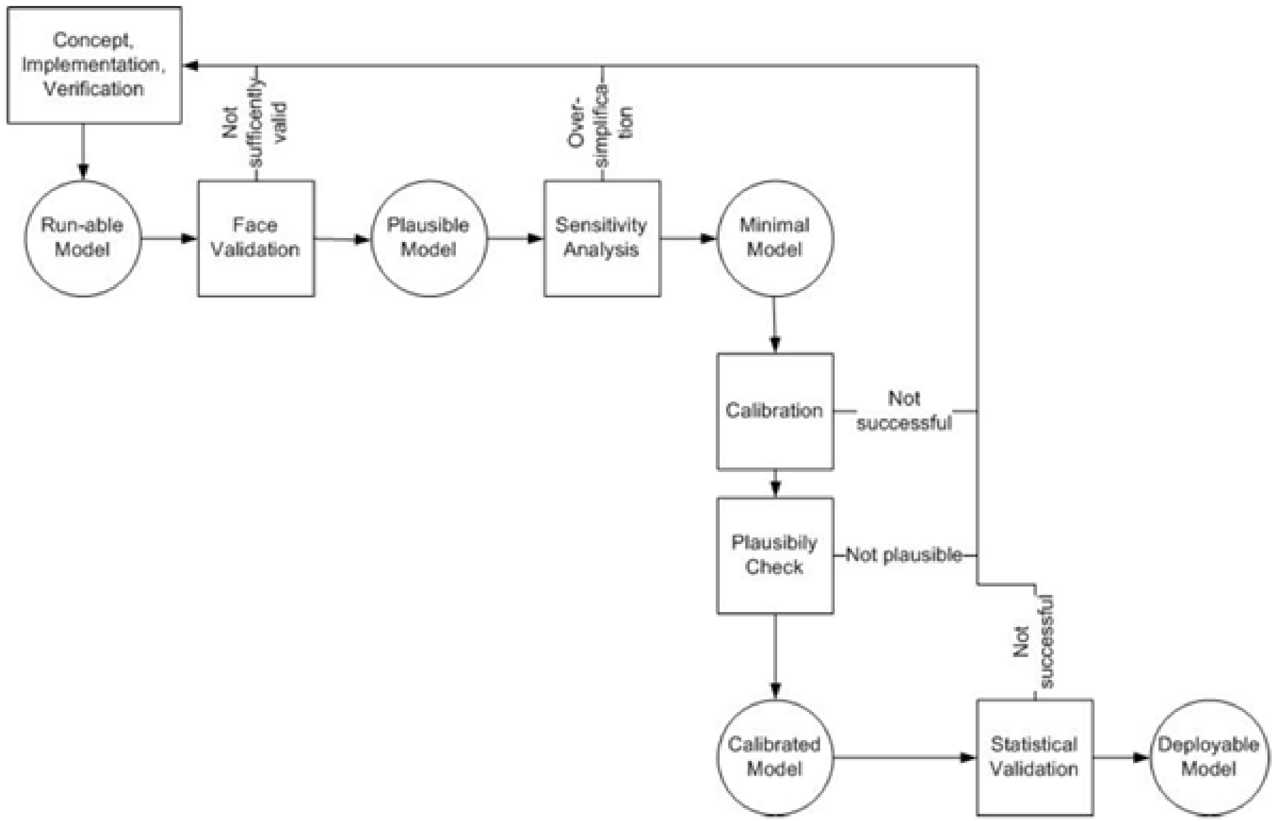


Figure 8.1. Validation strategy. (Klügl, 2008)

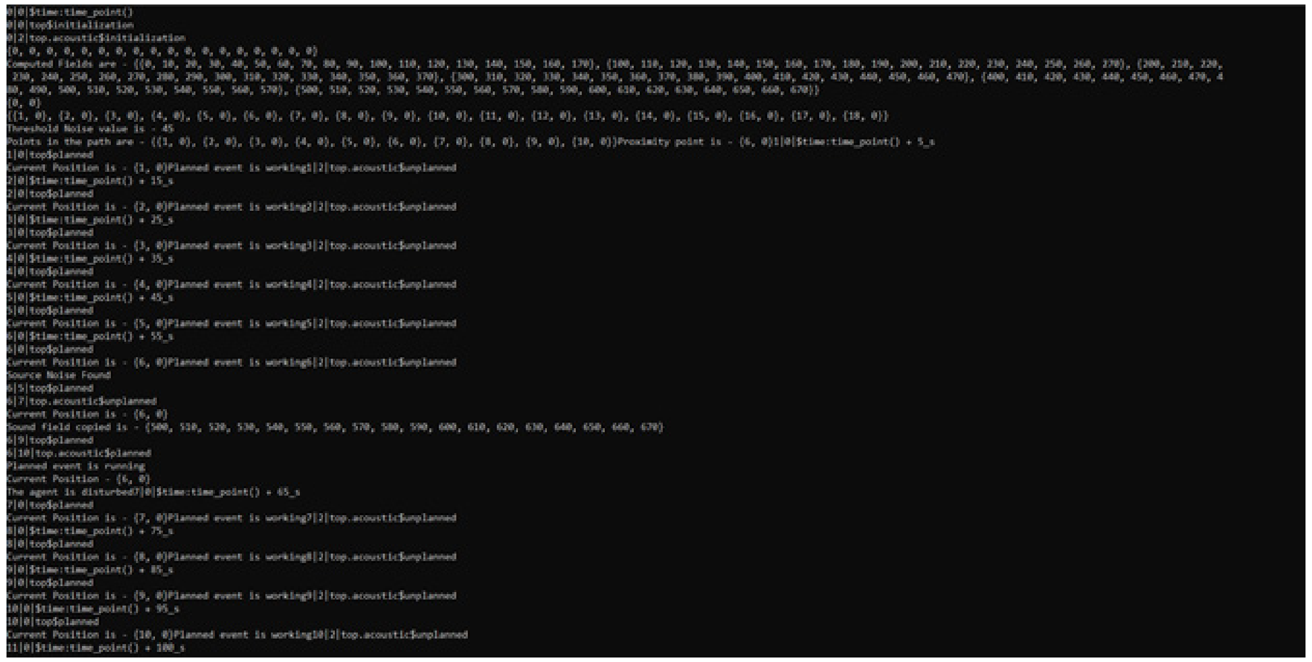


Figure 8.2. Screenshot of successful prototype run.

Simulation of adaptive user behavior with repsect to noises in offices

The last step of the research was an evaluation phase consisting of validation and deriving conclusion from the model. The strategies for validation of agent-based models have been suggested by various researches (Klügl, 2008; Olsen & Raunak, 2016; Rand & Rust, 2011; Wilensky & Rand, 2015). The strategy adopted is suggested by Klügl F. and is shown in Figure 8.1. below.

8.1 VERIFICATION

The model was developed using the methodology of the spiral model, which was implemented by improving the model through several iterations. The final prototype was conceptually verified by conducting several test runs with variable parameters. The test results in Figure 8.2. showed that the prototype was able to implement an acoustic node, noise node, and movement node in the 5s test run. After all the test runs and debugging, the final prototype, as discussed in Section 6.7 was used to simulate a full day of 8 hours with 0.5s time step.

8.2 FACE VALIDATION

The first part of the validation was face validation. Face validation is performed by checking if the output results of the simulation match with the expected realtime scenario (Klügl, 2008; Olsen & Raunak, 2016). The analysis performed in Section 7.2 showed that the values of time the agents got disturbed match the values as highlighted by the employees in their questionnaire responses. The values for the time of disturbance ranged between 44 minutes to 135 minutes. This was also noticed in the responses when the agents answered that they felt disturbed sometimes or frequently.

The trajectory analysis also showed that the results of the simulation were similar to the expected results. The high movement of the agent with ID=0 was correctly predicted as it was of intrepid explorer personality. The occupancy density also yielded expected results with high occupancy in the pantry area, as suggested by the results of questionnaire responses. The peak noise levels suggested high noise in the pantry area, meeting room, and discussion room. This further added to the face validation as the results overlapped with the employees' responses.

8.3 SENSITIVITY VALIDATION

Sensitivity analysis was also performed for the model by running simulation for four random schedules and introvert speaking personality, as discussed in Section 7.3. The results of sensitivity analysis showed that the model consistently predicted results with low sensitivity for schedule parameters. The time of disturbance and occupancy density results did not vary a lot or show extreme results. The current results range in between 1.5 times the standard deviation, and it is expected that the sensitivity would reduce with more agents. The model, as expected, was found sensitive to the speaking personality as the values changed significantly with change in speaking personality.

8.4 APPLICATION TESTING

For the final phase, the simulation workflow developed earlier was tested using case study B. The simulation workflow was performed using 58 agents divided into several teams. The scenarios performed are listed below in Figure 8.3. These scenarios were chosen based on the discussion with the architect. The acoustical simulation was performed using the below acoustical material values and simulation settings in Pachyderm environment.

Element	Material	63 Hz	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz	8000 Hz
Floor	Wood	10	15	11	10	7	6	7	7
Ceiling	Wood	10	15	11	10	7	6	7	7
Ceiling	Acoustic Board	40	45	70	80	80	65	45	40
Ceiling	Baffle	10	25	74	100	100	100	98	74
External Walls	Steel	20	30	25	20	10	10	15	10
Internal Walls	Steel	20	30	25	20	10	10	15	10
Internal Walls	Glass	10	15	5	3	3	2	2	2
Partition	Particleboard	5	5	10	30	60	80	80	75
Partition	Vegetation	40	46	42	36	38	45	50	40
Occupied Work	Seating +Person	50	60	74	88	96	93	85	80
Unoccupied	Seating	30	35	40	45	50	55	55	50
Column	Steel	20	30	25	20	10	10	15	10

Table 14. Absorption coefficient in %. (Cox & D'antonio, 2009)

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

Table 15. Setting for acoustical simulation in Pachyderm.

Figure 8.3. Scenarios for simulation of case study B.

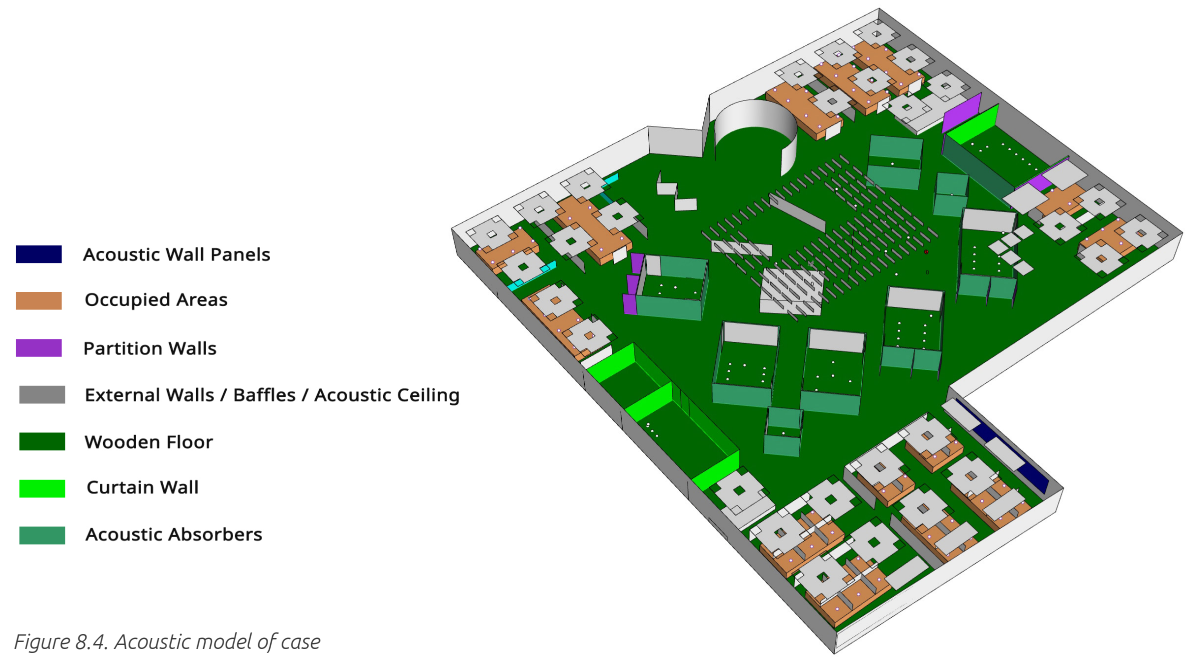


Figure 8.4. Acoustic model of case study B.

