ACOUSTICAL DESIGN STRATEGIES FOR OPEN-PLAN WORKSTATIONS IN GREEN OFFICE BUILDINGS

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FACULTY OF BUILT ENVIRONMENT
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ACOUSTICAL DESIGN STRATEGIES FOR OPEN-PLAN WORKSTATIONS IN GREEN OFFICE BUILDINGS

ABSTRACT

Although it was well established that acoustic is a significant environmental stressor, it was often overlooked as an environmental element in office design. Being a quarter part of indoor environmental quality (IEQ), the introduction of green building movement was anticipated to bring improvement to all aspects of the IEQ including acoustics. Unfortunately, it did not seem to be the case. At present, office is the most prominent type of workplaces, and open-plan office is the most favourable type of offices. Acoustic quality in offices is essential as people spend most of their waking hours in the office. Good acoustic quality is achievable through design measures which consciously complement the acoustical environment. With regards to green office buildings in Malaysia, there is a gap in knowledge where this area of study has yet to be explored. Hence, before any proposal of acoustical design measures can be made, understanding of the underlying acoustic conditions in open-plan offices in green office buildings in Malaysia is essential. Therefore, the first two objectives of this study are to evaluate the level of acoustic quality in selected open-plan offices and identify the green design elements that influence the acoustic quality in those same open-plan offices. Understanding the basic acoustic and design conditions would assist in the investigation of suitable alternatives of design strategies and variables, and the formulation of design measures that need to be taken to achieve acoustically comfortable open-plan offices. This study was done using the combination of case study through site visits, observations, and field measurement; as well as computer modelling and acoustic simulation on experimental open-plan office layouts. Data findings revealed that internal design elements such as partitions between workstations and the layout arrangements play a significant role in achieving speech privacy in open-plan offices. However, design measures should not be limited to internal design strategies alone as

attention towards other design factors such the room geometry and consideration of all relevant acoustic parameters could help in attaining acoustically comfortable open-plan offices.

Keywords: acoustic, acoustic design, open-plan offices, green buildings

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ABSTRAK

Akustik merupakan satu daripada punca tekanan persekitaran yang mustahak. Walaubagaimanapun, ia sering diabaikan dalam proses reka bentuk persekitaran ruang pejabat. Akustik merupakan salah satu daripada empat aspek Kualiti Persekitaran Dalaman (IEQ). Pengenalan terhadap pergerakan Bangunan Hijau dijangka dapat membawa kemajuan dan penambahbaikan terhadap semua aspek-aspek IEQ termasuklah akustik. Malangnya, jangkaan tersebut tidak berlaku seperti yang diharapkan. Pada masa kini, pejabat merupakan sejenis ruang bekerja yang paling terkenal, dan pejabat pelan-terbuka merupakan sejenis ruangan pejabat yang paling digemari. Kualiti akustik di dalam ruang pejabat merupakan satu aspek yang penting memandangkan kebanyakan orang menghabiskan sebahagian besar masa mereka di pejabat. Kualiti akustik yang baik boleh dicapai melalui langkah-langkah reka bentuk yang mengambil kira tentang persekitaran akustik secara khusus. Dalam perihal bangunan pejabat hijau di Malaysia, terdapat jurang dalam ilmu pengetahuan di mana bidang ini masih belum diterokai. Oleh yang demikian, sebelum sebarang langkah reka bentuk akustik boleh di cadangkan, pemahaman tentang keadaan akustik asas di pejabat pelan-terbuka dalam bangunan pejabat hijau di Malaysia adalah diperlukan. Sehubungan itu, dua objektif pertama di dalam kajian ini adalah untuk menilai aras kualiti akustik di dalam pejabat pelan-terbuka yang terpilih, serta mengenal pasti elemen reka bentuk hijau yang mempengaruhi kualiti akustik tersebut. Pemahaman tentang keadaan akustik dan rekaan bentuk asas akan membantu dalam proses mengenal pasti strategi reka bentuk alternatif dan seterusnya dalam pembentukan langkah-langkah reka bentuk yang perlu diambil untuk mencipta ruang pejabat pelan-terbuka yang selesa secara akustik. Kajian ini dijalankan dengan mengguna pakai gabungan kaedah penyelidikan kajian kes melalui lawatan tapak, pemerhatian, dan ukuran lapangan; serta simulasi akustik keatas susun atur pejabat pelan-terbuka eksperimentasi. Hasil penemuan data menunjukkan bahawa elemen reka bentuk dalaman seperti sesekat diantara stesen-stesen kerja serta susun atur ruang pejabat memainkan peranan yang penting dalam pembentukan “speech privacy” dalam pejabat pelan-terbuka. Walaubagaimanapun, usaha reka bentuk tidak boleh dihadkan kepada strategi reka bentuk dalaman semata-mata. Perhatian terhadap faktor reka bentuk lain seperti geometri pejabat pelan-terbuka serta pertimbangan keatas semua parameter akustik yang berkenaan juga boleh membantu dalam usaha mencapai ruang pejabat pelan-terbuka yang selesa secara akustik.

Kata kunci: akustik, reka bentuk akustik, pejabat pelan-terbuka, bangunan hijau

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LIST OF SYMBOLS AND ABBREVIATIONS

3D	:	Three dimensional
BEI	:	Building Energy Index
BN	:	Background noise
BREEAM	:	Building Research Establishment Environmental Assessment Methodology
CASBEE	:	Comprehensive Assessment System for Built Environment Efficiency
dB	:	Decibel
dBA, dB(A)	:	A-weighted decibel
DOSH	:	Department of Occupational Safety and Health
$D_{2,\mathrm{S}}$	:	Spatial decay rate of A-weighted SPL of speech
EE	:	Energy efficiency
GEO	:	Green Energy Office
GBI	:	Green Building Index
GBRT	:	Green building rating tools
Hz	:	Hertz
IAQ	:	Indoor air quality
IEQ	:	Indoor environmental quality
JND	:	Just noticeable difference
LEED	:	Leadership in Energy & Environmental Design
LEO	:	Low Energy Office
$L_{p,\mathrm{A,S,4\,m}}$	:	A-weighted SPL of speech at 4 meters
LR	:	Literature review
m	:	Meter
Max	:	Maximum
min	:	Minimum
ms	:	Milliseconds

NC	:	Noise criteria
OPO	:	Open-plan offices
OSHA	:	Occupational Safety and Health Administration
POE	:	Post occupancy evaluation
P_{HEIGHT}	:	Partition height
P_{TYPE}	:	Absorptive partition type
r_D	:	Distraction distance
r_P	:	Privacy distance
RT	:	Reverberation time
RWH	:	Rainwater harvesting
s, sec	:	Seconds
SI	:	Speech intelligibility
SLM	:	Sound level meter
SPL	:	Sound pressure level
SS	:	Sound source
STI	:	Speech transmission index
W_{LA}	:	Workspace layout arrangement
W_{SIZE}	:	Workstation size
$W_{DENSITY\_RATIO}$	:	Workspace density ratio

LIST OF APPENDICES

CHAPTER 1: INTRODUCTION

This chapter will outline the basis of the research work. It will discuss the research issue and problems, the central research questions, and the aim and objectives of the research. The thesis structure would also be addressed and research methods applied in the study will also be highlighted in accordance with the research objectives. The outline of the whole thesis work will also be summarised at the end.

1.1 Research Background

Nowadays, people generally spend 80 to 90% of their time indoors (Frontczak & Wargocki, 2011; Kamaruzzaman & Sabrani, 2011). Out of the said percentage, career driven people mostly spend their '9 to 5' at work, for at least five days a week; which amount to a minimum of 40 hours per week, just working. This conjecture excluded the time some people have to commit for 'over-time' due to their heavy workload and financial needs.

Since office is considered as the most prominent type of working place (Danielsson, 2010; Danielsson & Bodin, 2010; Veitch, 2012), it is only common that the majority of working people tend to spend most of their time indoors, in the office. Thus, it is evident that an indoor office environment needs to achieve a certain level of quality. This is important because occupants' sense of comfort in their office relates closely to their health, well-being, behaviour, and productivity (Heerwagen, 2000; Hodgson, 2008; McGuire & McLaren, 2009; Danielsson, 2010; Veitch, 2012).

In designing an office environment that would work in favour of the occupants physically and psychologically, design criteria called the indoor environmental quality (IEQ) was introduced (Cone, 1998). IEQ is made up of many elements, but the four essential environmental factors are thermal comfort, indoor air quality (IAQ), visual comfort, and acoustic comfort (Bluyssen, 2009; Sakhare & Ralegaonkar, 2014).

Acoustics is one of the crucial elements in creating a practical office environment. It relates closely to human health and well-being; by its influence on human stress level, motivation, and productivity (Evans & Johnson, 2000; Bradley, 2003; Salter et al., 2003; Singh et al., 2010). However, it is one of the most undermined factors among other IEQ elements.

The acoustical design of an office environment can either enhance a person's productivity or damage it. A person's work efficiency is more likely to increase when they are working in a comfortable workplace with distraction-free environment, which at the same time assists easy verbal communication between co-workers. Conversely, a person's productivity would tend to decrease when they are working in a noisy and uncomfortable workplace (Venetjoki et al., 2006; Hodgson, 2008). Moreover, noisy and uncomfortable working space would create disturbance and break concentration; and eventually resulted in stressful occupants (Sundstrom et al., 1994; Evans & Johnson, 2000). According to the survey done by The Centre for the Built Environment (CBE) at University of California, Berkeley; over 50% of occupants working in cubicles reported that the poor acoustics in their offices tends to distract them from getting their work done (Jensen, Arens, & Zagreus, 2005).

Poor acoustic environment is not only bad for employees' work performance and productivity, but it is also depriving to their health and well-being. Exposure to loud noises can cause annoyance, cardiovascular disease, sleep disturbance, and psychiatric disorder (Stansfeld & Haines, 1997; Basrur, 2000; Stansfeld & Matheson, 2003; McReynolds, 2005). Meanwhile, Burt (1996) found that low-frequency noises originated from mechanical ventilation system could cause health symptoms which related to Sick Building Syndrome (SBS) such as fatigue, headaches, nausea, difficulties in concentration, dizziness, and many other negative symptoms.

The green building movement raised concerns on so many aspects of the building and construction industry. However, the ultimate purpose of green building movement is to be ‘sustainable’ (Kibert, 2004; Hodgson, 2008). One of the branches of sustainability in green building movement is to provide an aspect of sustainability for the end users. In other words, green buildings should provide spaces which can promote occupants’ health and well-being. The way green building approaches this aspect is through the measure of indoor environmental quality (IEQ). With the introduction of green building rating tools (GBRT) such as LEED (USA), BREEAM (UK), CASBEE (Japan), Green Star (Australia), Green Mark (Singapore), and Malaysia’s Green Building Index (GBI), improvement in IEQ levels were highly expected.

A post-occupancy evaluation (POE) was done by Abbaszadeh et al. (2006) on LEED-certified office buildings to evaluate the effectiveness of GBRT towards the occupants’ satisfaction. The evaluation was done to identify the differences between occupants’ satisfaction on the IEQ in green buildings and non-green buildings. The findings concluded that as overall, occupants in green buildings were more satisfied with their IEQ compared to those in non-green buildings. However, the satisfaction level of acoustic quality for occupants in green buildings did not show any major improvement when compared to the findings on occupants in non-green buildings. The satisfaction level for acoustics environment in green and non-green buildings were both recorded on the negative side. What’s even worse, the occupants’ satisfaction level for acoustics quality in green buildings was recorded lower than those in non-green buildings’ (See Figure 1.1).