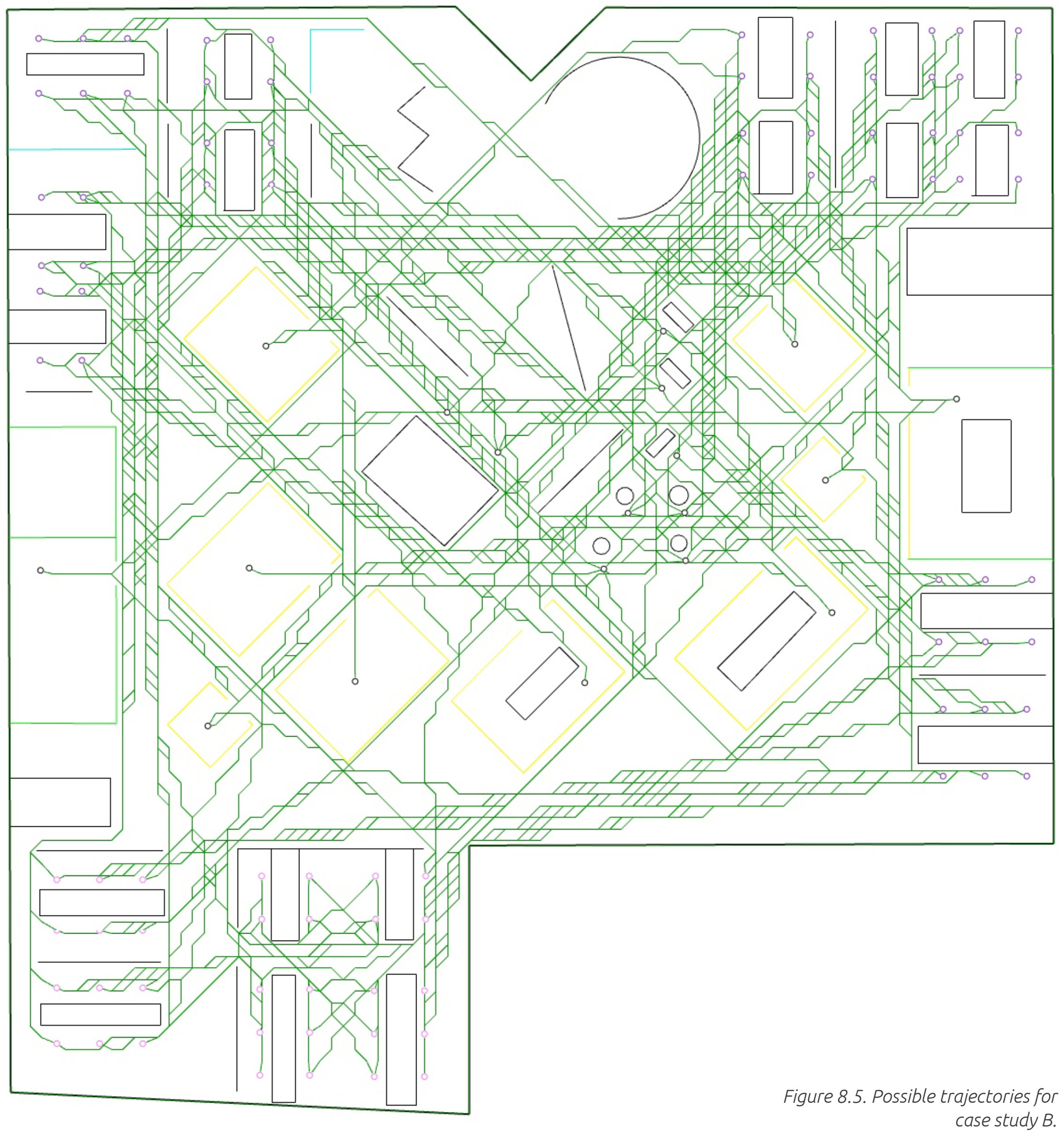


Figure 8.5. Possible trajectories for case study B.

The possible paths for the simulation framework were extracted using the Space Analysis package as shown below in Figure 8.5. The simulation model was used to test different scenarios of 30 minutes and 10 minutes. These scenarios were selected to evaluate the spatial layout in terms of user behaviour. For each scenario, a random number of agents from each team were allotted meeting or discussion representing the possible scenario in a real case. The scenarios are listed in Figure 8.3. The simulation model allotted the particular meeting room and discussion space to the agents depending on the availability. For instance, in scenario 1, the meeting room at the left was selected for team A as it was vacant and could fit five people. The same algorithm was followed for all the scenarios.

Due to the limited time available, the agents were allotted personality randomly with the total statistics, as shown in Figure 8.6. The traveller personality was chosen more in terms of the number to explore the sufficiency of concentration spaces. It is noted that further runs can be done in the future with varying personalities types. The normal speech spectrum is considered for the simulation, as shown in Table 10. The threshold value of the disturbance was taken as 45dB.

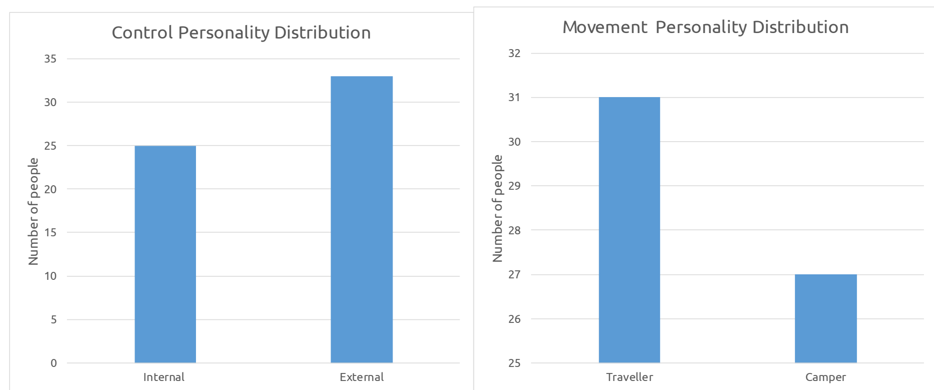


Figure 8.6. Personality distribution selected by the simulation model.

The overall results showed that the office is designed positively in terms of disturbances caused due to speech interactions in the office. The results are discussed below in the sequence of the scenarios tested –

Simulation of adaptive user behavior with repsect to noises in offices

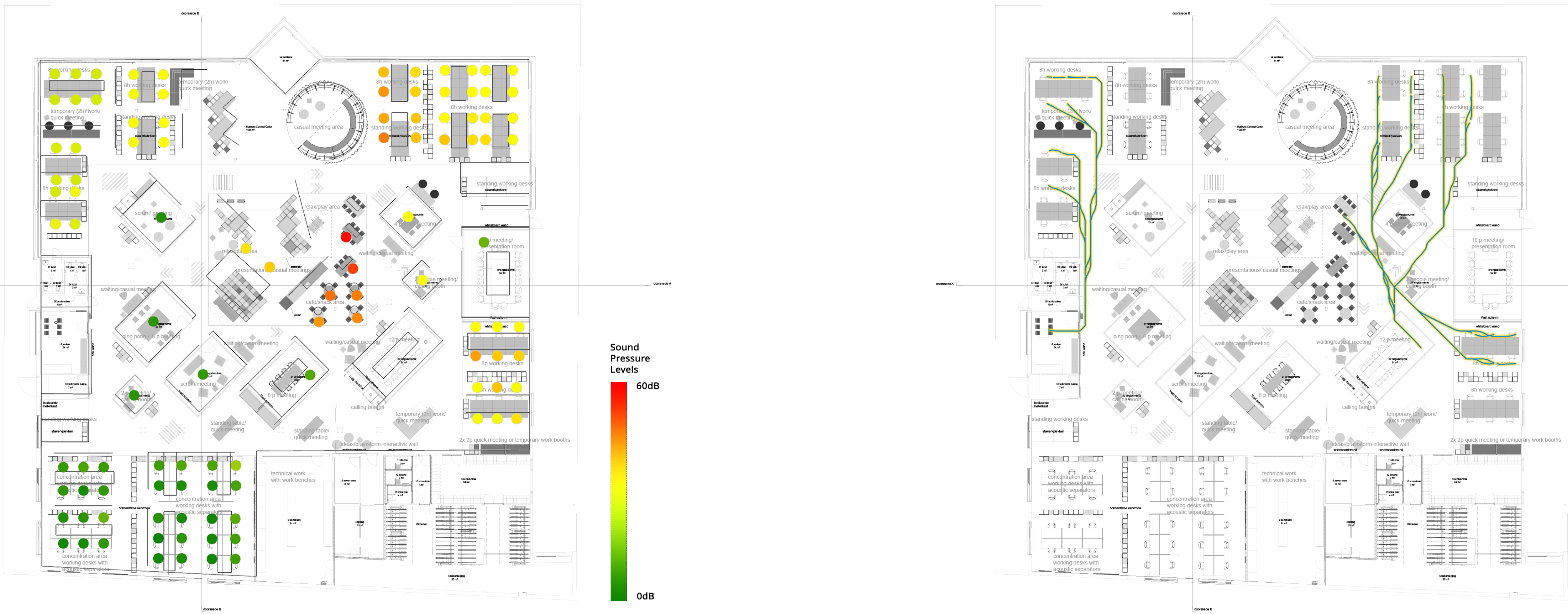


Figure 8.7. Average Noise Levels (left) and trajectories visualisation (right) for scenario 1.

SCENARIO 1

It was noted that simultaneous meetings did not cause much disturbance in the office. It can be attributed to the closed meeting room made of glass and sound-absorbing partitions. The discussion by Team C also did not cause disturbance as the maximum SPL was 44 dB in the area of Team B, as shown in Figure 8.7. Thus, the agents did not get disturbed at the workspaces. The trajectory analysis shows the path traced by the agents during the simulation run. It shows that there could be congestion near the discussion area between team B and team C.