Mean satisfaction score	Database buildings: all (non-green)	Database buildings: age<15 (non-green)	LEED-rated / green buildings
Office Layout	0.95	1.03	0.94
Office Furnishings *	0.84	1.03	1.26
Thermal Comfort *	-0.16	0.17	0.36
Air Quality * ^	0.21	0.52	1.14
Lighting	1.12	1.16	1.08
Acoustics	-0.20	-0.01	-0.27
Cleaning and Maint…*	0.91	1.15	1.48
Overall Workspace *	0.84	1.03	1.13
Overall Building *	0.93	1.14	1.47
Number of buildings	160	35	21

* Difference b/w LEED-rated/green and the rest of CBE database is statistically significant.
^ Difference b/w LEED-rated/green and new buildings in the rest of CBE database (age<15) is statistically significant.

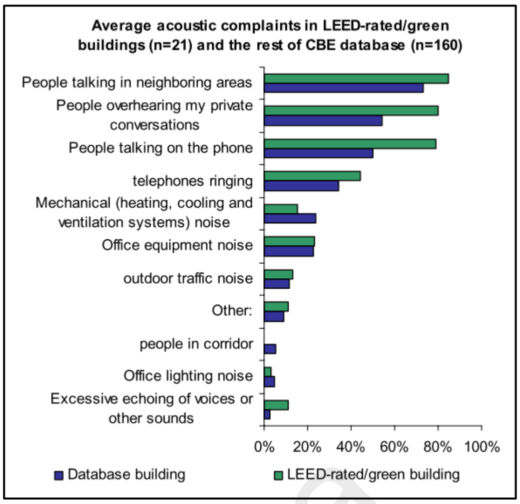


Figure 1.1: Comparison on satisfaction score on IEQ items between green and non-green buildings; and the types of acoustic complaints recorded in the study. (Source: Abbaszadeh et al., 2006).

Further discussions of the POE results showed that the main acoustics complaints recorded in the survey were: “people talking in neighbouring area”, “people overhearing my private conversation”, “people talking on the phone”, and “telephone ringing” (Abbaszadeh et al., 2006). These complaints suggested that occupants concern on the acoustic quality in their workplaces focus more towards the lack of speech privacy (Jensen et al., 2005). Good speech privacy is when speech is incomprehensible to the unintended listener. Muehleisen (2010) stated that the lack of speech privacy was a result of low level of background noise.

According to Hodgson (2008), the US’s LEED basically disregards the consideration for acoustic, which makes it very unlikely to be taken as an essential aspect by architects and building designers. This was confirmed by Lee and Guerin (2009) in their study on occupants’ satisfaction and performance in LEED-certified buildings. The study explained that LEED’s IEQ requirement addressed only on issues related to mechanical aspects of the indoor environment such as IAQ, low emitting materials, indoor chemical and pollutant source control, controllability of systems, thermal comfort, and daylighting systems. Factors such as space layout, ergonomics, electric and natural lighting, acoustics, and aesthetic; which would contribute to healthy, comfortable, and productive indoor environment were slightly ignored. It was later shown in the findings that occupants' satisfaction in acoustic quality in LEED-certified buildings was very poor (See Figure 1.2).

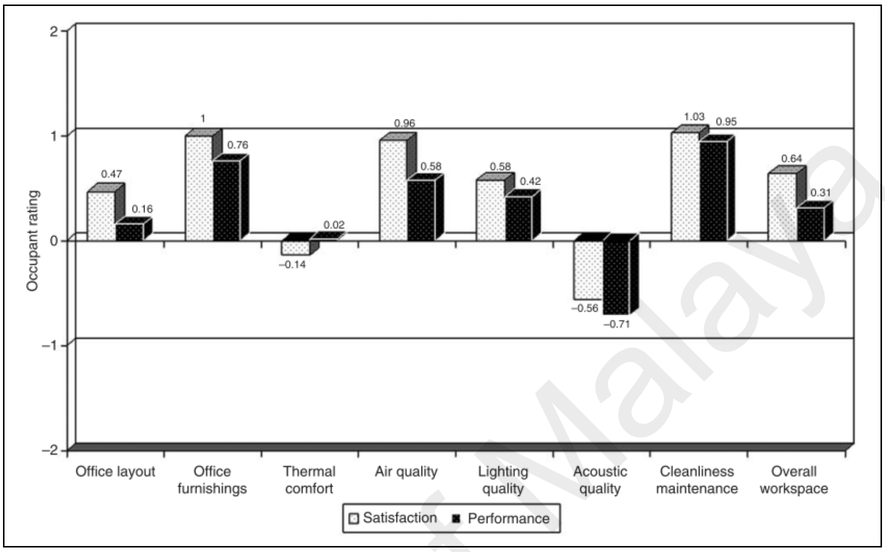


Figure 1.2: Mean score distribution for occupant satisfaction and performances as reported in Lee & Guerin (2009).

Meanwhile, in Malaysia's GBI, IEQ is the second most important requirement that has to be taken into consideration. The requirement stated that its purpose is "to achieve good quality performance in indoor air quality, acoustics, visual, and thermal comfort" (Green Building Index, 2009). Figure 1.3 illustrates the consideration for IEQ under the GBI assessment criteria for Non-Residential Building Category.

PART	ITEM	MAXIMUM POINTS	SCORE
1	Energy Efficiency	35	
2	Indoor Environmental Quality	21	
3	Sustainable Site Planning & Management	16	
4	Material & Resources	11	
5	Water Efficiency	10	
6	Innovation	7	
	TOTAL SCORE	100	

Figure 1.3: Overall score points of GBI assessment criteria.
(Source: Green Building Index, 2009)

Even though IEQ requirement is regarded highly as the second most important element in the GBI assessment criteria with a total score point of 21 points, only one score point is reserved for acoustic quality. This reserved point can be found under the requirement EQ 13 – Internal Noise Level (Green Building Index, 2009). Figure 1.4 illustrated the breakdown of allocated score points for IEQ in GBI and how little attention was given to acoustic comfort. Seemingly, low attention to acoustic quality does not only occur in US's LEED but also in Malaysia's GBI. This is not entirely unexpected as the GBI was mainly modelled after the US's green building rating tool LEED (Green Building Index, n.d.).

PART	CRITERIA	ITEM	POINTS	TOTAL
2	EQ	INDOOR ENVIRONMENTAL QUALITY		21
	Air Quality			
	EQ1	Minimum IAQ Performance	1	
	EQ2	Environmental Tobacco Smoke (ETS) Control	1	
	EQ3	Carbon Dioxide Monitoring and Control	1	
	EQ4	Indoor Air Pollutants	2	
	EQ5	Mould Prevention	1	
	Thermal Comfort			
	EQ6	Thermal Comfort: Design & Controllability of Systems	2	
	EQ7	Air Change Effectiveness	1	
	Lighting, Visual & Acoustic Comfort			
	EQ8	Daylighting	2	
	EQ9	Daylight Glare Control	1	
	EQ10	Electric Lighting Levels	1	
	EQ11	High Frequency Ballasts	1	
	EQ12	External Views	2	
	EQ13	Internal Noise Levels	1	
	Verification			
	EQ14	IAQ Before & During Occupancy	2	
	EQ15	Post Occupancy Comfort Survey: Verification	2	

Figure 1.4: Assessment criteria score for IEQ items in GBI.
(Source: Green Building Index, 2009)

While it is clear that acoustic is one of the leading factors that need to be considered to achieve excellent IEQ and a crucial element in creating a practical office environment; architects and building designers regularly neglected it. In most cases, design attention would be focused on other aspects of the IEQ such as thermal comfort, IAQ, and visual comfort (Jensen et al., 2005; Hodgson, 2008). Often, these design predispositions practised in green buildings were the cause of poor acoustic quality in green buildings. Design strategies tailored to optimise other sustainability factors such as the energy efficiency (EE) and other IEQ requirements namely IAQ, thermal comfort, and visual comfort; involuntarily work against the favour of the currently unfortunate acoustic performance (Muehleisen, 2010; Hodgson, 2008).

1.2 Research Issue and Problem

The main issue identified for this research is that acoustic quality and satisfaction in green office buildings has no significant improvement when compared to that in non-green office buildings. While acoustic comfort is one of the basic elements of indoor environmental quality (IEQ), acoustic quality has not been given the equal amount of consideration as its counterparts such as indoor air quality (IAQ), thermal comfort, and visual comfort.

There are a few salient problems that can be acknowledged as a contributor to the issue above:

i. There is limited amount of awareness on the importance of good acoustic quality in open-plan offices.

ii. Green building rating tools (GBRT) has inadequate acoustic consideration for open-plan offices.

iii. Design strategies implemented to cater for other IEQ elements contributed to the degradation of acoustic quality in open-plan offices.

1.3 Research Questions

Review of literature revealed the cause and effect of the lack of attention given from LEED towards acoustic comfort and how it affected the acoustic quality and occupant's satisfaction of their acoustic environment. However, this study is interested in exploring the same issue but in the context of Malaysia's architecture. Hence, the study intents on answering these four main research questions:

1. What is the current situation on acoustical performance in open-plan offices in green office buildings in Malaysia?
2. Which green building design elements contribute to the current acoustic quality in open-plan offices in green office buildings in Malaysia?
3. What kind of design strategies that could assist in the acoustic design of open-plan offices in green office buildings in Malaysia?
4. How to improve the acoustic design of open-plan offices in green office buildings in Malaysia?

1.4 Aim and Objectives

This research aims to propose measures to assist in the improvement of the acoustical design in open-plan offices (OPO), specifically open-plan offices in green office buildings in Malaysia. To achieve the main purpose of the study, the objectives are:

1. To evaluate the level of acoustic quality in selected open-plan offices.
2. To identify the green design elements that influences the acoustic quality in selected open-plan offices.
3. To investigate a workable alternative of design strategies that could assist in achieving an acoustically comfortable open-plan office (within the structural parameters of selected open-plan offices).
4. To recommend relevant acoustic parameters and design strategies to be considered for the design of acoustically comfortable open-plan offices.

1.5 Thesis Structure

Figure 1.5 summarises the structure of the thesis. The research work is divided into four main stages.