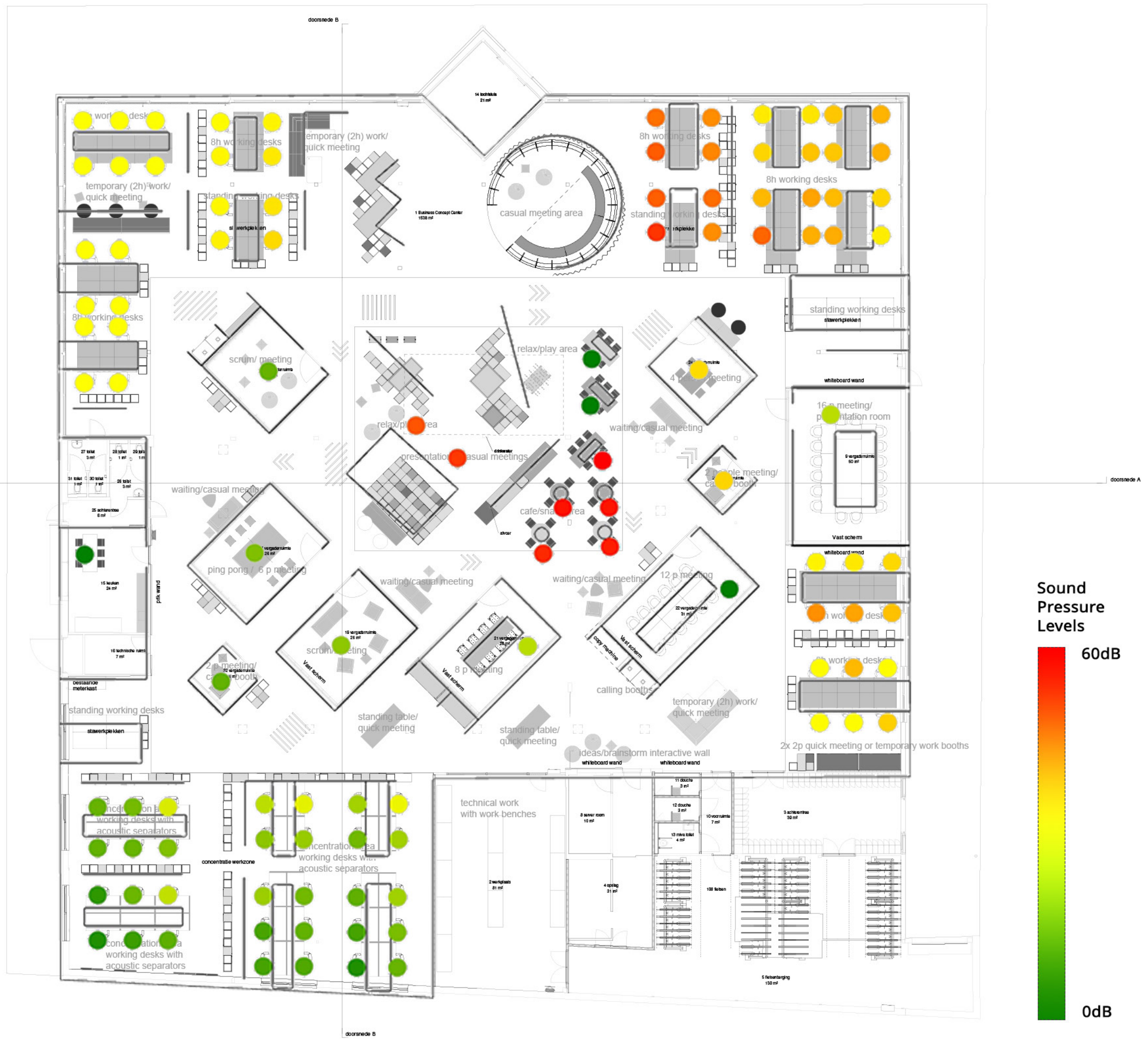
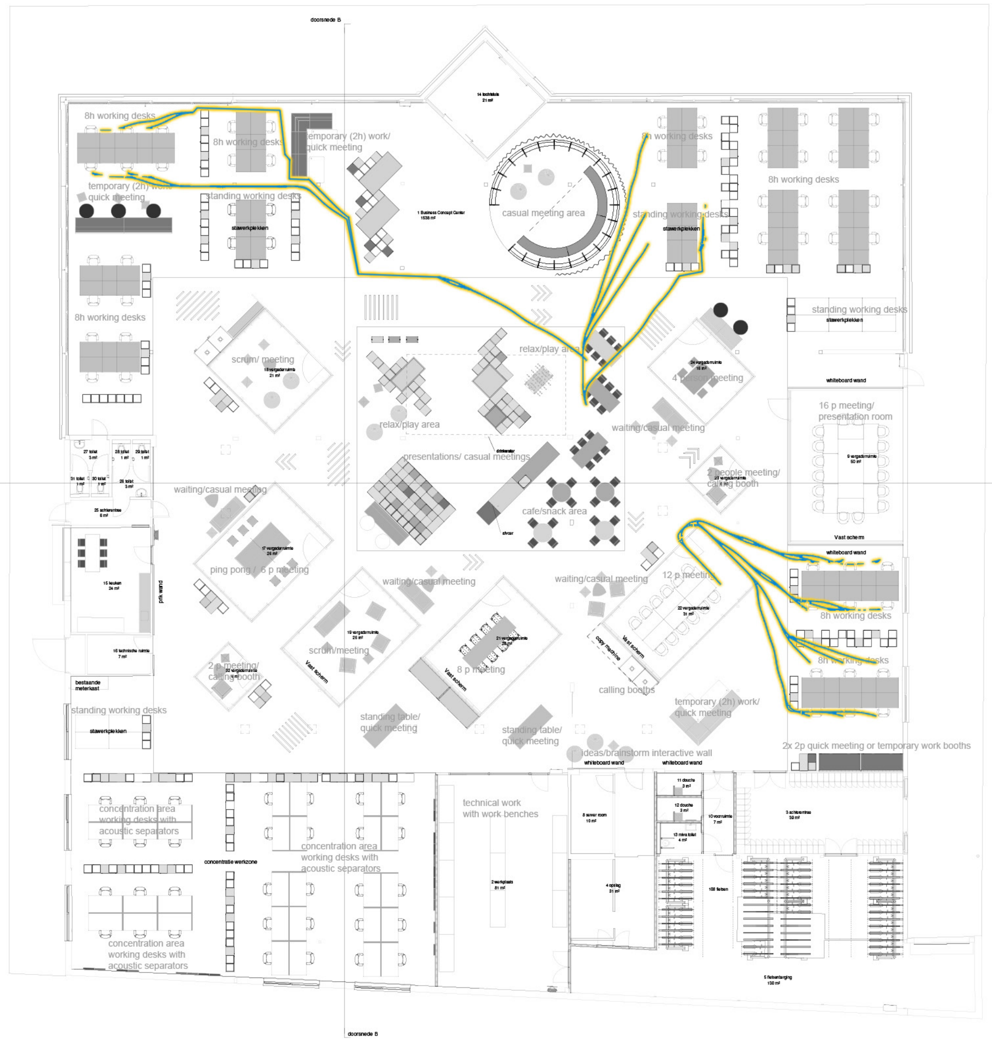


Figure 8.8. Average Noise Levels (left) and trajectories visualisation (right) for scenario 2.



SCENARIO 2

In this scenario, team A and B held the discussions at the same time while team C went for the meeting. The results showed that multiple discussions created higher noise levels than before but were well below the threshold.The noise levels were disturbing were discussion happening to each other but were less than the threshold for other workers as shown in Figure 8.8.

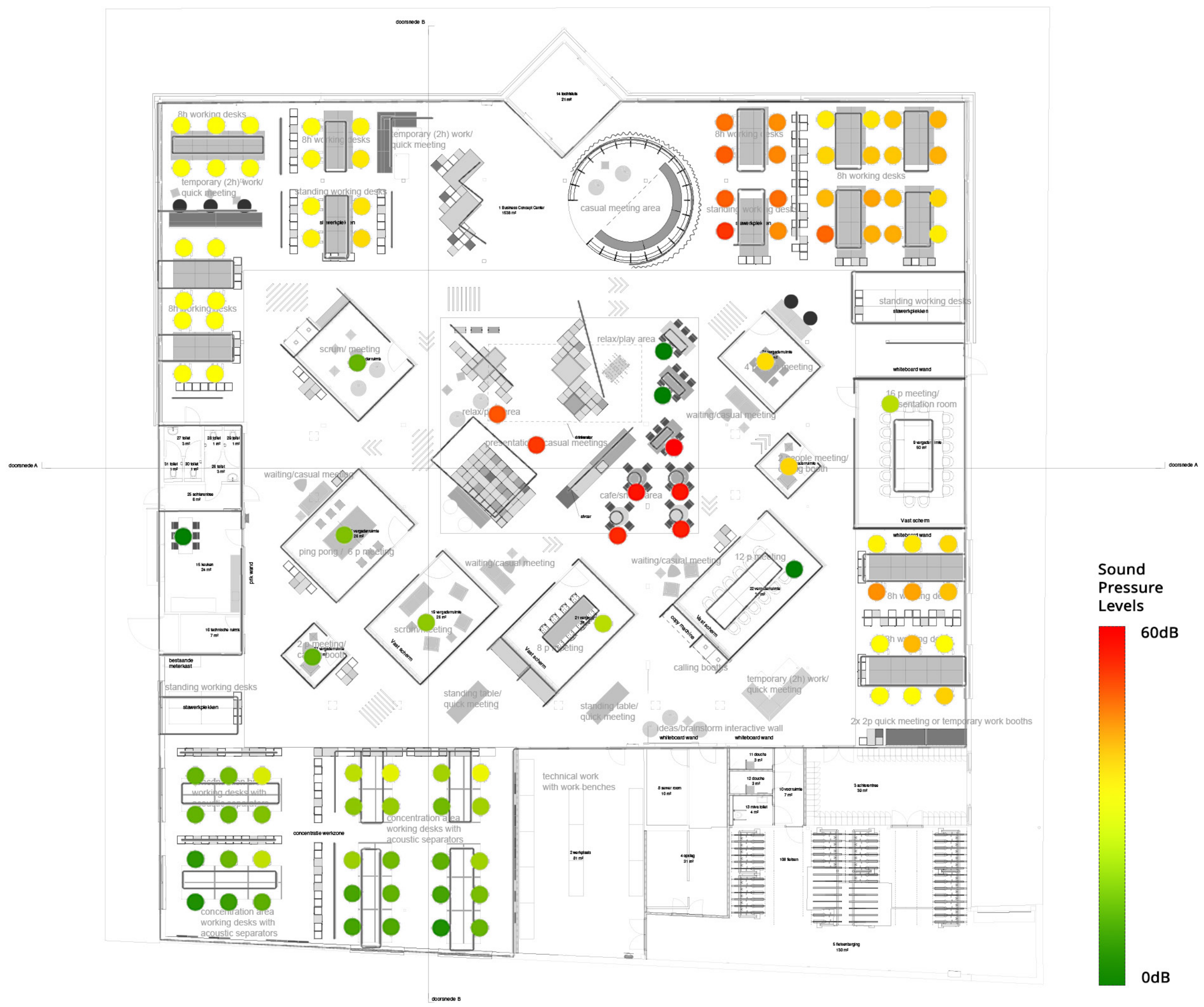
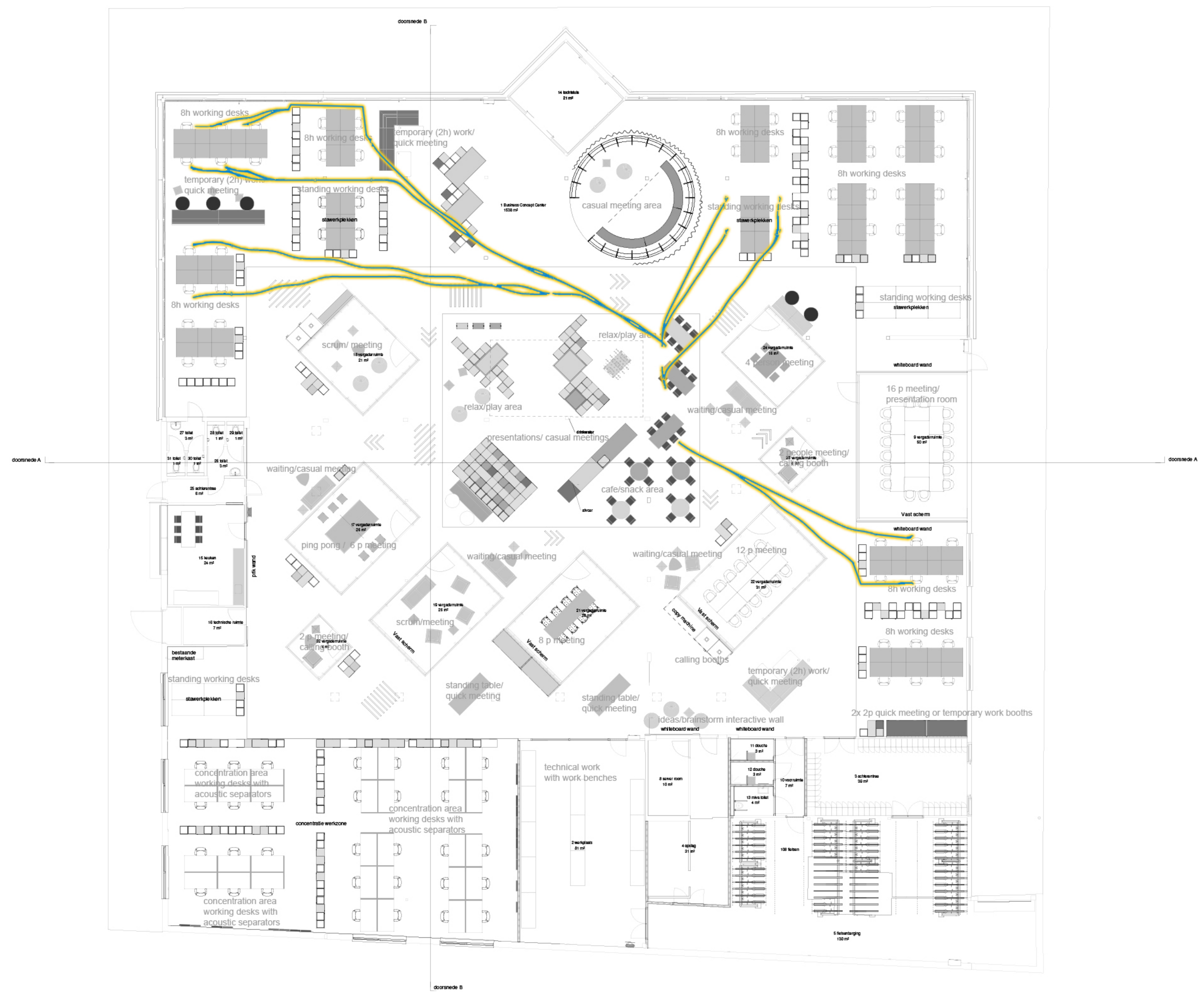


Figure 8.9. Average Noise Levels (left) and trajectories visualisation (right) for scenario 3.



SCENARIO 3

This scenario was tested for multiple discussions and no meeting. 6 members from team A, 4 members from team B and 2 members of team C were chosen for the discussion at the same schedule. The result showed a significant increase in the average noise level of the workspaces, as shown in Figure 8.9. The agents who were were working at their own workspace were never disturbed as the noise level was below the threshold value of 45dB.