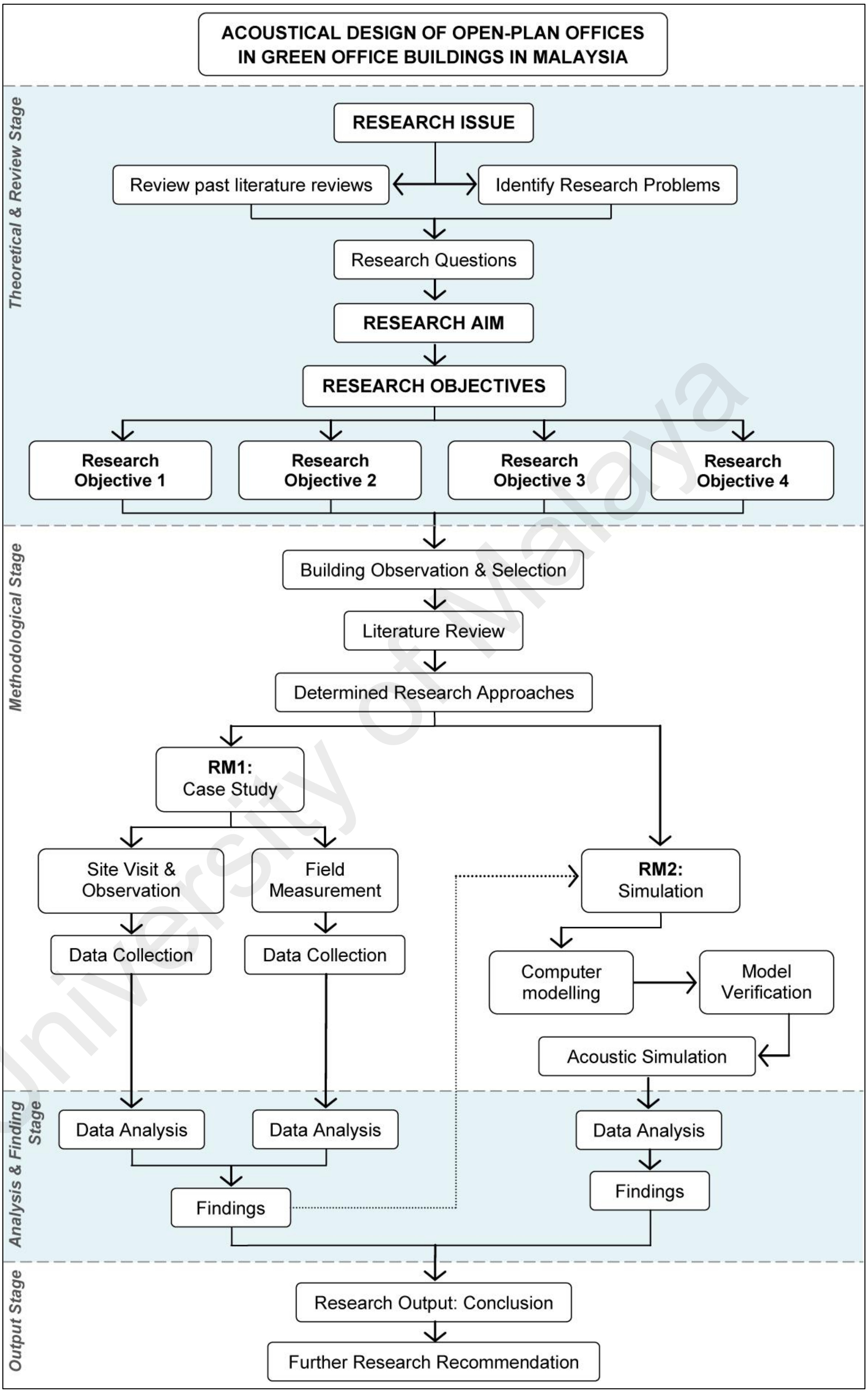


Figure 1.5: Structure of thesis

Stage 1: Theoretical and Review

Previous literature related to acoustics, green buildings, and office buildings were reviewed to identify prior research work related to the topic. Issues and arguments brought up from the studies were then identified and analysed. Further literature reviews were done to determine the research questions which were used in the construction of the study and to corroborate the importance of the study. Research problems were identified to find the possible research gap. Research aim was developed, and objectives were constructed to assist in achieving the aim. Figure 1.6 summarises the workflow of the theoretical and review stage of this research.

Stage 2: Methodology

After the research objectives were established, Malaysia's green architecture was observed for the selection of green office buildings. Three green office buildings were selected as subjects of the research. Research work was done through two research methodologies of case study and simulation. The case study was broken down into two research methods. First one is through literature review and observation which covers the study of background and design elements of selected green office buildings. The second method is through field measurements which covers the acoustical measurement of selected open-plan offices through the measurement of relevant acoustic parameters such as background noise (BN) level, reverberation time (RT), speech transmission index (STI), and sound pressure level (SPL). Simulation consisted of computer modelling and acoustic simulation work of design experimentation of several design strategies and variables on selected open-plan offices. Detail of methodology stage workflow is presented in Chapter 3 (Figure 3.1). Meanwhile, Table 1.1 illustrates the relationship between the research questions, objectives, and the research methods applied in response to them.

Stage 3: Analysis and Findings

Data collected from the two research methodologies would be discussed separately. Data collected from the case study work would be deliberated through a narrative analysis in Chapter 4 (*Case Study*), and acoustics measurement data obtained through the field measurement would be described in a descriptive analysis in Chapter 5 (*Measurement Findings and Analysis*). Meanwhile, results from the simulation work would be analysed thoroughly in Chapter 6 (*Simulation Findings and Analysis*). Detail explanation of the analysis and finding stage workflow is presented in Chapter 3.

Stage 4: Output

This stage would discuss and deliberate on the data findings by linking it to the research questions and objectives. The conclusion would be made by discussing all the findings and responding to the research aim formulated at the beginning of the research work.

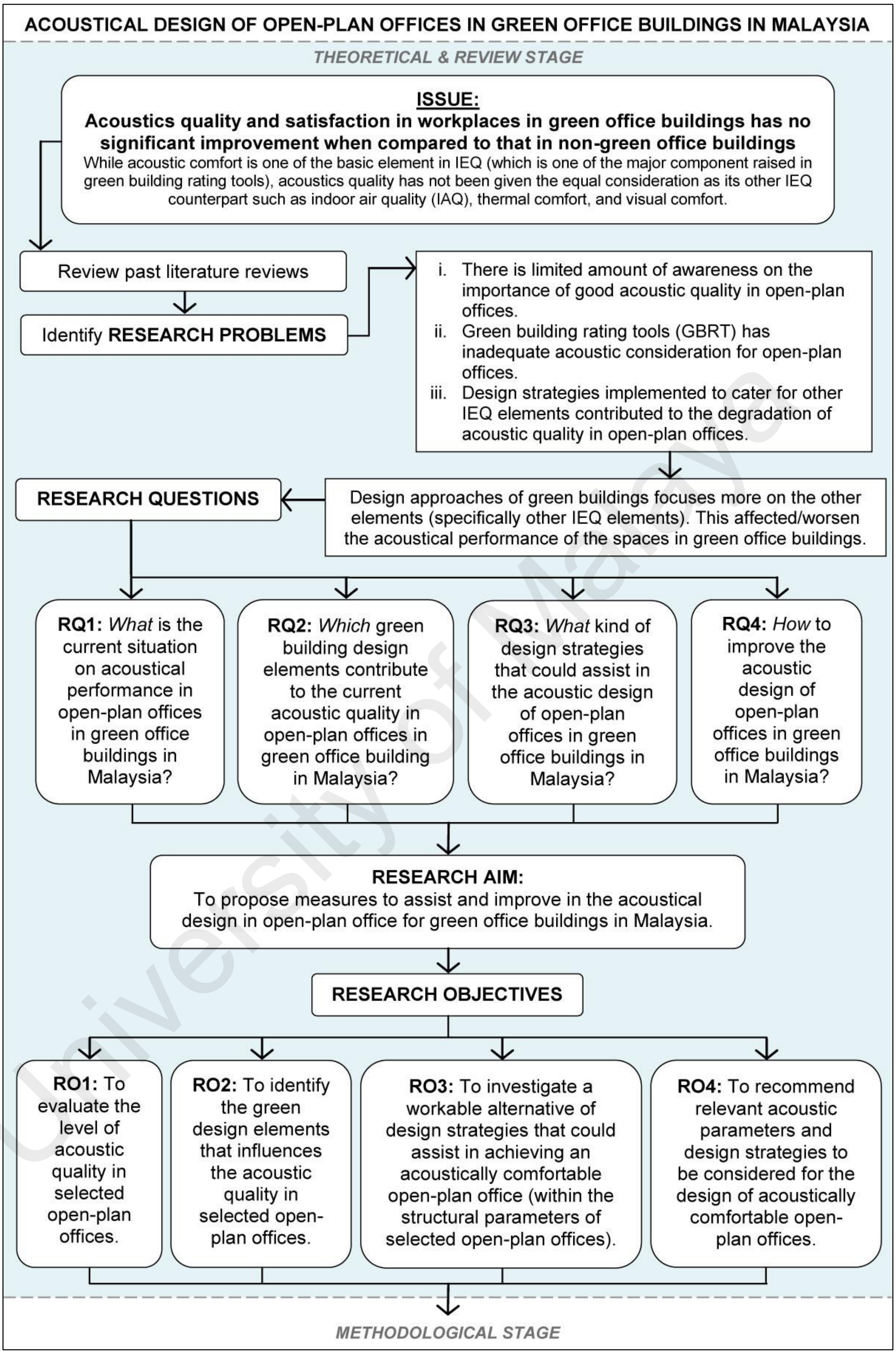


Figure 1.6: Theoretical and review stage workflow

Table 1.1: Methods applied based on research objectives

RESEARCH QUESTIONS	RESEARCH OBJECTIVES	RESEARCH METHODS
1. What is the current situation on acoustical performance in open-plan offices in green office buildings in Malaysia?	To evaluate the level of acoustic quality in selected open-plan offices.	Field measurement
	▪ Understand the current standard of comfortable acoustic level for workplaces.	Literature review (LR) & review of existing acoustical standards.
	▪ Identify the relevant parameters for acoustical measurement in open-plan offices.	
	▪ Identify the methods of acoustical measurement for open-plan office spaces.	
2. Which green building design elements contribute to the current acoustic quality in open-plan offices in green office building in Malaysia?	To identify the green design elements that influences the acoustic quality in selected open-plan offices.	LR & Observation
	▪ Understand how specific design element / features could affect the acoustical quality of open-plan offices.	LR
	▪ Identify the prominent green design elements / features available in selected OPO.	LR & observations
3. What kind of design strategies that could assist in the acoustic design of open-plan offices in green office buildings in Malaysia?	To investigate a workable alternative of design elements that could assist in achieving an acoustically comfortable open-plan office (within the structural parameters of selected open-plan offices).	Computer modelling & acoustic simulation
	▪ Identify the design strategies that could influence the relevant acoustical parameters in OPO.	LR
	▪ Building of design alternatives using the combination of identified design strategies.	Computer modelling
	▪ Simulation of relevant acoustic parameters on design alternatives	Acoustic simulation
4. How to improve the acoustic design of open-plan offices in green office buildings in Malaysia?	To recommend relevant acoustic parameters and design strategies to be considered for the design of acoustically comfortable open-plan offices.	LR & acoustic simulation

1.6 Significance of Study

With the ever-growing demand and supply of office buildings in Malaysia, the bounds of acoustics research need to grow as well. Currently, the study of architectural acoustics in Malaysia is relatively very marginal and selective. While there are studies regarding architectural acoustics in Malaysia, they mostly focused on large-scale acoustically significant buildings such as mosques (Putra et al., 2013; Abdullah & Zulkefli, 2014; Kassim et al., 2014), churches (Che Din, Yong, & Abdul Razak, 2016), or theatre hall (Husin, Syed Mustapa, & Kamal, 2004). Office spaces, on the other hand, get very little attention acoustically.

At present, the study of acoustics in office spaces in Malaysia is very minimal, be it in green office buildings or conventional office buildings. Studies found on acoustic in office buildings are mostly part of an IEQ studies in which acoustics was considered as a minority (Khalil & Husin, 2009; Mahbob et al., 2013). Meanwhile, others studies on occupants' comfort, well-being, and work performances in the office focused on other IEQ elements such as indoor air quality (IAQ), thermal comfort, and lighting and visual comfort (Zain-Ahmed et al., 2002; Aizat et al., 2009; Kamaruzzaman & Sabrani, 2011; Shaharon & Jalaludin, 2012; Lim et al., 2012; Nikpour, Kandar, & Mosavi, 2013; Rahman, Putra, & Nagapan, 2014; Putra, 2015).

Eventhough office acoustics might seem trivial, it is certifiably one the leading causes of physical and psychological concerns in building occupants' health and well-being. To provide the most acoustically optimum workplaces, the current acoustic situation in existing office buildings need to be understood. This study wishes to fill the gap in this area of research by initially recognising and understanding the issues, and further determine not just mere resolutions, but the appropriate ones to counter those issues.