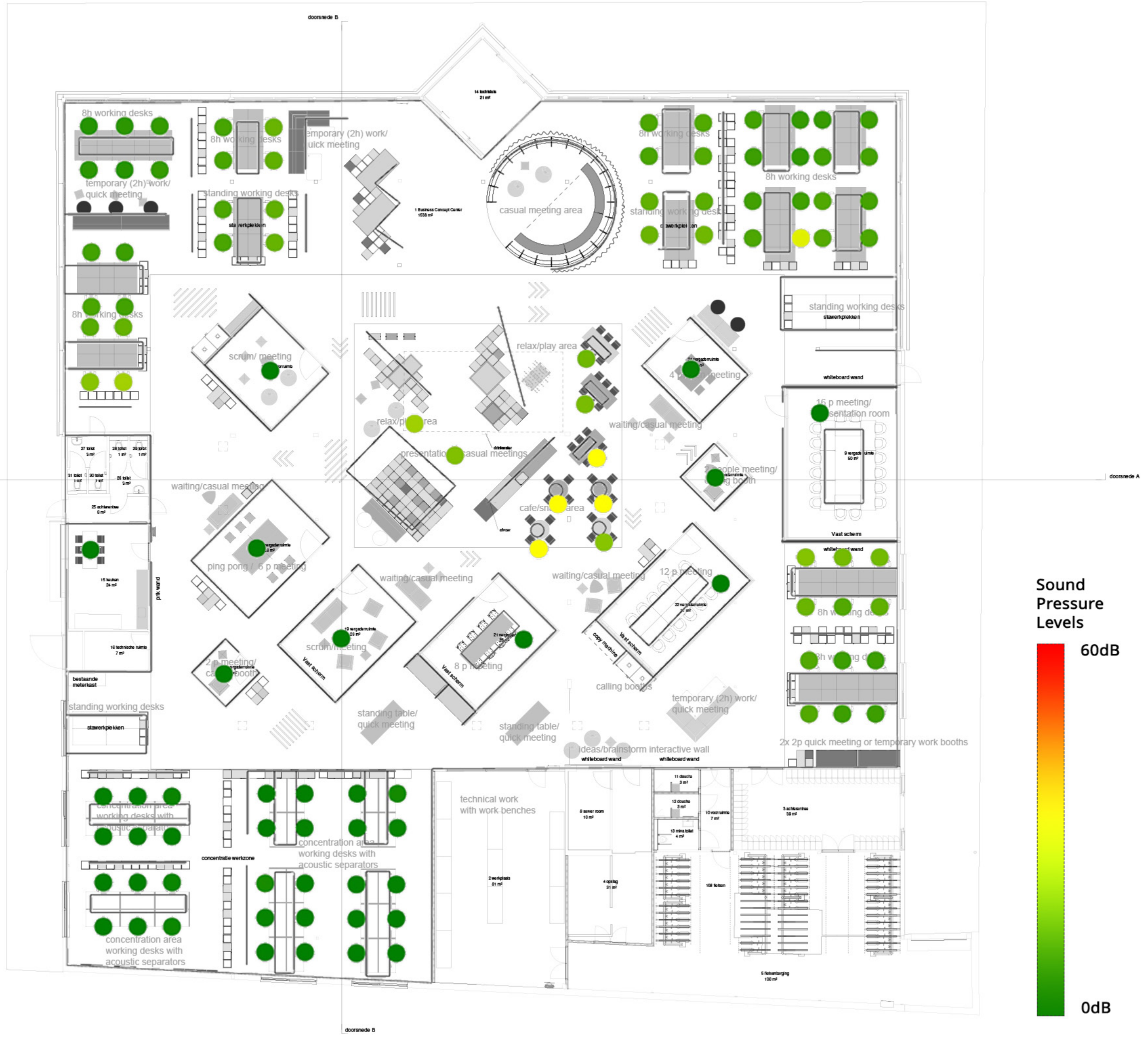


Figure 8.10. Average Noise Levels (left) and trajectories visualisation (right) for scenario 4.

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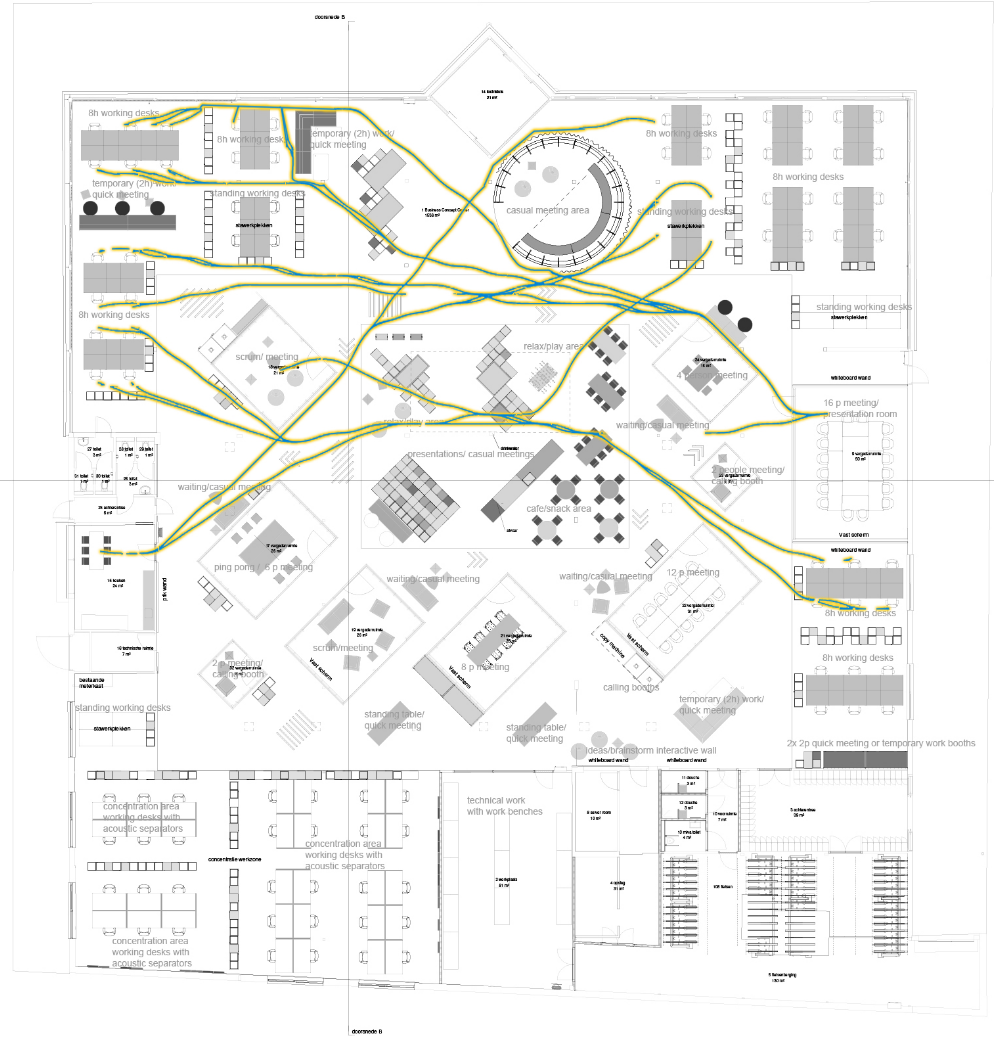

SCENARIO 4

The final scenario for big team division was chosen, where all the teams went for the meeting simultaneously. As expected, the average noise values of the overall office recorded were lower than previous results as shown in Figure 8.10. None of the agents was disturbed at the workspace, and trajectory analysis shows that they remained seated at their place for the work as shown in Figure 8.10 (right).

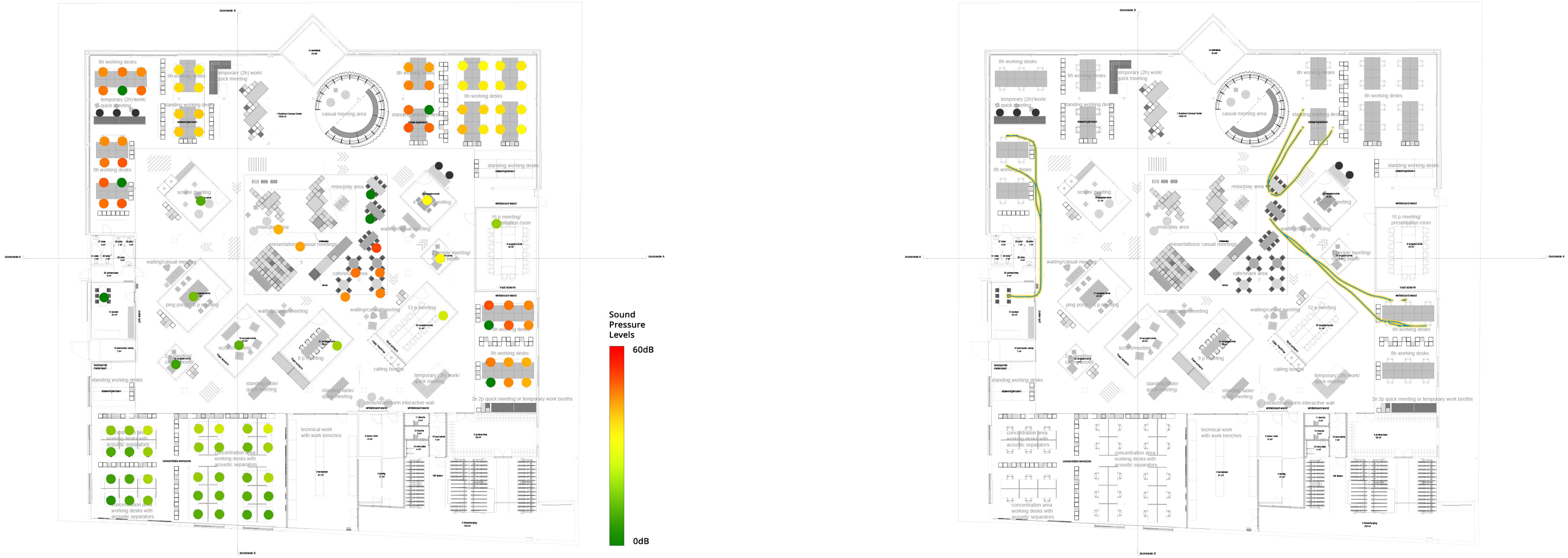

Figure 8.11. Average Noise Levels (left) and trajectories visualisation (right) for scenario 5.

SCENARIO 5

In this scenario, the agents were divided into 7 teams, as shown in Figure 8.3. The aim of this scenario was to evaluate the disturbance when agents talk at their own space. The agents were selected randomly allotted the schedule, and the simulation was run for 10 minutes scheduled time. The agents who created noise at the workspace are highlighted in dark green as in Figure 8.11. It was evident from the results that brief interactions at the workspace may disturb the fellow team members but did not disturb the other teams due to vegetative partitions.

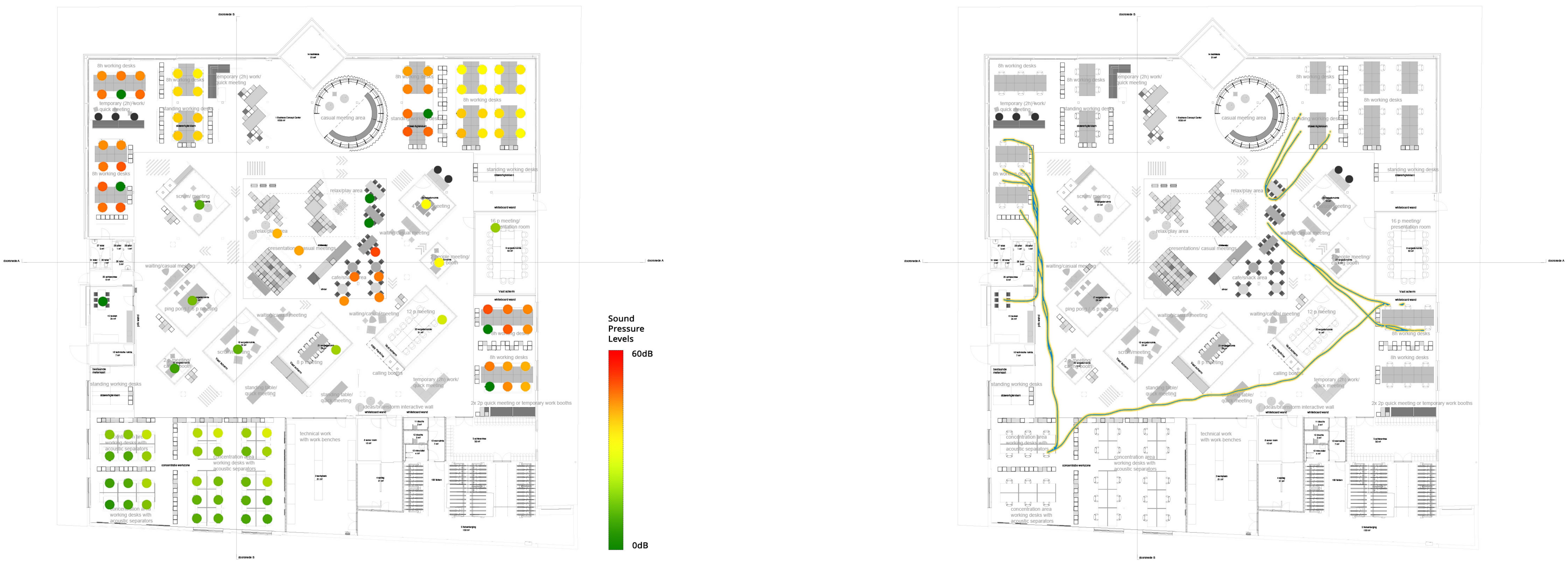

Figure 8.12. Average Noise Levels (left) and trajectories visualisation (right) for scenario 6.

SCENARIO 6

The final scenario was aimed to evaluate the extreme case for checking the number of concentration spaces provided. All the agents were set to ‘traveller movement’ and ‘internal control’ personality to allow movement to the concentration spaces when disturbed. The result showed that the agents who got disturbed due to nearby disturbance moved to the concentration space, as shown in Figure 8.12.

9. DISCUSSION & CONCLUSIONS

Chapter Overview

This chapter consists of the conclusions that were drawn from the research process during the entire phase. It collects and discusses the answers to the research questions framed at the beginning of the research. The chapter, in the end, also provides the author's point of view regarding future research that can be carried out for this research topic. It also includes the limitation of the simulation model.

9.1 RESEARCH CONCLUSION

The primary research question of the study was framed as below -

How can computational simulation methods of various users' movements support the evaluation and improvement of the spatial design quality of office space in terms of noise?

The primary research question was answered by answering the sub-research questions. The research was carried out by adopting the three-step research methodology – discovery, experiment, and evaluation. The discovery phase consisted of a thorough literature study to answer the sub research questions highlighted below. During the evaluation phase, it was observed that the model predicted agents behaviour according to the expectations and can help the designer evaluate the space in better terms. The model is able to bring in the time component during the design phase. It is possible to evaluate and predict the change in noise level at a particular workspace as done in the case study A. The simulation method can also be used to check the probable use of flexible spaces. In the case study B, it was noted that the building has sufficient concentration spaces and can be used when a lot of disturbance is there on fixed workspaces.

The general acoustic simulation only provides static results for a noise source, but through the simulation model, it was possible to evaluate the dynamic nature of workspaces. For instance, in the case of study A it was noted that the meeting room was used often and caused disturbance to other employees. An acoustic curtain or flexible partition can be used to separate noise and still maintaining the transparency it provides. Thus, the model can identify the hotspots of major noise concentration; thus, the result can be used effectively to treat the zone.

The unique aspect of this simulation workflow observed was the data it generated. The data can be used and analysed in numerous ways giving freedom to the designer. The designer can create its own performance indicators based on the need for office type and management. One such performance indicator evaluated for case study A is peak noise value. This indicator would give an insight if the agent got disturbed and by how much dB levels. This result can be interesting if the designer wishes to treat the place of disturbed agent individually. The simulation results also allowed for insights that can be used to take policy-based or behavioural decisions. During the case study B, it was noted that it would be better

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to make a policy for the office for less interaction at the workspace. It also showed the need for private phone booths and small meetings room.

This research completed in the limited time provides a base for future development. One such application for improvement of spatial design quality is the optimization of office acoustics based on the personality or user behaviour. Another application where this simulation workflow can be used is generative design. The design options can be evaluated using the performance matrix made on the output data. The simulation model, as a result of this research, is open source and can be used to evaluate any workspace by following the simulation workflow, as highlighted in Section 6. The code for the simulation model is made publicly available at

https://gitlab.com/divyae.iitr/acoustic-simulation-in-offices

What are the various factors which contribute to the noise disturbances in the typical workspace?

The literature review for the noise disturbances in the office suggested that the disturbance could be caused by more than one specific reason in the office. The primary sources of noise in the office noticed were – speech, appliances, and telephones. The secondary sources included typewriters, HVAC, and traffic. It was important to notice that speech disturbance and overhearing telephone conversations were quoted as the most disturbing factors by a large number of studies. Thus, the factor of speech-related disturbance caused in the office was chosen for the simulation workflow.

What are the types of social user interactions or patterns that take place in an office?

It was also discussed that there are mainly two types of networks that create interactions between the employees in an organization – diverse and cohesive. These networks decide on how the employees interact with each other socially, either following a single point of contact or cross networking. The research by Lee et al. explored the social pattern occurring in an office. It suggested that employees follow a certain comfortable distance when they interact, also called as 'privacy distance' in other researches. This results in a diverse pattern that occurs in relation to the spatial layout of the office.

What are the factors that affect the interaction or movement patterns of users of a workspace?

The study conducted by Henn & Allen concluded that there exists a correlation between the communication of employees and the distance to which they are seated in a large organization. It found out that the probability of interaction between employees decreases with the distance asymptotically. They called this curve as Henn-Allen curve. Lee et al. also concluded that the spatial layout of an office also affects the social interaction between the employee (Lee et al., 2019). They noticed that the social proxemics and the medium of communication lead the occupants to adjust their privacy distance for increased or decreased interaction.

How can noise disturbances due to user interactions be predicted in a spatial layout of a workspace?

The domain of philosophy provides a concept called Action theory, which suggests that the agent takes the actions in a situation based on its behavioural trait. Another extension of the same theory provided the framework which enables the agent to decide for action based on rational logic. The same theory was used in the simulation framework to understand when two agents get together. The research by Veitch also suggested employees respond to the noise depending on their personality traits (Veitch, 1990).

What are the prevalent methods used to simulate building use patterns in the built environment?

The building use patterns have been simulated in the recent past for various applications, including fire evacuation, energy modelling, and transport planning. The applications use one of the methods out of these – system dynamic, discrete event, discrete-time, or agent-based models. Each of these methods is suitable for a particular application and can be used depending on the complexity and requirements of the model. System Dynamics can be used in the case when simulation follows a pre-known mathematical equation. The discrete event and discrete-time models are used when the agent's state changes at a particular event or time state, respectively. Agent-based models are used when more than one agent interact and create an effect in the given time frame. It is particularly used in complex systems that can't be replicated easily.

What could be the workflow for simulating user movement patterns for the selected office space with respect to the noise disturbances?

The workflow for simulation of the user movement pattern evolved throughout the research with a starting point of taking a clue from action theory in the philosophical domain. The studies about the workspace and new ways of working suggested that users adapt to the changing environmental conditions. The actions taken by the employees are results of the behavioural property. The simulation workflow suggested take into account the actions taken by the agent when the environmental conditions change, in this case, the acoustics of the space. The workflow precomputes the acoustic values in the room and the possible paths of agents in the office space. This was done to keep the simulation framework free of any geometry and fasten the computational time. The simulation framework is a hybrid model of a discrete event, discrete-time, and agent-based modelling. The inputs for the simulation also include personality traits, initial location, schedule, and speech levels of the agents. The overall workflow emerged, as shown in Figure 9.1.

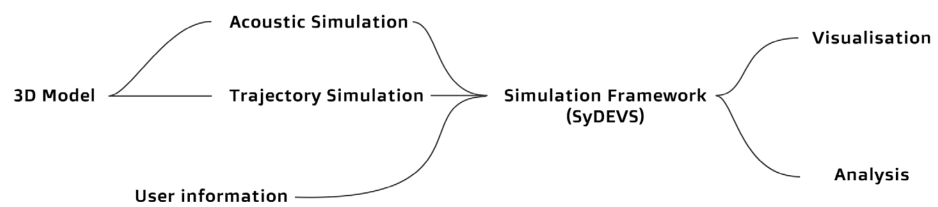

Figure 9.1. Final simulation workflow.

To what extent the simulation workflow can represent the real-time scenario for the selected case study?

The aim of an agent-based model is to study the complex phenomenon which can not be recreated physically (Wilensky & Rand, 2015). This can be done by simplifying the complex system into small observable parts as done in the workflow. The validation process revealed that the model could be considered as the 'minimal model' on the validation strategy suggested by Klügl. This means that the model was able to predict the result up to a certain extent, the real-world scenario. The further test for accuracy and evaluation, which were planned during the initial research phase, couldn't be completed due to the unavailability of extensive data. It was noticed that the results obtained from the simulation relied heavily on the results of the discovery phase and assumptions. The model is

based on the conclusions of the literature study as the input for the logical framework, which means further additional findings of human behaviour can improve the model to predict results with high accuracy.
The model was only tested for a limited office scenario of a maximum of 14 agents. Thus, it cannot be surely said that the acoustical patterns emerging for a large organization would reflect the results with high accuracy. Indeed the model can be used in the initial design phase to test the performance of different design options as it takes into consideration building usage, acoustics, and behaviour into account at the same time. It can also be used to improve the design of the current office according to the personality of the users if extensive data about the users is available.

What strategies can be adopted to reduce the noise disturbances in the spatial layout while maintaining the privacy and design requirements of the workspace?

The simulation results consistently showed that the employees sitting on the first floor are disturbed for 40 minutes to 180 minutes in the day due to speech distractions. Currently, the agents adapt to these by putting headphones or ignoring the disturbance. The noise source identified as the most disturbing is the pantry. Thus, the strategy to acoustically treat the pantry area can reduce the noise disturbance caused. Also, another strategy could be to set up another pantry on the upper floor to reduce the movement of the employees for a break on the lower floor.
The meeting room and discussion room also cause moderate disturbance to the ground floor work desks. These spaces are not used regularly but for specific tasks. Thus, a simple strategy to use the acoustic curtain during the use can reduce the disturbance caused to the other workspaces.

9.2 STAKEHOLDER FEEDBACK

The last phase of the research was to evaluate the model from industry perspective. The key stakeholder for the developed simulation model are architects, designers and consultants. Thus there feedback was taken with high importance and critical points are also added to the limitation and future research. The feedback was collected from Bence Torok and N.Mert Ögüt who were involved for case studies and their tests as architects from DOOR Architects. Additionally, feedback from Aron Wuarbanaran was collected who works as a consultant for Veldhoen + Company BV. All of them were asked two questions regarding the application of the simulation model. The questions were kept neutral to get honest feedback from them. Their replies are collected in Appendix E.

What do you think about the usability of the results provided by the simulation workflow in the design process?

All the respondents agreed that the simulation workflow provided useful insights apart from the traditional simulation approaches. Bence highlighted that such results would help architects look for optimal distribution and layout of the workplaces. While Mert added that such results could also act as an evaluative reflection for architects about their design, Aron asserted that the result would be helpful for consultants designing the collaborative environments as they rely heavily on human interactions. He also mentioned that in the current design process, designers rely on experience and through this simulation workflow, they can test different scenarios which convincing output. All of them agreed that the simulation workflow brings new insights on the aspect of the acoustics of workspaces.

What improvements do you suggest for the simulation workflow in terms of use as an architect/consultant?

Regarding the improvements, Mert highlighted a need to make the simulation model parametric. He believes that ability to change the number of agents, materialization, and characteristics of the agents would give more insights to the architects during the design process. Though STI results were evaluated during the acoustical simulation, only SPL levels were used for the agent-based model. Mert feels that the inclusion of STI values in simulation model would also be a great improvement. Adding to it, Bence suggested that informal interaction taking place between agents (excluded from current research scope) could be a great improvement in the next version of the simulation model. Aron, as consultant mentioned that clients generally look for scientific answers to the problems. Though the model is really useful in the design process, he thinks it can be beneficial if the model can be further improved to create results for the clients. He thinks, in the future, it can be improved by researching further on the user behaviour in the workspaces.

9.3 LIMITATIONS AND FUTURE RESEARCH

The model developed for the research objectives was designed, keeping in mind the limited availability of data, time, and restrictions. The learnings from the model have uncovered many aspects of the user behaviour simulation in which future research can be carried out. The model in the coming time can be improved on the following points –

- *Private Interactions* – The model currently excluded individual interaction, which takes place in the office. The current availability of data could not give enough evidence to model such interactions with higher accuracy. Thus, in the future, these could be included using the extensive databases or real-time measurements.