1.7 Scope and Limitation

The scope of the study covers the acoustic quality in green office buildings in Malaysia. Three green office buildings around the Klang Valley area were selected as the sample to represent the building category. Since the primary acoustical concerns in office buildings mainly revolve around the main working spaces, the study focused on studying the acoustical performance in open-plan offices only.

The evaluation of the acoustical performance in the selected open-plan offices was limited to physical measurement through acoustic measurements of selected acoustic parameters only. Assessment of the acoustic performance through the analysis of occupants' satisfaction towards the acoustical environment was not included in the study.

Acoustic simulation stage was done through the simulation of experimental designs via alterations of internal design elements without compromising on the structural elements of the selected open-plan offices. The scope of acoustic simulation work included the verification work done on the 3D computer models used for the experimental designs.

1.8 Summary

The four-stage research work of this study was divided into seven chapters. The output of the first stage (Theoretical and Review) would be divided into the first two chapters namely *Introduction* and *Literature Review.* The second stage (Methodology) would be thoroughly discussed in Chapter 3 which is *Research Methodology*. Analysis and Findings Stage would be divided into three chapters of *Case Study*, *Measurement Findings and Analysis*, and *Simulation Findings and Analysis*. Each chapter would discuss the respective output of the research methods applied in the research. The final stage (Output) would be discussed and concluded in the final chapter called *Conclusion*. Figure 1.7 summarised the outline of the whole thesis.

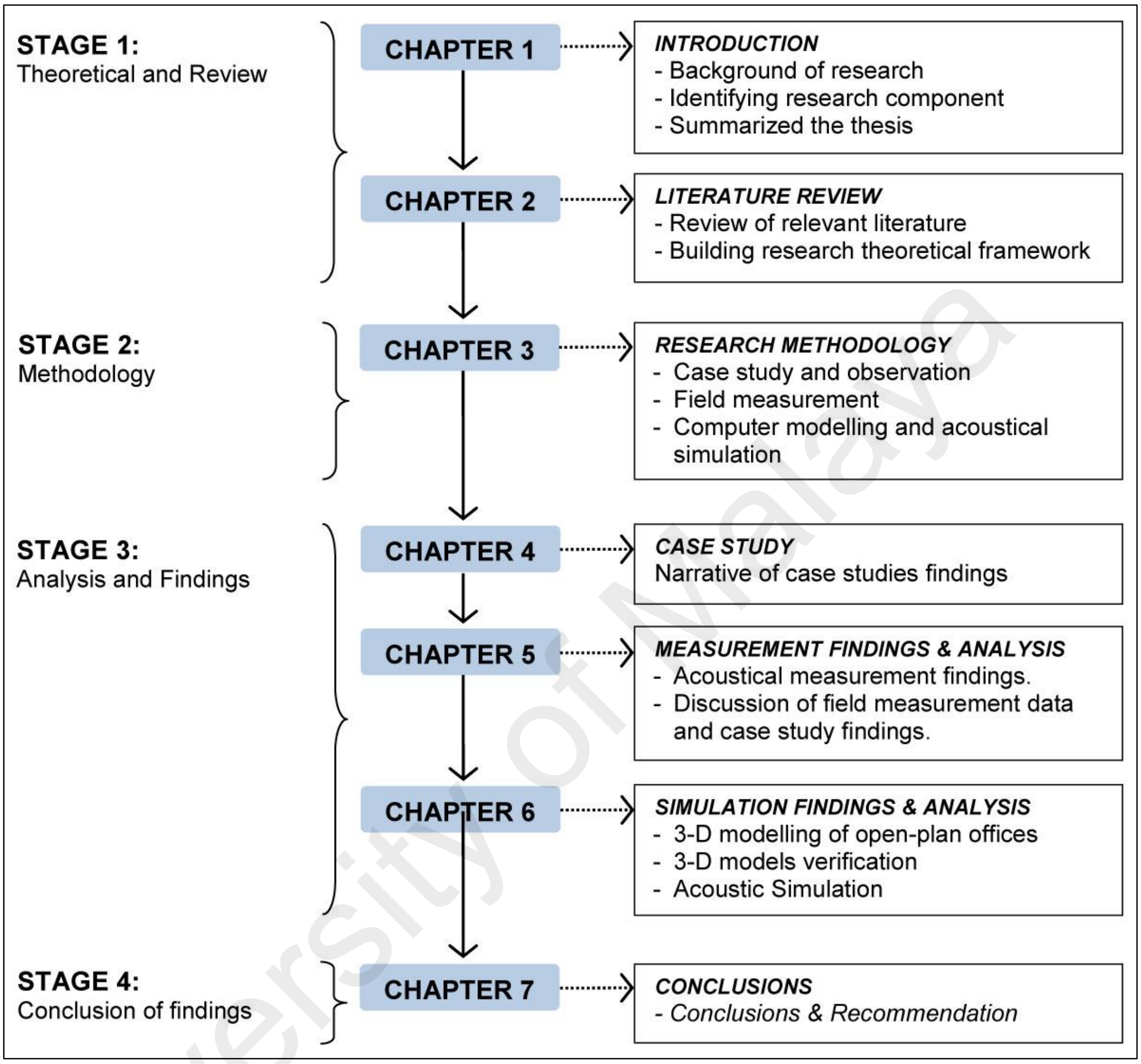


Figure 1.7: Outline of thesis

CHAPTER 2: LITERATURE REVIEW

This chapter will discuss the main keywords of the research. In depth discussion regarding *office / open-plan office* and *acoustics* would be discussed individually and furthermore the interrelationship of the two elements and its effect on *human health* would also be discussed. The chapter would also deliberate on the topic of *green buildings* and its relation to acoustical design in the office environment.

2.1 Green Building

2.1.1 History of the Green Building Movement

The green building movement started from the concept of sustainable development. Sustainable development as defined in the Broundland's Report 1987 is "a development that meets the need of the present without compromising the ability of future generations to meet their own needs." Sustainable development derived from the alarming awareness on the depletion of natural resources and environmental pollution in the 1970s (Xiaoping, Hiumin, & Qiming, 2009). Kibert (2004) mentioned that Rachel Carson book entitled Silent Spring was one of the first efforts in addressing these environmental issues. Attempts on encouraging sustainable development lead to the United Nations Conference on Environmental and Development (UNCED) held in Rio de Janeiro, Brazil in 1992. The by-product of the conference was the document entitled 'Agenda 21'.

In attaining environmental, economic, and social development: building and construction industry plays a very critical role (Zuo & Zhao, 2014). Housing is one of the basic necessities in raising a community. Besides houses, buildings are needed for education purposes (schools and research centres); for economic growth (office buildings, factories, and commercial buildings); for health care (clinics and hospitals); and for spiritual growth (worship places); just to name a few. However, these buildings are massive resources and energy consumers, thus how the concept of green building started.

Kibert (2004) stated that there are several terminologies used to describe the concept of green building. Terms such as green building, sustainable building, sustainable construction, high-performance buildings, and so forth have been used interchangeably to describe green building. Sustainable construction comprehensively addresses the ecological, social, and economic issues of a building in the context of its community, while green buildings are a division of sustainable construction, which represent the structures exclusively.

Green buildings are defined in Kibert (2004) as "facilities designed, built, operated, renovated, and disposed of using ecological principles for the purpose of promoting occupants' health and resource efficiency plus minimizing the impacts of built environment on the natural environment." (p. 491-492). Resource efficiency in this context refers to the efficient usage of energy and water, proper use of land and landscaping, the utilisation of environmentally friendly materials, and minimisation of the life cycle effects of the buildings' design and operation (Nelson, Rakau, & Dörrenberg, 2010).

In the pursuit of sustainable construction through green buildings, green building delivery system in the form of assessment/rating tools were developed. Green building assessment/rating tools were utilised to guide the processes of building construction and assess the performance of the building (Xiaoping et al., 2009).

2.1.2 Green Building Rating Tools (GBRT)

Due to the rapid awareness on green and sustainable development as a way to preserve the environment (Zuo & Zhao, 2014), building stakeholders were actively conscious about green building concepts and the theoretically discussed benefits it offers. This formed scepticism among stakeholders on whether participating in green building would actually offer any tangible benefits in practice. This is where the role of green building rating tools (GBRT) follows. GBRT not only work as guidelines for the process of green building construction, but it also worked as an assessment tool in measuring the building performance; which would later be transformed into benefits for building stakeholders including the owners and the building occupants.

There are many GBRT developed by research organisations to guide and promote green building development. Green building councils developed these assessment tools in their respective country or regions. In general, it is not an obligatory requirement in the construction industry but rather a voluntary tool for building owners and stakeholders that desire their building to be recognised as 'green' (Zuo & Zhao, 2014). Some of the well-known GBRT across the globe are UK's BREEAM, US's LEED, Japan's CASBEE, Australia's Green Star, and Singapore's GreenMark. Furthermore, Malaysia has joined in the green building movement with its very own GBRT called the Green Building Index (GBI). Appendix A summarises the GBRT mentioned above (BREEAM, n.d.; LEED, n.d.; CASBEE, n.d.; Green Star, n.d.; BCA Green Mark, n.d.; Green Building Index, n.d.).

It is undeniable that the main focus of green buildings is directed towards energy efficiency (EE). This fact is highlighted by GBRT assessment criteria credit point systems (BRE Global, 2016; USGBC, 2017; IBEC, 2014; Green Building Council of Australia, 2015; Singapore BCA, 2015a; Green Building Index, 2009), where any criteria regarding 'energy' or 'energy efficiency' are given bigger credit points than any other assessment criteria (See Appendix B). However, while criteria for energy efficiency tackles the issue of depleting environmental resources (Kibert, 2004;

Xiaoping et al., 2009), the importance of health and comfort of the end users of the buildings are imperative, if not more imperative than being ‘energy efficient’. This can be argued by the fact that people or humans are the exclusive reason why all buildings are being built, or in the case of this study, construction of office buildings are meant for working people.

In ensuring human health and comfort in green buildings, GBRT outlined one key assessment criteria to regulate the internal environment of the building. Among the available GBRT, there are some similarities and differences in their requirements and assessment approaches. The differences mostly stem from the distinct weather condition and the local building industry of each country or region. However, the key assessment criteria to tackle the issue of human health and comfort in green buildings, albeit not being labelled precisely similar, exist in every GBRT across the globe and in the six GBRT discussed. This key criterion is most commonly known as Indoor Environmental Quality (IEQ). LEED, Green Star, BCA Greenmark, and GBI referred to this assessment criteria as ‘Indoor Environmental Quality (IEQ)’ (LEED, n.d.; BCA Green Mark, n.d.; Green Star, n.d.; Green Building Index, n.d.). Meanwhile, BREEAM called it ‘Health and wellbeing’ and CASBEE categorised it as ‘Indoor Environment’ (BREEAM, n.d.; CASBEE, n.d.).

Indoor environmental quality (IEQ) deals with environmental elements that occur indoors which relates closely to human health and well-being. As people spend most of their time indoors (Frontczak & Wargocki, 2011; Kamaruzzaman & Sabrani, 2011; Bluyssen, 2009), it is essential to pay attention towards the quality of indoor environmental elements which affected human health, wellbeing, and comfort.