- *Acoustic Simulation* – The workflow used the precomputed acoustic simulation results obtained from the Pachyderm plugin, and thus, noise sources were restricted. It was done as the scope of the research was not an acoustical simulation in its entirety. Thus, in the future acoustic model can be combined into the SyDEVS framework to increase the sample space of the model.

- *Trajectory evaluation* – The walking paths of the agents are calculated using the shortest path algorithm of the SpaceAnalysis package. In the real case scenario, the agent may take a route based on the different parameters. It acts as a limitation for the model as precise routes can not be modelled for every behaviour due to limited data.

- *Application* – The current implementation of the model is restricted to the acoustical behaviour of the agents. But the model in the future can be extended by including behaviour towards other indoor environmental parameters such as daylight, visual distraction, and thermal comfort. Further, the development of agents as AI agents can help in creating the simulation precise and faster.

- *Analysis* – The model concludes with a lot of data that can be used to conduct extensive analysis. In the current research, the analysis was performed by visualizing the output data on the spatial layout. It can also be extended to the creation of performance indicators for which optimization could be done in the future.

- *Time complexity* - It was noted during the case study B that the simulation time increases exponentially with number of agents. It was rather expected as with each agent, the computational calculation increases due to increase in number of nodes. It means the same calculation is done for more agents but gets unique result everytime.

10. REFLECTION

Chapter Overview

The graduation project was a learning experience full of challenges, solutions and critical thinking. This chapter presents the author's reflection on the process, experience and expectations. It also highlights the aspects which are important for societal relevance when it comes to the graduation topic in whole.

10.1 GRADUATION TOPIC AND APPROACH

The journey from inspiration to the finalization of graduation topic was quite long, driven by personal interest and passion. The graduation topic for the studio was proposed after the inspiration was drawn from leading researches published in SimAUD Conference. The interaction with experienced individuals with a background of real estate managers, academicians, consultants, and architects helped me narrow down the topic to what was possible. The graduation topic primarily combined the knowledge of design information and acoustics but also required additional expertise of agent-based modelling, feedback for which was taken care of by external supervisor.

The overall planning of the graduation project was done based on the projected time frame. The concept of user behaviour analysis relies heavily on user data, which made it difficult for the process to get started soon enough. The data acquisition for the case study caused few delays due to the late initiation and documentation process. It is also a matter of important consideration that the research in this domain is still in the nascent stages. The approach followed for the research and design is a proof of concept that has not been tested before and requires further validation. It was one of the reasons why the research scope was reduced only to designing the simulation workflow and not extended to its applications. It was also noticed that the research approach required additional knowledge of coding, workspace planning, and psychology. These hurdles were hard to overcome but were passed through extensive discussion with workspace consultants, professors, and software developers in the network. The collaboration with OMRT was fruitful in terms of getting regular feedback from computational perspective. The discussions with Rhys Goldstein also helped alot in overcoming obstacles regarding SyDEVS.

The modelling method of the agent-based method is highly stochastic and is widely used in areas of social sciences, economics, and finances. In this thesis, it is used to predict user behaviour with respect to noises. The method relied heavily on the literature review, and a lot of time was spent on it. User behaviour is a topic of continuous research. It evolves, improves and adapts with every new research publication. The personalities of the users were evaluated using tests published in various psychological publications. These questions may have been the choice for current research but could have been redesigned for improved

insights. Additionally, it was also noted that self-reported results could not be considered the best approach, but it is a prevalent method in user behaviour research. For future development and accurate personality tests, these questions need to be validated further independently.

It was also noted that the accuracy of the model would increase with more data and insights about human behaviour in the future. The ethical standards were followed throughout the research and did not hinder the process. The model relied heavily on the assumption of the developer how to represent behaviour in the model. This could mean the presence of moral bias, but it was taken care of through cross-questioning and regular feedback from mentors and external supervisors. Without any previous graduation topic to look behind to, the research seemed impossible in the beginning. The constant motivation to innovate and encouragement by the mentor helped a lot to achieve the desired result in the end.

Since it is a predictive model, the feedback from the mentors and external supervisors was crucial in the process of selecting the proper validation technique. It allowed me to deep dive into scientific research methods and learned the aspects which could have been missed. The validation of such a predictive model is usually done through stakeholder feedback.

The change in the course of situations due to pandemic COVID-19 caused a large change in the planning of my thesis. I had to look for another plan of validation as compared to real-time data collection. The final test was aimed to be a 'calibrated model' in the final phase of the research by conducting real-time measurements of the noise values at the case study office and comparing it with the simulation results. But due to the restriction in place due to COVID-19 during the research phase, the final test was simply not possible. The current model was further tested with an additional case study with a large number of the agent. The model proved to be working as expected, suggesting another minimal model validation. For now, it can be used in the early design process by the architects to evaluate initial design proposals and explore design space with respect to user behaviour, followed by the statistical validation, it can also be used by acoustical engineers and consultants also for detailed designing and evaluation. In the future, I aim to combine and further explore the model from a machine learning perspective. The model is aimed to be further combined with the BIM model in the single framework with its graphical user interface (GUI).

10.2 SOCIETAL RELEVANCE

A human being typically spends 90% of their time indoors throughout his lifetime and a substantial amount of that time at work. However, there are pieces of evidence that users are not satisfied inside the office designs leading to reduced productivity, increased stress, and sick building syndrome. The number of workspaces is going to increase, and thus we need more than the conventional design process to improve users' satisfaction.

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 with the real use of the building. This is currently studied through a post-occupancy evaluation process, which means stakeholders are left with the only choice of improvement or refurbishment of the building. Such action leads to an increase in cost as the cost of design increases with the subsequent design phase. The research in this domain is still in nascent stages, with few researchers trying to simulate the user behaviour. This research will be the contribution of their findings and learning. With the advent of super-computing, this research domain expects to contribute in terms of the overall sustainability of the built environment. A few of those factors that can be identified right now are user comfort, cost efficiency, energy efficiency, and space efficiency.

With the use of the model obtained as the result of this research, the design could be improved to reduce noise disturbances in the workspace. This could, in turn, help to reduce the ignored adverse effects because built environments such as stress and sick building syndrome. If the model is extended into the domain of indoor environmental quality and energy efficiency, it could help the architects design a more healthy and productive environment. The model could also contribute to the cost savings, but avoiding late design changes and making predictions in the early design phase.

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12. APPENDIX

A. QUESTIONNAIRE

The questionnaire is developed by adopting well know personality tests. The questions for movement personality has been borrowed from Leesman Index (Leesman, 2017). The control personality test is derived from the Locus of Control Test by Rotter and the adoption on http://www.psych.uncc.edu/pagoolka/LC.html. (Rotter, 1966). The speaking personality test has been adopted from a research on the similar grounds (Khatib et al., 2011).

Survey for acoustic analysis

Response ID - ___________

This survey is being conducted to analyze and design a simulation of 'user behavior' with respect to noise disturbances in the office. The survey features questions about user personality, the acoustics of the space, and the responses. All the questions are mandatory.

Section A

1. On the scale of 1 to 5, how do you rate the acoustics of the space? (5 being the best)

1 2 3 4 5

2. How often are you disturbed by noise in the office?
a. Not often
b. Sometimes
c. Frequently
d. All the time

3. Rank the actions in order, you would take when you are disturbed by the noise?

a. Put Headphones Rank - ____
b. Move to another place Rank - ____
c. Ignore the disturbance Rank - ____
d. Other ____________ Rank - ____

4. What part of the office according to you is the noisiest?
a. Pantry
b. Meeting Area
c. Own workspace

5. How often do you talk to your colleagues for work-related talk?
a. Not often
b. Sometimes
c. Frequently
d. All the time

6. How often do you talk to your colleagues for private talk?
a. Not often
b. Sometimes
c. Frequently
d. All the time

Section B

7. What do you consider the best profile for you for the work that you do?
   - I perform most/all of my activities at a single work setting and rarely use other locations within the office
   - I perform the majority of my activities at a single work setting but also use other locations within the office
   - I perform some of my activities at a single work setting but often use other locations within the office
   - I use multiple work settings and rarely base myself at a single location within the office

8. Answer the below questions by choosing one option for each statement–

The control personality is calculated by adding the responses to the below questions. 1 point is added for the first option and 2 for the second option. The cumulative score between 13-19 suggests internal control personality, while greater score suggests an external personality.

a. Many of the unhappy things in people's lives are partly due to bad luck
People's misfortunes result from the mistakes they make.
b. One of the major reasons why we have wars is because people don't take enough interest in politics.
There will always be wars, no matter how hard people try to prevent them.
c. Overall, people get the respect they deserve in this world.
Unfortunately, an individual's worth often passes unrecognized, no matter how hard he tries.
d. The idea that teachers are unfair to students is nonsense.
Most students don't realize the extent to which their grades are influenced by accidental happenings.
e. Without the right breaks, one cannot be an effective leader.
Capable people who fail to became leaders have not taken advantage of their opportunities.
f. No matter how hard you try, some people just don't like you.
People who can't get others to like them don't understand how to get along with others.
g. I have often found that what is going to happen will happen.
Trusting to fate has never turned out as well for me as making a decision to take a definite course of action.
h. In the case of the well-prepared student, there is rarely, if ever, such a thing as an unfair test.

Many times, exam questions tend to be so unrelated to course work that studying is really useless.

i. Becoming a success is a matter of hard work; luck has little or nothing to do with it.
Getting a good job depends mainly on being in the right place at the right time.

j. The average citizen can have an influence in government decisions.
This world is run by the few people in power, and there is not much the little guy can do about it.

k. When I make plans, I am almost certain that I can make them work.
It is not always wise to plan too far ahead because many things turn out to be a matter of luck anyway.

l. In my case, getting what I want has little or nothing to do with luck.
Many times we might just as well decide what to do by flipping a coin.

m. What happens to me is my own doing.
Sometimes I feel that I don't have enough control over the direction my life is taking.

9. Answer the below questions by choosing one option –

The speaking personality is calculated by adding the responses to the below questions. 1 point is added for the first option and 2 for the second option. The cumulative score between 5-7 suggests extrovert personality, while a greater score suggests an introvert personality.

1. I usually like ……
a. mixing with people
b. working alone

2. At a party, I ….
a. interact with many, including strangers.
b. interact with a few people I know.

3. My usual pattern when I'm with other people is to …..
a. be open and frank, and take risks.
b. keep to myself and not be very open.