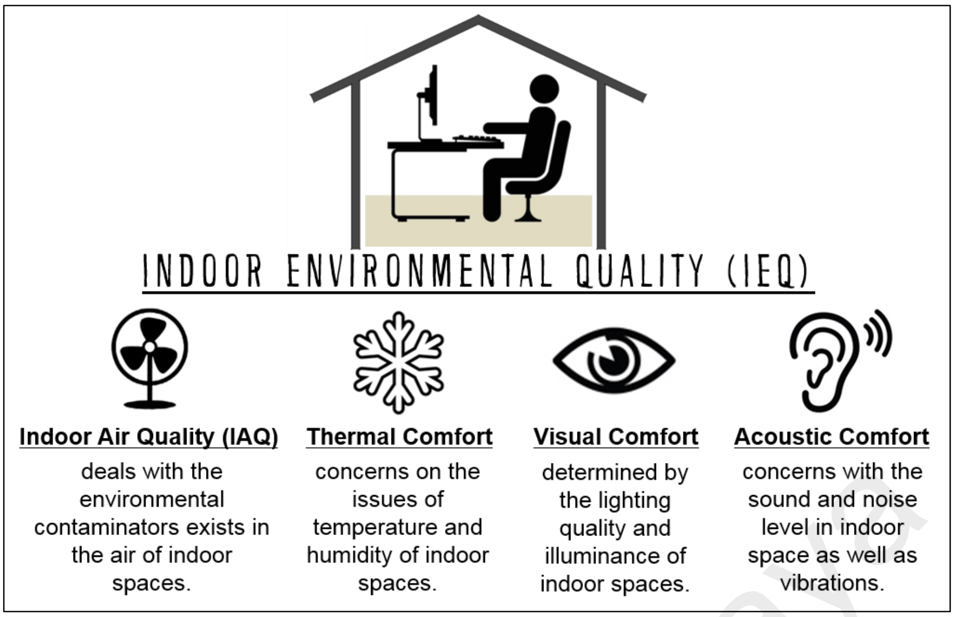


Figure 2.1: The four elements of indoor environmental quality (IEQ)

Indoor environmental quality (IEQ) consisted of various elements that make up the indoor space. Table 2.1 shows the different components that were listed down as the requirements to achieve an optimum IEQ in the six GBRTs discussed. However, in term of environmental parameters, there are four fundamental elements namely indoor air quality (IAQ), thermal comfort, visual comfort, and acoustic comfort (Bluyssen, 2009). Figure 2.1 illustrates and summarises the four environmental elements of IEQ.

2.1.3 Acoustic Requirements in GBRT

Although acoustic comfort has just as much importance as other elements in creating a quality indoor environment, it was often the most neglected criteria among the IEQ elements. Typically, GBRT would provide some credit points for acoustic comfort under its IEQ requirement. However, most of the assessment credit stands for the bare minimum assessment which concerns mainly on the background noise (BN) level. Table 2.1 highlights the credit points allocated for acoustic comfort in the six GBRTs discussed.

Table 2.1: Reserved point for acoustic quality/comfort for the six GBRTs under their respective category

No	GBRT	Category	Assessment Key Criteria	Credits
1.	BREEAM (UK)	Health and Wellbeing (21)	Visual comfort	Up to 6
			Indoor air quality (IAQ)	5
			Safe containment in laboratories	2
			Thermal comfort	3
			Acoustic performance	Up to 2
			Accessibility	2
			Hazards	1
			Private space	1
			Water quality	1
2.	LEED (US)	Indoor Environmental Quality (16)	Minimum IAQ performance	R
			Environmental tobacco smoke control	R
			Enhanced IAQ strategies	2
			Low emitting materials	3
			Construction IAQ management plan	1
			IAQ assessment	2
			Thermal comfort	1
			Interior lighting	2
			Daylight	3
			Quality views	1
			Acoustics performance	1
3.	CASBEE (Japan)	Indoor Environment (3.5)	Sound environment	3.0
			Thermal comfort	4.1
			Lighting and illumination	3.6
			Air quality	3.2
4.	Green Star (Australia & NZ)	Indoor Environmental Quality (17)	Indoor air quality (IAQ)	4
			Acoustic comfort	3
			Lighting comfort	3
			Visual comfort	3
			Indoor pollutants	2
			Thermal comfort	2
5.	BCA GreenMark (Singapore)	Smart and Healthy Building (30)	Indoor Air Quality	10
			Spatial Quality	10 (2)
			Smart Operations	10
6.	GBI (Malaysia)	Indoor Environmental Quality (21)	Air quality	6
			Thermal comfort	3
			Lighting, visual, and acoustic comfort	8 (1)
			Verification	4

The previous version of BREEAM technical manual, the BREEAM International New Construction (2013 Version) merely allocated two (2) credit points for 'Acoustic Performance' in non-residential building category (BRE Global, 2013). The first point is allocated for 'Ambient Noise Level', and the other point is specified for 'Reverberation Time'. Despite the allocation of two (2) credit points, there was still no minimum standard limit. Although the latest BREEAM International New Construction

(2016 Version) (BRE Global, 2016) specified that the credit points for 'Acoustic Performance' is up to 4 (See Table 2.1), the specification changed was purely due to the document update. The actual credit point's allocation for non-residential buildings is still two (2) points with no minimum limit.

On the other hand, LEED's new rating system, LEED v4 for Building Design and Construction (USGBC, 2017) recently added a requirement named 'Acoustic Performance' under its Indoor Environmental Quality (IEQ) criteria. The one (1) credit point requirement (See Table 2.1) was specified for various acoustic concerns such as "room noise levels, speech privacy and sound isolation, reverberation time, and paging, masking, and sound reinforcement systems" (USGBC, n.d.). Unlike BREEAM which itemized its own room-type-specific recommendations for the optimum ambient noise level and reverberation time (BRE Global, 2016); LEED simply stated that these acoustic parameters should correspond to ANSI and ASHRAE standards (USGBC, n.d.) should building owners wish to achieve the one (1) credit point allocated for the criteria. Nevertheless, the previous version of the rating system which is the LEED 2009 for New Construction and Major Renovations (USGBC, 2012) did not allocate any credit point for acoustic performance in any form.

The Japanese green building rating tool CASBEE provided a somewhat equivalent score rating for its IEQ requirement labelled 'Sound Environment' compared to other requirements for IAQ, thermal comfort, and visual comfort (See Table 2.1). While other GBRTs focused on tackling the acoustic performance through its acoustic parameters such as background noise level and reverberation time, CASBEE focused on rating the performance of materials which would, in turn, assist in regulating the acoustic parameters. CASBEE observed three main conditions for 'Sound Environment'. They are the 'Background Noise Level', 'Sound Insulation' (for openings, partition walls, and floor slabs), and 'Sound Absorption' (IBEC, 2014). CASBEE for Building (New Construction) Technical Manual (2014 Edition) (IBEC, 2014) also specified the allowable indoor noise levels for multiple building types such as offices, schools, retailers, restaurants, hospitals, apartments, etc.

In Green Star – Design & As Built v1.1 (Green Building Council of Australia, 2015) the requirement 'Acoustic Comfort' was given three (3) credit points (See Table 2.1) which were specified for three acoustic criteria namely 'Internal Noise Levels', 'Reverberation', and 'Acoustic Separation'. Green Star guidelines on each criterion are quite specific. The 'Internal Noise Levels' requirement stated the maximum noise level that needs to be adhered to according to a specific Australian Standards AS/NZ 2107:2000 and the requirement categorised the maximum noise level according to the type of ventilation system used. The same goes for the acoustic criteria named 'Reverberation'. The criteria 'Acoustic Separation' focused on the properties of materials regarding the noise transmission (Green Building Council of Australia, 2015).

The recently updated Green Mark for Non-Residential Buildings NRB: 2015 (Singapore BCA, 2015a) was an upgrade from the previous version which is the BCA Green Mark for New Non-Residential Buildings (Version NRB/4.1) (Singapore BCA, 2013). The updated version is a completely refurbished tool compared to its predecessor as it arranged the assessment key criteria and renamed them into different names altogether. Previously, the GBRT which is tailor-made for Singapore focused much more towards energy efficiency (EE). Due to this, the criteria for acoustic comfort under the IEQ requirement in BCA Green Mark for New Non-Residential Buildings (Version NRB/4.1) only allocated one (1) Green Mark Point for 'Noise Level' (Singapore BCA, 2013). The new version (Singapore BCA, 2015a) updated the acoustic comfort requirement by making the noise level criteria into a prerequisite and allocated two (2)

Green Mark Points for acoustics under the requirement 'Spatial Quality'. The assessment specified two (2) points for 'Sound Transmission Reduction' and 'Acoustic Report' which is essentially an outline of acoustic considerations made for the building design including the calculation of reverberation time (RT60) (Singapore BCA, 2015b).

As for Malaysia's very own GBI, the acoustic consideration is allocated under the key criteria Indoor Environmental Quality (IEQ) with the allocation of up to 21 credit points. However, the assessment for acoustic only touches on 'Internal Noise Level' for a maximum credit of one (1) point. The GBI Assessment Criteria for Non-Residential New Construction (NRNC) outlined the maximum ambient noise level for general office spaces such as open-plan office and closed offices (Green Building Index, 2009). Table 2.2 summarised the acoustic assessment (related to offices/open-plan offices) specified in the six GBRT discussed above. Specifics on the assessment criteria for these points are compiled in Appedix C.

With recent extensive researches on the importance of indoor acoustic comfort, GBRT such as the BCA Green Mark has indeed responded and updated their assessment considerations for acoustic comfort. For other GBRT such as LEED and BREEAM, despite having upgraded their schemes, the acoustic requirement continued to be a minor criterion. Although, it should not be overlooked that some of the GBRT discussed above such as CASBEE and Green Star do consider acoustic comfort very seriously through their careful assessment requirement which combined the importance of physical acoustic parameters and acoustic properties of building materials.

Table 2.2: Acoustic assessment specified for credit points in the six GBRT

No	GBRT	Acoustic Assessment (related to offices / open-plan offices)	Credits
1.	BREEAM	i) Ambient noise level ii) Reverberation time iii) Noise rating (NR) curves	2
2.	LEED	i) HVAC background noise ii) Sound transmission iii) Reverberation time	1
3.	CASBEE	i) Noise (Background noise level) i) Sound insulation ii) Sound absorption	3.0
4.	Green Star	i) Internal noise levels ii) Reverberation iii) Acoustic separation	3
5.	BCA GreenMark	i) Sound transmission reduction ii) Acoustic report	2
6.	GBI	i) Ambient internal noise levels	1

(See Appendix C)

2.2 Noise, Sound, and Acoustics

2.2.1 Definition of Noise

Noise is known as 'unwanted sound' (Basrur, 2000; McReynolds, 2005; Rabinowitz, 2000; Robinson, n.d.; Stansfeld & Haines, 1997; Stansfeld & Matheson, 2003; Stansfeld, Clark, & Crombie, 2012). Cohen and Weinstein (1982) defined noise as "…a psychological concept and is defined as sound that is unwanted by listener because it is unpleasant, bothersome, interferes with important activities, or is believed to be physiologically harmful." (p. 46).

As most people are affected by its negative impacts, noise has deemed to be a significant component of environmental stressors (Basrur, 2000). It is also considered to be one of the most frequent types of threat under occupational and environmental hazard (Rabinowitz, 2000). However, it has always been placed at the bottom of the environmental priority list because of its least direct life-threatening effects on human health compared to air, water, and hazardous waste (Basrur, 2000).