4. Interaction with people I don't know ……
a. stimulates and energizes me.

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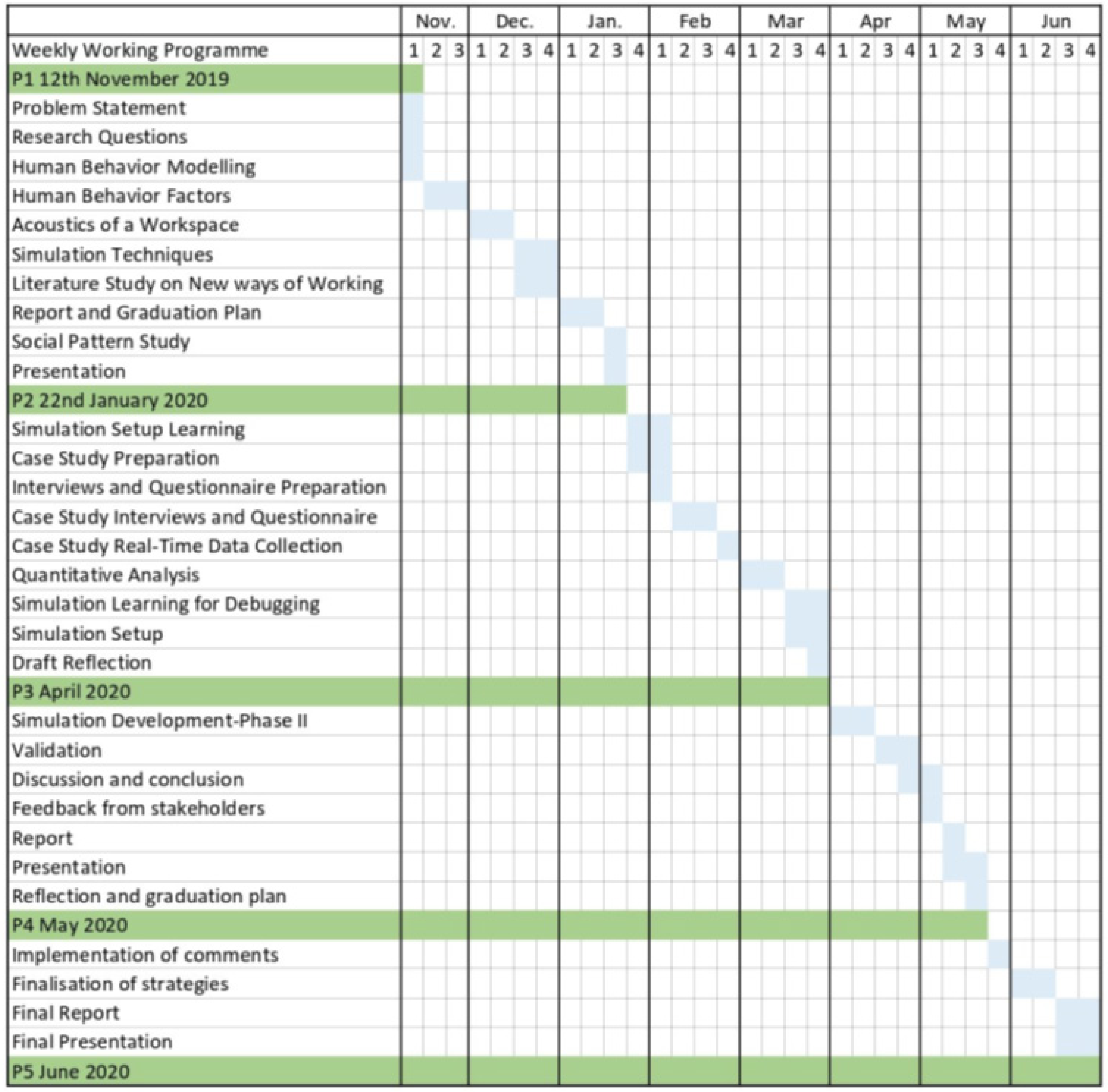
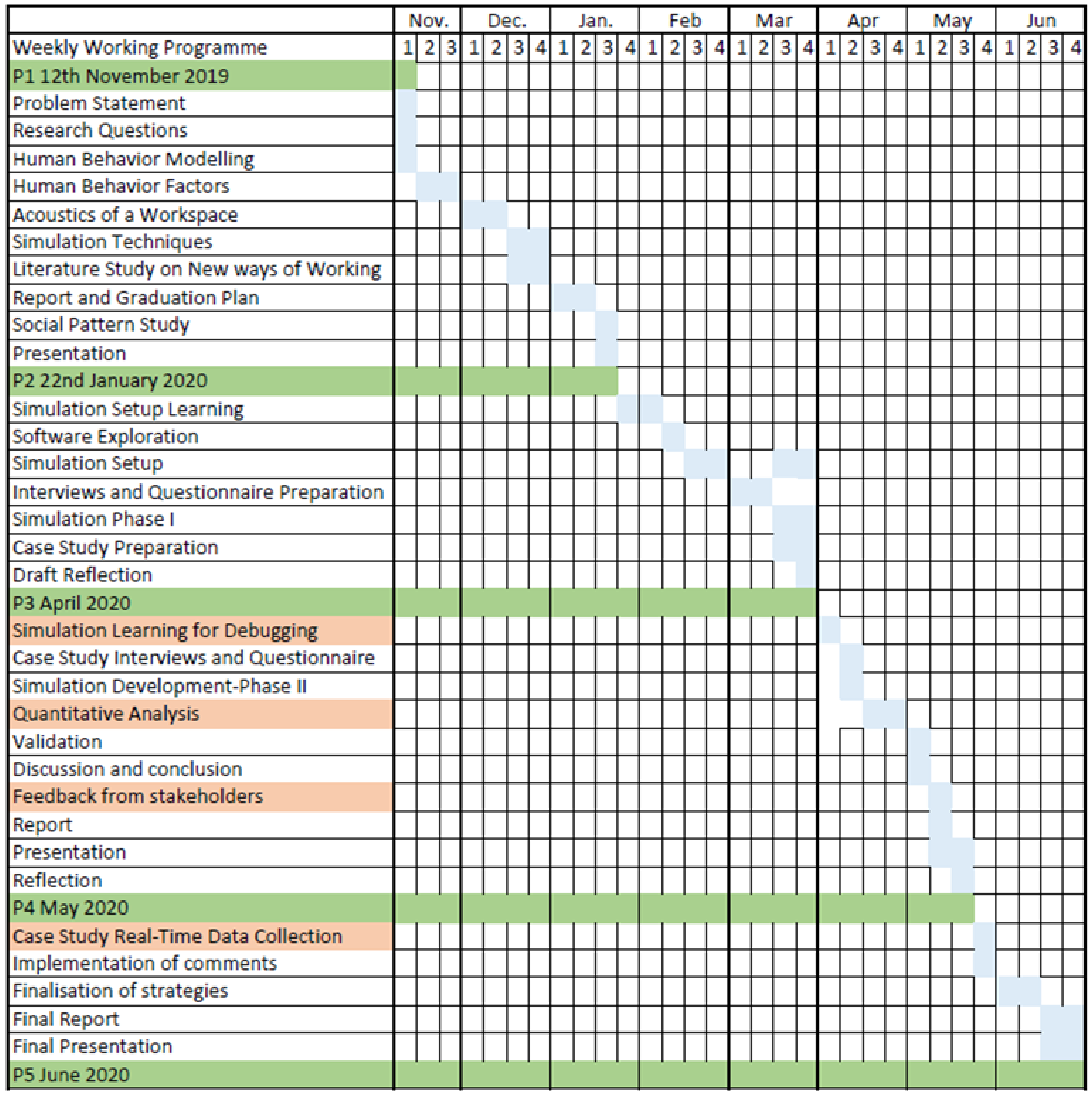
b. taxes my reserves