Humans are exposed to noise every day, and it is impossible to avoid its effects, both the positive and the negative ones. Besides being labelled as an *annoyance* or *nuisance* to most people, the consequences of noise exposure goes beyond the "polite" labels. Besides interfering with activities and communication (Haka et al., 2009), noise exposure was found to affect human health physiologically and psychologically (Stansfeld et al., 2012). Health and Welfare Canada (1989) described *noise* as:

> "Noise is more than just a nuisance since it constitutes a real and present danger to people's health. Day and night, at work and at play, noise can produce serious physical and psychological stress. No one is immune to this stress. People appear to adjust to noise by ignoring it but the ear, in fact, never closes. The body at times still responds with extreme tension, such as to a strange sound in the night." (As cited in Basrur, 2000, p.10).

However, the effects of noise on human health depend on the characteristics of the sound, individual receptiveness, and personal lifestyle (Basrur, 2000; Rabinowitz, 2000; Stansfeld & Haines, 1997; Stansfeld & Matheson, 2003). Characteristics of sound, in this case, refer to sound intensity (loudness), frequency (pitch), complexity, duration of exposure, and the meaning of the sound (Rabinowitz, 2000; Stansfeld & Haines, 1997; Stansfeld & Matheson, 2003). For instance, impulsive or sudden sounds are perceived more negatively by human rather than continuous humming sound. Also, an intermittent noise would have a higher effect on humans than a louder constant noise (Basrur, 2000).

2.2.2 Effect of Noise on Human Health

Noise has been the most studied environmental stressors. It affects hearing and has harmful effects on human health and well-being. Noise can cause annoyance and affects cardiovascular health; and exposure to very high noise level can result in stress-related problems (Veitch, 2012; Stansfeld et al., 2012). Physiologically, noise could interfere with human health in two ways: through auditory effects, and non-auditory effects (Basrur, 2000; Stansfeld & Haines, 1997).

2.2.2.1 Auditory Effect of Noise

Auditory effect of noise is when noise exposure contributes directly to human health by affecting the human hearing organ, the ears (Basrur, 2000). It occurs when a high level of noise damages the sensory hair cells of the inner ear. These hair cells are delicate and once damaged, it cannot grow back. This is what causes permanent hearing loss or impairment (Basrur, 2000; McReynolds, 2005; Robinson, n.d.; Bluyssen, 2009).

The World Health Organisation (WHO) defined hearing loss or impairment as permanent and irreparable and categorised it into five grades from grade 0 (no impairment) to grade 5 (profound impairment including deafness) (Duthey, 2013).

Hearing loss caused by noise exposure or commonly known as noise-induced hearing loss (NIHL) is the second frequent contributor of hearing loss cases right after age-related hearing loss (Rabinowitz, 2000). This type of hearing loss develops gradually through continuous and chronic exposure to loud intermittent noise (McReynolds, 2005; Rabinowitz, 2000). Chronic exposure in this case stands for being exposed to high level noises of more than 85 dB(A), for a continuous period of eight hours per day (Basrur, 2000; McReynolds, 2005; Robinson, n.d.; Stansfeld & Matheson, 2003; USA, Occupational Safety and Health Administration, 2013). Other causes are explosive or impulsive noises that come from gunshot, explosive, or jet take off (Rabinowitz, 2000; Robinson, n.d.; Bluyssen, 2009).

Figure 2.2 shows a simplify decibel scale to demonstrate common environmental noise, the sound pressure level in decibel (dB), and the subjective impression of how human ear perceived them. Cavanaugh (1999) exhibited that zero dB as the threshold of human hearing and 140 dB as the maximum pain threshold.

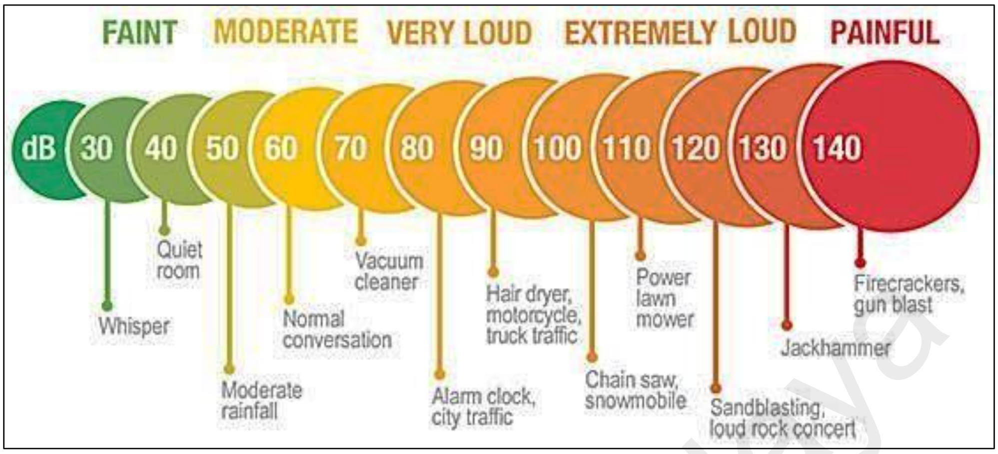


Figure 2.2: The decibel scale
(Source: http://www.hearingandaudiology.com.au)

2.2.2.2 Non-Auditory Effect of Noise

Non-auditory effect of noise is a name to describe any health problems caused by noise exposure excluding those related to the hearing organ (Stansfeld & Haines, 1997; Stansfeld & Matheson, 2003). The list of non-auditory effects of noise can range from modest effect such as annoyance to complex issues such as modified social behaviour (Stansfeld & Matheson, 2003; Stansfeld et al., 2012).

When exposed to noise, human activities and communication are being interrupted. Instead of communicating and carrying out task normally, the human senses are forced to adapt to the abnormal auditory situation and this lead to stress responses, and henceforth the health problems.

Some of the most common non-auditory effects of excessive noise exposure are annoyance, cardiovascular disease, sleep disturbance, decrease in performance, and psychiatric disorder (Basrur, 2000; McReynolds, 2005; Stansfeld & Haines, 1997; Stansfeld & Matheson, 2003; USA, Occupational Safety and Health Administration, 2013).

(a) ***Annoyance***

Annoyance is the most widespread non-auditory effect of noise exposure. Annoyance is defined as a negative feeling a person experienced when their ‘peace of mind’ is being disturbed or interrupted. Feelings of annoyance include fear and mild anger. In case of noise exposure, annoyance often occurs when a conversation is being disrupted by unintended sounds which ruin the flow of communication.

(b) ***Cardiovascular disease***

This non-auditory noise effect is vastly studied in the workplace and other occupational settings. The excessive exposure to occupational noise or frequently industrial noise resulted in increased blood pressure and hypertension. Other effects include irregular heartbeats, faster pulse rate, and slower recovery of vascular constriction.

(c) ***Sleep disturbance***

Noise exposure during sleeping hours causes awakenings and changes in sleep stages which consequently lessen the quality and duration of sleep. Besides disturbing the sleep cycle itself, noise exposure during sleeping hours was also found to increase blood pressure, heart rate, and finger pulse amplitude, as well as body movements. The after effects of disturbed sleep were also found to be more harmful. With lesser sleep quality, people are more prone to mood swings, decrease in performance and reaction time.

(d) ***Decrease in performance***

In retrospective, there is some evidence which suggested that noise strongly affect human performance. This study is a common study in workplace settings. The dynamic of how this effect comes about is that noise creates distractions, which in turn decreases attention. As a result, focus on task handling will decline and thus deteriorate performance.

(e) ***Psychiatric disorder***

There is no evidence that linked noise exposure to psychiatric disorder exclusively. Conclusion on noise as a health risk factor on psychiatric disorder usually comes from self-reported sensitivity. Self-reported symptoms which lead to psychiatric deductions include nausea, headaches, argumentativeness, change in mood, and anxiety disorder. Previous studies usually relate noise to psychiatric disorder through the effects of annoyance.

2.2.3 Definition of Sound

Sound occurred when a medium with both inertia and elasticity such as air, water, or even stretched strings is being disturbed (ANSI S1.1, 1994; Cavanaugh, 1999; Maekawa, Rindel, & Lord; 2011; Rossing, 2007). Scientifically, sound can be defined as "a rapid variation of atmospheric pressure caused by some disturbances of the air." (USA, Occupational Safety and Health Administration, 2013; p.2). Vigran (2008) stated that audible sound occurs "due to the oscillations in the air pressure propagating as waves." (p. 1). This means that once the air is being disturbed at one point (speaker), the air molecules near the speaker move back and forth at a regular speed affecting the adjacent molecules (and that adjacent molecules then affects its adjacent molecules, and so on and so forth in a "chain reaction" manner). This creates movement in space away from the speaker, at a certain rate depending on the properties of the medium; towards another point (receiver) which can be translated as waves (Bluyssen, 2009; Cavanaugh, 1999). Maekawa et al. (2011) stated that sound can be physically visualised as a wave motion, hence it is called a sound wave.

Theoretically, sound can be described as "sensations" or "impressions" which is experienced by humans through the sense of hearing (Merriam-Webster, 1999; Rossing, 2007). Casati and Dokic (2014) stated that sound could be described as the qualitative aspects of auditory perception if they are defined as the object of the audition.

However, pressure variations created by disturbing air molecules are intangible visually. Nonetheless, sound waves are distinctively perceptible by the human ears as a type of stimulus. Sound waves would be directed through the auditory canal to the eardrum. Parts of the sound waves would be absorbed, and this consequently causes the eardrum to vibrate. This eardrum vibration would then be transmitted to the auditory ossicles in the middle ear to be intensified and furthermore, transferred to the fluid of the inner ear. The inner ear would then work its way to convert the vibrations into nerve impulses that are then transferred to the brain and be translated into a sensation of hearing by the human brain (Bluyssen, 2009; Cavanaugh, 1999).

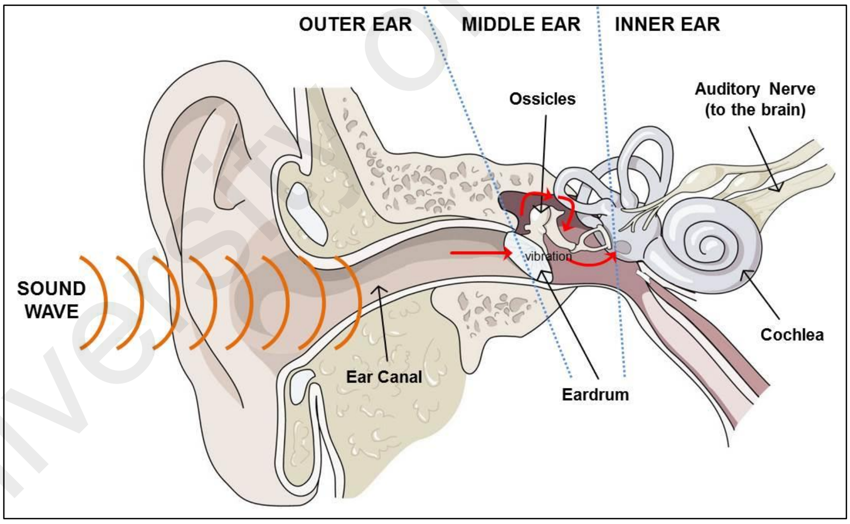


Figure 2.3: Transmission of sound wave in the human ear

2.2.4 Definition of Acoustics

Acoustic can be simply defined as *the science of sound*. Acoustics study the origin, cause, and the effect of sounds. It ranges from the production of the sound; its transmission from the sources to the receivers in any medium, state, and conditions; and the consequences arose when the sound is detected and perceived (ANSI S1.1, 1994; Kuttruff, 2007; Rossing, 2007).

Everything around us is somewhat related to acoustics. This can be verified through the existence of comprehensive interdisciplinary field of acoustical studies. It can be found in physics, engineering, psychology, speech, music, medicine, architecture, and many other fields of study (Rossing, 2007).

Acoustical studies cover a wide variety of knowledge. Branches of acoustical knowledge include (but not limited to) physical acoustics (study of acoustics and physics), musical acoustics, psychoacoustics and physiological acoustics (study of perception and effects of sound), electroacoustic (branch of acoustic engineering), underwater acoustics, noise control, shock and vibration, and architectural acoustics (Rossing, 2007).

2.2.4.1 Architectural Acoustics

The need for architectural acoustics ascends from the change in behaviour sounds made indoors compared to the behaviour of sound outdoors. When sound is generated in the outdoor sound field, or the "free field", sound wave spreads out unrestrictedly in space away from the sound source and attenuates accordingly with distance (Maekawa et al., 2011; Cavanaugh, 2009; Attenborough, Li, & Horoshenkov, 2007). This sound level decay with distance in the outdoor sound field follows the inverse square law, and when the length of sound travel has doubled, the falloff rate would be approximately about 6 dB (Cavanaugh, 2009).

On the other hand, sound attenuation indoors is not as simple as it is outdoors. While the outdoor sound field is referred to as "free field", the indoor sound field is usually referred to as "reverberant field" (Cavanaugh, 2009). In the reverberant field, sound level does not attenuate accordingly to distance due to the vertical and horizontal reflective surfaces that make up the indoor area or the "room" such as the walls, ceilings and floor. In most buildings, sound intensity would merely fall off accordingly within several feet from the sound source only. The increase of distance would not be much help as the reflected sounds would engulf the room and preserves and maintains the sound level in the space (Maekawa et al., 2011; Cavanaugh, 2009). Figure 2.4 illustrates the relative difference between sound behaviour outdoors and indoors.

The practice of architectural acoustics was commonly known or even slightly misunderstood as to be applied only for the treatment of concert halls or auditoriums (Rossing, 2007). It was understandable as acoustics application in architecture during the ancient world revolved around the design of Greek amphitheatres (Addis, 2009). It is undeniable that the acoustical design of amphitheatres is essential in the fields of architectural acoustics. The man that was coined as "the father of architectural acoustics", Wallace Clement Sabine, also started his architectural acoustics endeavour through his attempt at improving the poor acoustics of the new Fogg Lecture Hall in Fogg Art Museum. It was through Sabine's successful attempt at Fogg Lecture Hall that *reverberation time* or also known as "the mother of all room acoustic parameters" was discovered (Addis, 2009; Skålevik, 2010; Maekawa et al., 2011; Kuttruff, 2007; Ginn, 1978; Egan, 1972).

However, as the modern field of architectural acoustics evolved, coupled with human understanding and awareness of the acoustical environment around them, architectural acoustics does not only applicable for halls and theatres anymore. It covers all building types, or more accurately, all-habitable or 'occupy-able' building types.

Maekawa et al. (2011) stated that the purpose of architectural acoustics or in a more specific term, room acoustics, is to control the elements that make up the acoustical properties in the room, in order to regulate the acoustical conditions to an appropriate level of acoustic environment. Nevertheless, it should be articulated that this suitable acoustics environment in a room or indoor space are meant for human comfort.

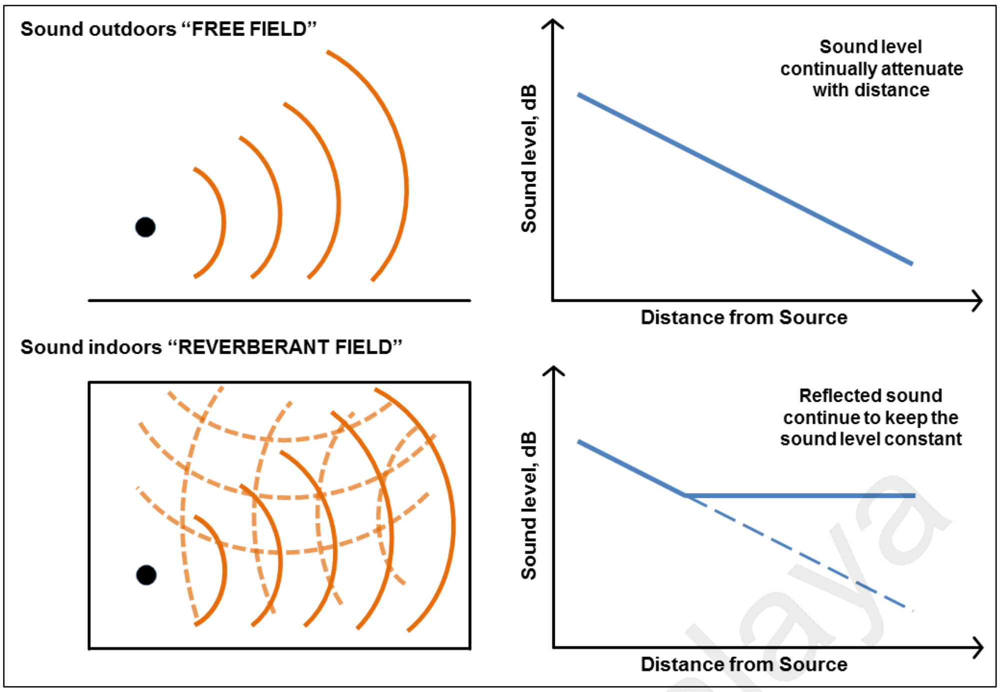


Figure 2.4: Relative difference between sound behaviour outdoors and indoors

Different kind of indoor space needs a different type of acoustical properties. This depends on the nature of activities carried out in that particular space. Lecture hall/theatres or classrooms need acoustical properties that would support the speech transmission for information and knowledge to be conveyed (Kuttruff, 2007; Ginn, 1978). Acoustical properties in office spaces must support information sharing but at the same time provides the occupants with acoustic or speech privacy from types of noises that would impair their work performance (Rossing, 2007; Brill, Weidemann, BOSTI Associates, 2001).

Meanwhile, theatres or halls for musicals may need a more complicated combination of acoustical properties. For example, to retain the harmony of music etc., the reverberation of that space cannot be too little, but it shouldn't be too much either. Also, the perception of music depends not only on the listeners' ears but also on their emotional judgement of the music (Kuttruff, 2007; Ginn, 1978; Rossing, 2007).

Acoustics design in homes, on the other hand, need to provide the interior space with acoustical separation from the exterior space, and also some degree of comfortable acoustical separation between private rooms in the house itself (Yu & Kang, 2009).

2.3 The Workplace / Office

Merriam-Webster (1999) defined workplace as “a place (as a shop or factory) where work is done.” UK, Health and Safety Executive (2007) applied the term ‘workplace’ to a wide variety of spaces such as factories, shops, offices, schools, hospitals, hotels, places of entertainment, common parts of shared buildings, private roads, industrial estate, business park and temporary worksites.

Workplace essentially means a location where people gather to achieve specific goals together. Depending on the nature of work carried out, a workplace can vary from permanent indoor spaces such as an office, factories, and stores; to outdoor areas such as farms, parks; and even temporary spaces such as construction sites, oil rig plants, etc.

In this era, office is undeniably the most prominent type of workplace (Danielsson, 2010; Danielsson & Bodin, 2010; Veitch, 2012). During the 1990s, the percentage of employees working in offices was reported to be more than half of the workforce industry in the US (Stallworth Jr, & Kleiner, 1996), and this number is growing every day (Veitch, 2012). Kroemer & Kroemer (2001) defined office as “a place to work and perform.” (p. 48).

Myerson and Ross (2006) identified the origin of modern offices as a “by-product of the bureaucratization of industry.” (p. 8). Although, as time goes by, and with the arrival of technological era; most of the repetitive, linear, process-driven tasks are made easier by using computers. The time it took to get thing done was optimised, and a new type of office work was established, and it is called ‘knowledge work’.

'Knowledge work' became the new dominant type of office work. Knowledge work consists of the application of theoretical knowledge and learning, collaboration and exploration work in which knowledge is often the significant player in the process (Myerson & Ross, 2006; Bjerrum & Bødker, 2003).

2.3.1 Types of Office Design

There are many definitions of office type categorisation. However, the primary classification of office types comes down to two categories: cellular/enclosed office and open-plan office (Danielsson & Bodin, 2008; Lee, 2010; Haynes, 2008; Haka et al., 2009; Kaarlela-Tuomaala et al., 2009; Neufert & Neufert, 2000; Duffy, 1997). These two main categories can be defined further by either spatial and work organisation or architectural and functional features of the offices.

Architecturally, the main office types can be further defined into several varieties of characteristics. Figure 2.5 illustrated the summary of significant branches of office types' from the various definitions presently available.

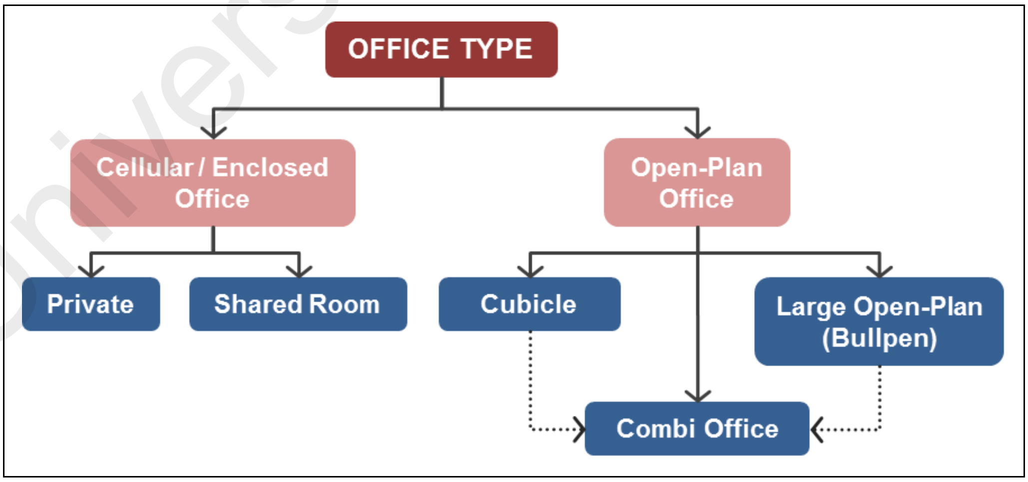


Figure 2.5: Office types defined by its architectural characteristics

The development of office designs was heavily influenced by the development of technology specifically the arrival of the work tool, the computer (Kroemer & Kroemer 2001; Myerson & Ross, 2006; van Meel, 2011). Previously, offices were designed to support quiet work, with the subtle intention to showcase organisational hierarchy and personnel status. The office layouts and designs drew the hierarchy lines by using different types of office location, size and furniture designs (Bjerrum & Bødker, 2003).

Cellular office type is often considered as the traditional office design. Popular in the 1950s, the functional features of individual office were to provide for independent, concentrated work or small team-based work. These types of work were catered by two kinds of individual offices: private cell office and shared room office. The archetypal layout of a cellular office entails long internal corridors that connect all the cellular offices located along the façade of the office buildings (Danielsson & Bodin, 2008; Neufert & Neufert, 2000). Figure 2.6 shows a typical office floor plan with a cellular design with its signature internal long corridors.