5. In a classroom situation, I prefer …..
a. group work, interacting with others.
b. individual work

10. Where do you consider your speech level?
a. Loud
b. Neutral
c. Soft

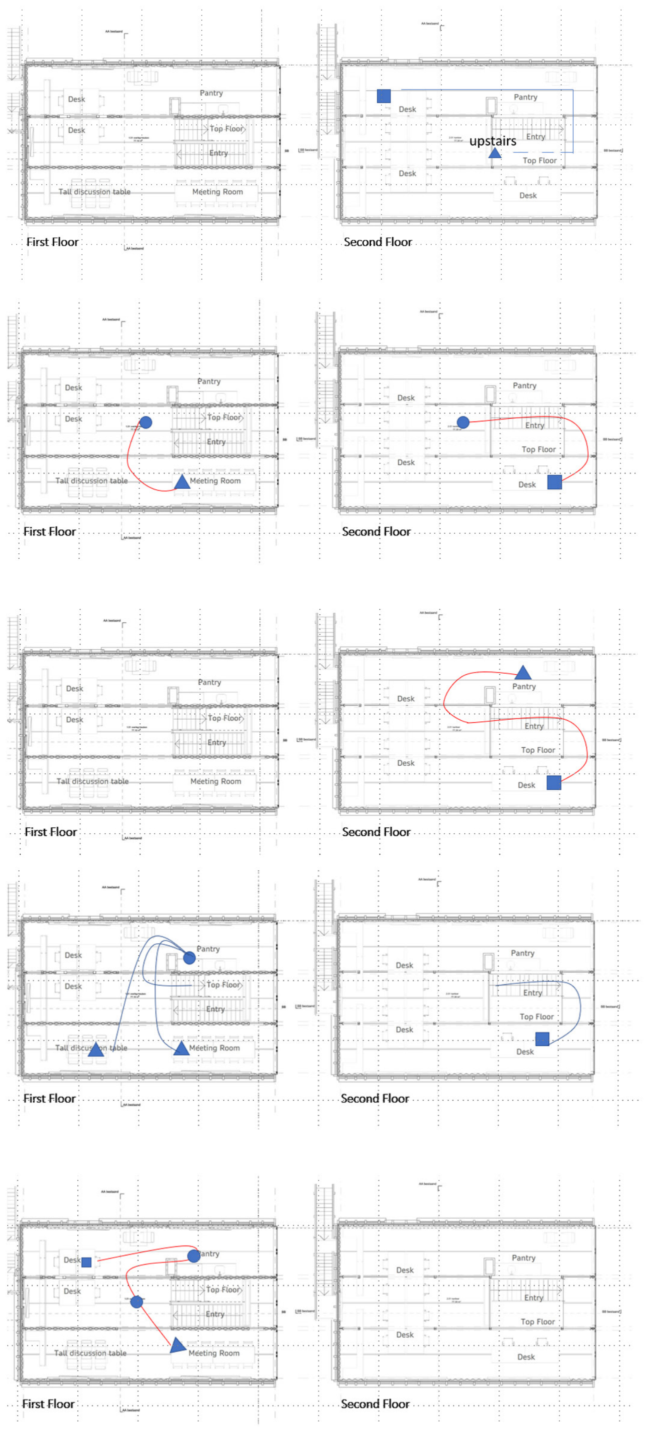
B. GRADUATION PLANNING



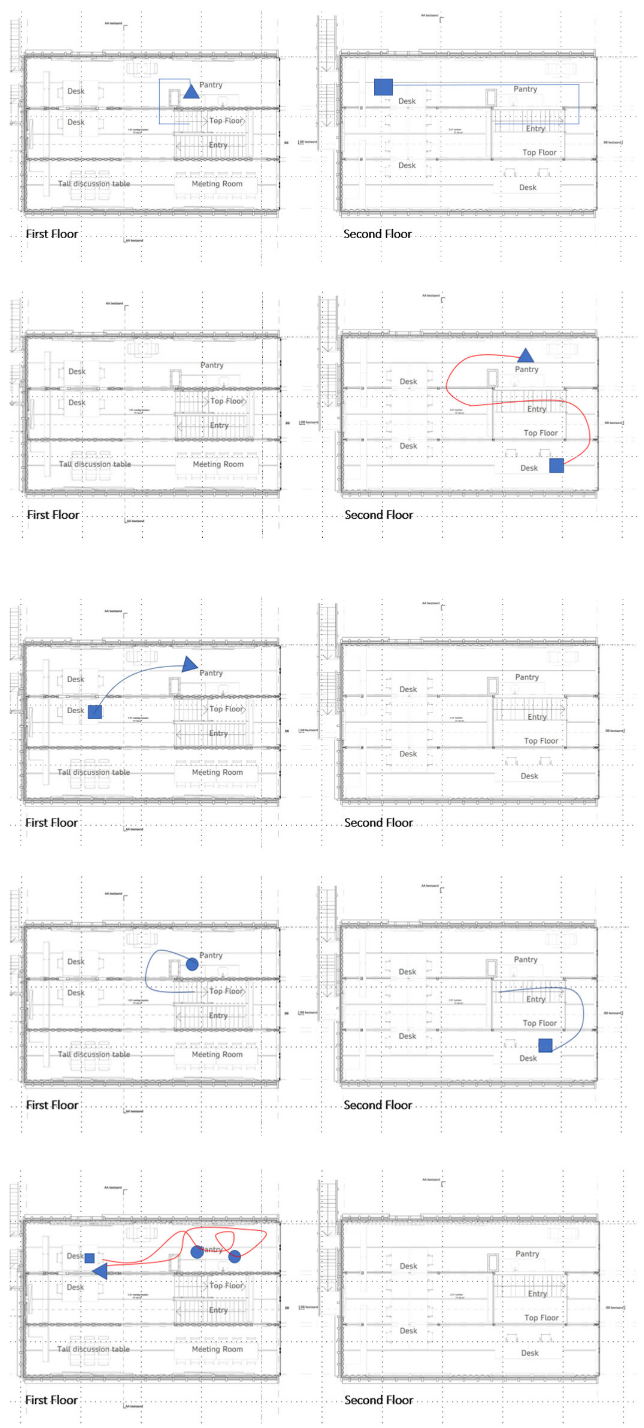


C. SURVEY RESPONSES FOR PATH IN CASE STUDY A

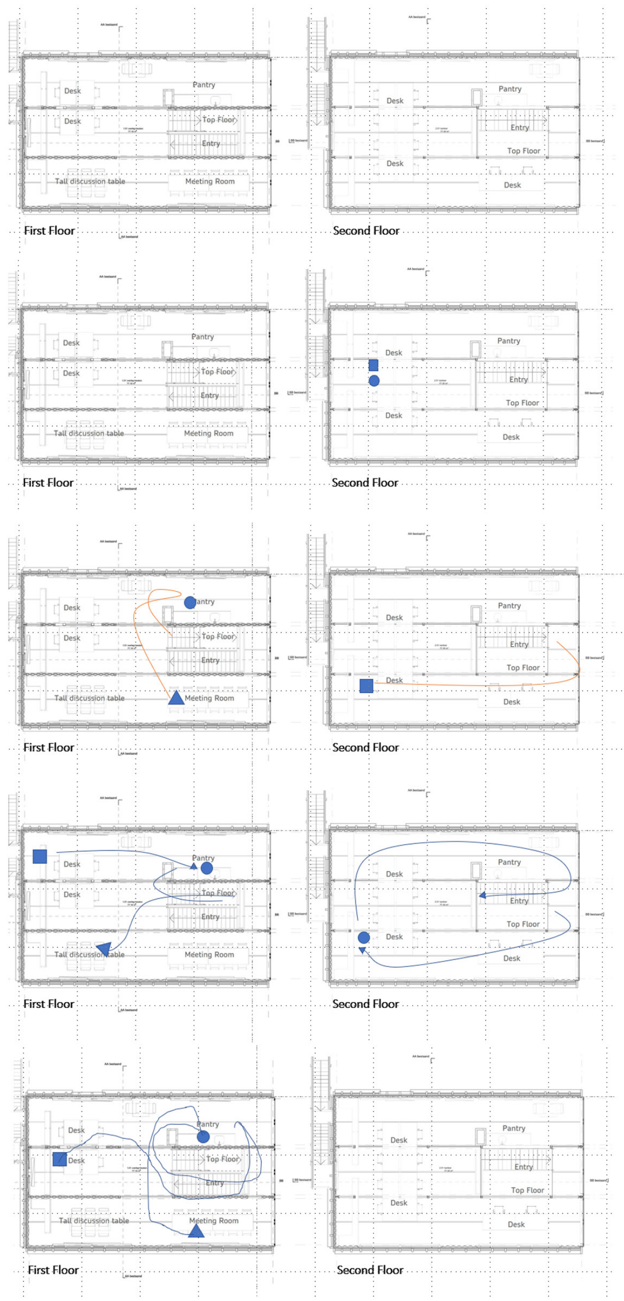
Path taken for meeting



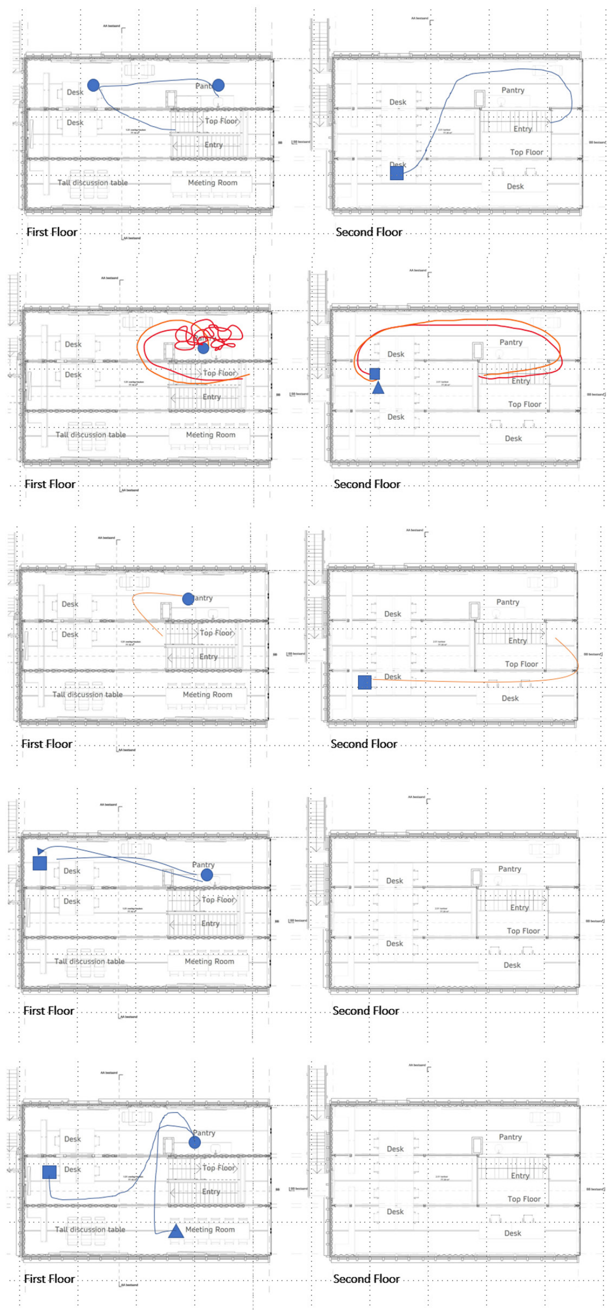
Path taken for break



Path taken for meeting



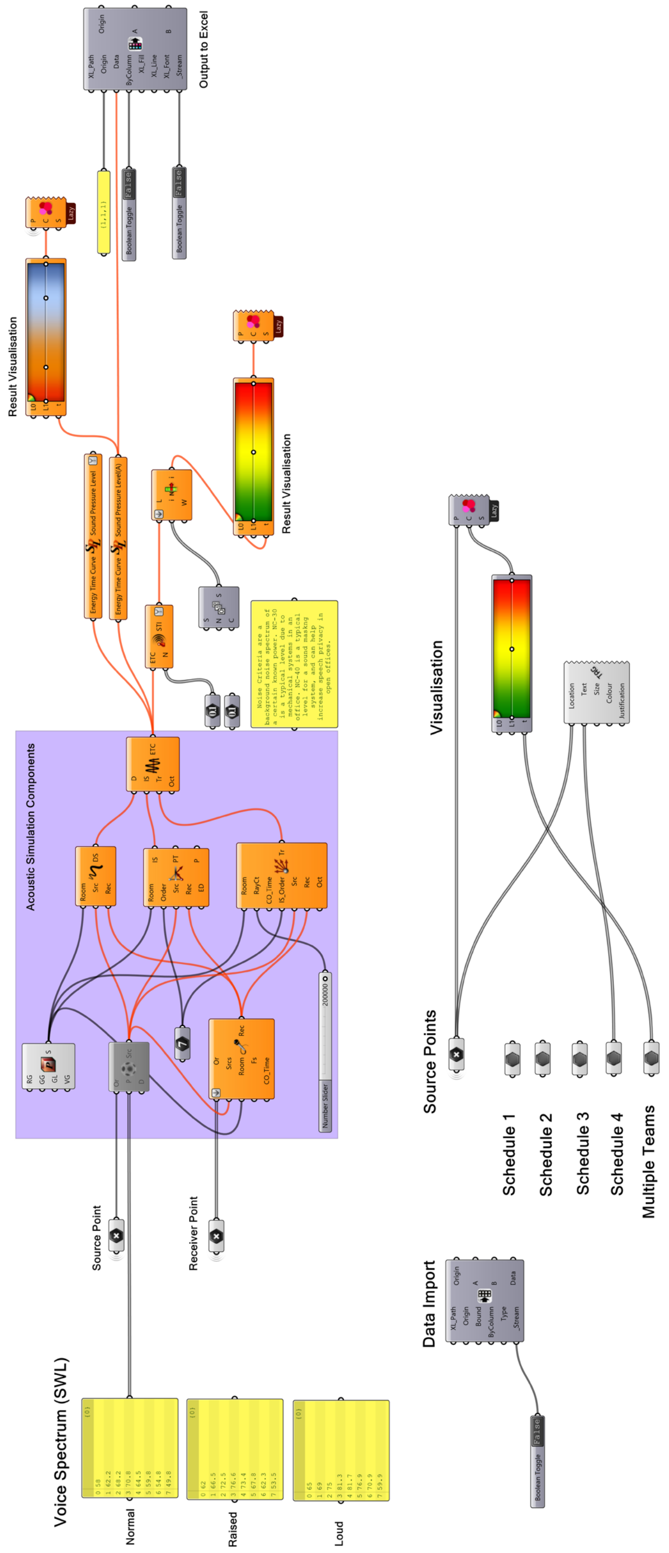
Path taken for break



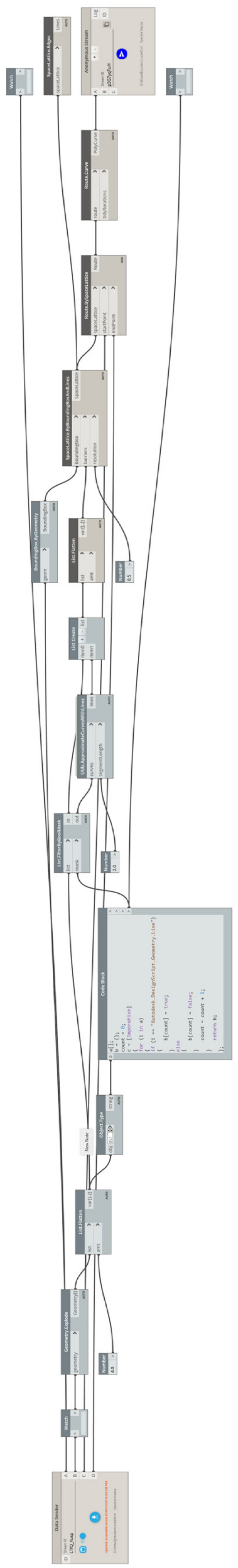
D. A-WEIGHTED SPL IN dB AT RECEIVER POINTS FOR CASE STUDY A

Source Position	Speech level	Receiver Positions														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	Normal	46.9	49	42	43.6	32.9	32.8	38.5	30.8	32.3	35.5	50.6	53.4	33.5	33.5	68.8
	Raised	54	56.1	49.3	50.8	40.1	40.1	45.7	38	39.5	42.6	57.7	60.5	40.6	40.6	75.8
	Loud	61.3	63.4	56.6	58.1	47.7	47.6	53	45.4	46.8	49.9	65	67.8	48.1	48.1	83
B	Normal	44.7	41.1	45.1	47.5	46	44.4	44.9	45.8	46.2	49.2	39.8	36.6	59.6	59.6	34.1
	Raised	51.7	48.2	52.1	54.6	53.2	51.6	52.1	52.9	53.4	56.3	46.9	43.7	66.6	66.6	41.4
	Loud	58.9	55.3	59.3	61.8	60.4	59	59.5	60.3	60.7	63.6	54.1	50.9	73.8	73.8	48.7
C	Normal	43.6	44.4	37.8	36.5	55.8	56.6	55.9	56.5	56.7	55.7	42.6	41.1	50.1	50.1	34.7
	Raised	50.6	51.3	45	43.5	62.8	63.7	62.9	63.6	63.8	62.8	49.5	48.3	57.2	57.2	42
	Loud	57.6	58.2	52.5	50.9	70.1	70.9	70.1	70.8	71.1	70	56.5	55.5	64.5	64.5	49.2

E. COMPUTATIONAL SCRIPTS

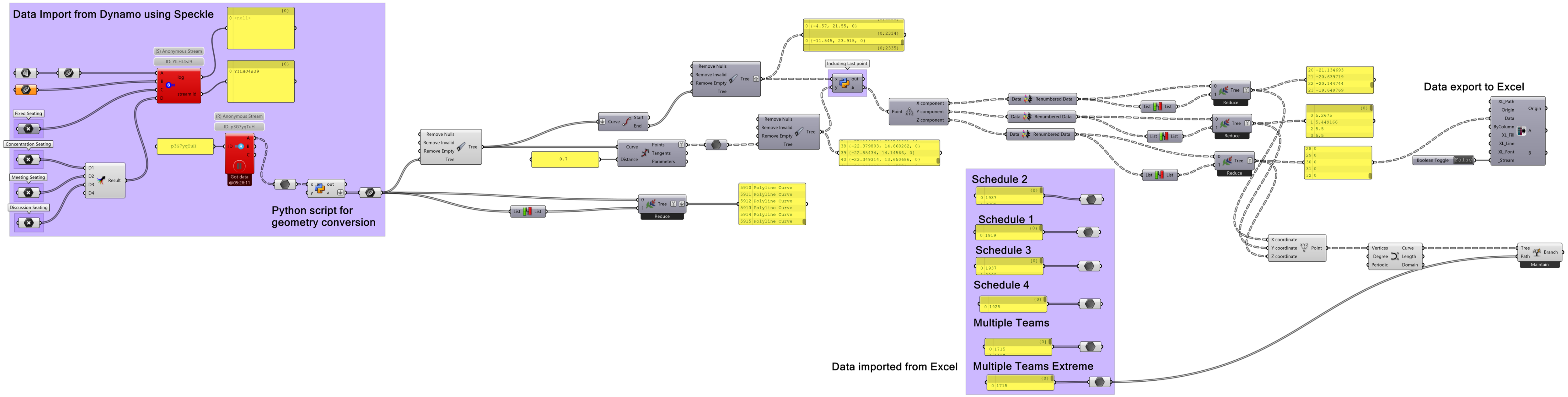


Acoustic simulation and visualisation



Trajectory Generation using Space analysis in Dynamo

Data transfer for paths and trajectory visualisation



Schedule Generator for Agents