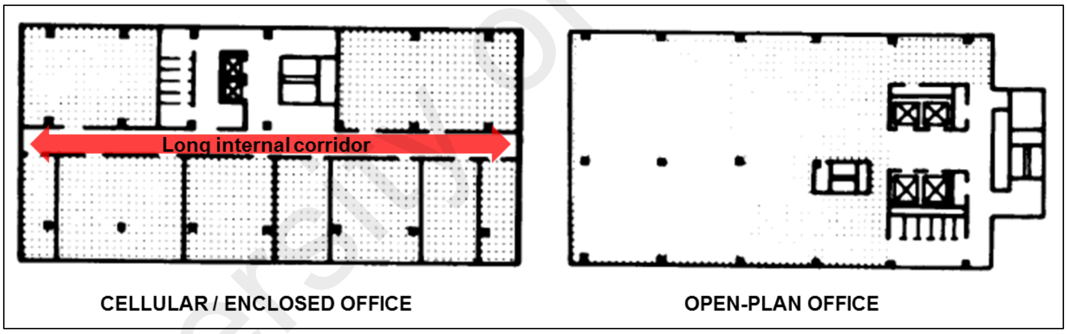


Figure 2.6: Typical layouts for cellular/enclosed office and open-plan office (Source: Neufert & Neufert, 2000)

Private cell offices are built of ceiling-heights partitions or walls and doors connected to the corridors. Private cell office accommodates one person per room. Often time, private offices were catered for higher-ranking personnel of the organisation. The status of the staff is further defined by the sizes and location of the cell offices. On the other hand, shared room office typically accommodates two to three employees who are working on a project together or have a similar type of work assignments. Working in a close-knit environment with likewise-interest co-workers would encourage interactive and more productive work. Workstations (with or without screens or partitions for privacy) are arranged freely in the room (Danielsson & Bodin, 2008; Haka et al., 2009).

Over time, as the need to support knowledge and information sharing between co-workers arises, flexibility is considered essential (Myerson & Ross, 2006). Flexibility in term of information sharing between co-workers demands flexible working environment. Thus began the era of the open-plan office. Open-plan office is a highly popular type of office design (Duval, Charles, & Veitch, 2002; Bradley, 2003; Haka et al., 2009). Many versions and variations of open-plan office were defined. Some definition was according to its physical conditions such as the sizes and the design elements within the open-plan office (Danielsson & Bodin, 2008), and some according to its conceptual arrangements which will be discussed in the next subtopic.

Holding true to its title, the basic layout plan of open-plan office is a vast open-plan office without the ceiling-height partitions and door combination (Danielsson & Bodin, 2008; Neufert & Neufert, 2000). Unlike cellular type office, there are no distinct internal corridors in the space (See Figure 2.6). Even though there are no distinct corridors in the open-plan office, the spatial arrangement in the open-plan space needs to cater for the circulation passages in between the workstations. Hence, workstations in open-plan offices were arranged in some organised method to accommodate for this necessity. A whole study of office ergonomics was dedicated towards the method of "division of space" for comfortable open-plan office layout arrangements (Neufert & Neufert, 2000; Kroemer & Kroemer, 2001).

The main differences between cubicle and bullpen office are the presence and absence of partitions or screenings between the workstations. While the two types of office design are considered as offsprings of open-plan office, some might argue that partitions are in fact, a significant design characteristic that makes up an open-plan office layout (Duval et al., 2002; Charles & Veitch, 2002). On the other hand, combi office is a modified version of open-plan office. It combined the quintessential essence of cellular and open-plan office (Neufert & Neufert, 2000).

Cubicle office
(Source: latimes.com)

Bullpen office
(Source: apresgroup.com)

Figure 2.7: Example of cubicle and bullpen office layout

2.3.1.1 Open-plan Office

Current trends show that open-plan office has become a primary design option for workplace designs (Bradley, 2003; Haka et al., 2009). Two West Germany brothers, Eberhard and Wolfgang Schnelle, founded the concept of open-plan office in the 1950s when they both work as furniture manufacturers (Navai & Veitch, 2003; Shafaghat et al., 2014). After being introduced to the US in the 1960s (Navai & Veitch, 2003; Shafaghat et al., 2014; Sundstrom, Herbert, & Brown, 1982), the concept of open-plan office took off in the 1970s as more and more companies adopted the concept into their workplace designs (Brennan, Chugh, & Kline, 2002).

The widespread popularity of open-plan office concept was due to its flexibility. Veitch (2012) credited the reasons why organisations often opted for open-plan office on two factors: *economic reasons* and *ideological reasons*.

Economically, open-plan office would assist in reducing the footprint of spaces needed to create the working space for the employees. Moreover, when the office needs to go through a management reshuffling and the need of office layout rearrangement arises; open-plan office would make the process effortlessly more manageable. This, in turn, reduces the organisational cost for the company (Neufert & Neufert, 2000; Veitch, 2012; Kaarlela-Tuomaala et al., 2009; Duval et al., 2002).

Ideologically, the idea of reducing barriers between co-workers is appealing to the employers as it seen as an opportunity to minimise isolation and excite social interaction, which promotes teamwork and creative collaborations (New Zealand, Government Property Management, 2014; Kaarlela-Tuomaala et al., 2009).

Successful implementation of open-plan office recorded numerous advantages. Much like the economic and ideological reasons, the advantages of open-plan office include (Navai & Veitch, 2003; Sundstrom et al., 1982; Brennan et al., 2002; McGuire & McLaren, 2009; Lee & Brand, 2005; Kroemer & Kroemer, 2001; Duval et al., 2002):

i. Ease of communication between co-workers, which would eventually, resulted in higher amount of quality work production.
ii. Space saving and practicality as a result from reducing the need for connecting corridors.
iii. Improved environmental conditions where open-plan office allows for the maximization of daylighting and natural ventilation.
iv. The aesthetic appeal that indulgences the occupants with a positive workspace vibes.

The advantages of open-plan office ultimately come down to benefitting the organizations through quality performance and productivity of socially and environmentally satisfied employees.

2.3.2 Office of the Future

Nowadays, the term “office” has become more of a concept or tools rather than a physical space (Waber, Magnolfi, & Lindsay, 2014). The existence of office has stretched more than a mere physical space provided by the employers, for the employees to perform tasks in. Often, office designs are used as a way to express the image and disposition of the organisations. A visible presence of a company in a cityscape would exude authority and prestige (Neufert & Neufert, 2000). Aesthetically attractive office designs are also arranged as a mean to attract new employees and help to motivate and keep existing ones (Kroemer & Kroemer, 2001; Danielsson & Bodin, 2008; Bjerrum & Bødker, 2003).

Frank Duffy, an architect and leading theorist in office design and workplace strategy once stated that designers and architects of early 21st century lack the awareness that office design is an essential element that could determine the employees’ work and psychological performances and productivity (Myerson & Ross, 2006). However, this awareness has slowly emerged with the abundance of research work linking the two elements together (Haynes, 2008; Waber et al., 2014; Seddigh et al., 2015; Oseland, 2009; Vischer, 2007; Duffy, 1997; Myerson & Ross, 2006).

The way of working highly influenced the development of office design. This working culture was in fact moulded by the emergence of technology (Neufert & Neufert, 2000). It was in the 1980s that the computers changed the work culture in the office. The usage of computers slowly changed the tasks and responsibilities of secretaries, and consequently other staff members, the managers, and even the bosses.

Word-processing was no longer a task exclusively done by the former (Kroemer & Kroemer, 2001). Subsequently, computers became lighter and smaller, as do other office equipment such as calculators, telephones, etc. (Kroemer & Kroemer, 2001; Myerson & Ross, 2006).

As work equipment became portable and no longer needed to be tie down to one place, so do the employees. Consequently, an explosion of technology called the 'Internet' further supported the advancement of work portability (De Croon et al., 2005). Organizations looking to save on the cost of office spaces introduced telecommuting (Gajendran & Harrison, 2007; Cooper & Kurland, 2002). Telecommuting, or also known as telework or remote work is referred to as working from any other places remotely from the central office for a certain part of their work schedule. Telecommuting relates typically to working remotely at home, but occasionally; it also refers to telework centres and remote offices (Gajendran & Harrison, 2007; Cooper & Kurland, 2002; van Meel, 2011; Picu & Dinu, 2016).

Back in the days, when technology was merely a vision, employers provided physical spaces for the employees to come at a fixed hours to carry out their work. With the Internet enabling long-distance communication, work was no longer bound to a place and time (Gajendran & Harrison, 2007). Telecommuting was considered worthwhile for both employers and employees. As mentioned earlier, employers benefitted from telecommuting by saving on the cost of office space and equipment. On the other hand, employees' would relish on the improvement of work-life balance and schedule flexibility, which in turn assists in keeping the employees' motivation and morale, and furthermore increase productivity. Needless to say, the latter advantage is also considered a plus for the employers (Gajendran & Harrison, 2007; Kurland & Cooper, 2002; Cooper & Kurland, 2002; van Meel, 2011).

Another advancement of technology happened in the form of cell phone (Myerson & Ross, 2006). Communication became borderless. People would no longer be calling a place; instead, they would be calling people. The smartphone was an even bigger explosion. Smartphones enabled the Internet to be accessed at all times, anywhere. Coupled with the ability for teleconferencing, communication for knowledge work sharing became niftier (van Meel, 2011). Due to this advancement in communication methods, telecommuting was embraced by many organisations. Various positive outcomes of telecommuting were reported. Employees have more freedom to synchronise work demands within their home and family territory, time and cost of commutes to work could be minimised, and not to mention the hassle of work commutes could also be reduced (Gajendran & Harrison, 2007; Kurland and Cooper, 2002; van Meel, 2011). This conveniently led to a theory that physical office might "cease to exist" except as an electronic databank and a switchboard (van Meel, 2011).

However, telecommuting does not come without a fault. Kurland and Cooper (2002) discussed the issues of managers-subordinates relationship in telecommuting. On one hand, managers were distressed over the reduced jurisdiction they have over their subordinates in term of work monitoring, and on the other hand, subordinate feared professional and social isolation due to the lack of face-to-face contact (Cooper & Kurland, 2002; van Meel, 2011). A potential loss of information and immediate feedback between managers-subordinates and co-workers were also reported as a vital threat of telecommuting (Kurland & Cooper, 2002; Hallowell, 1999).

Another blunder that was discussed about telecommuting is the work/home life balance (Olson-Buchanan & Boswell, 2006; Gajendran & Harrison, 2007; Kurland & Cooper, 2002). People being accessible all the time lead to conflicting overlaps in work-life and home-life. This is an especially crucial point when mediating about telecommuting. Although employees may choose to telecommute for the sole reason of finding that work/home life balance (Kurland & Cooper, 2002), it is actually difficult to separate the two. Telecommuting enabled work-life to intrude in home-life both physically and psychologically. The fine line dividing the two realms is diminishing, and psychological disengagement towards work becomes harder and thus disturbing personal and family time altogether which resulted in work/home life conflict (Olson-Buchanan & Boswell, 2006; Gajendran & Harrison, 2007).

Nonetheless, the role of literal physical office space was never invalidated. Current office design trends of big borderless, open space were justified by the newfound appreciation for face-to-face interaction. The recognition for face-to-face interactions was comprehended as a tool for informal learning among co-workers. As knowledge work is a dominant type of office work (Myerson & Ross, 2006; Bjerrum & Bødker, 2003), the exchange of knowledge between co-workers become a crucial element for office productivity. However, the vital kind of information and knowledge sharing is not merely the planned ones that take place in a conference or meeting rooms; it is the impromptu, accidental, unintentional, and by-chance encounters that sparks all the differences (Cooper & Kurland, 2002; Waber et al., 2014). Thus, new kinds of working culture were created and cultivated. The term “co-working”, “hot-desking”, “desk sharing”, and “non-territorial offices” were coined.

Waber et al. (2014) reviewed how big Silicon Valley companies such as Yahoo, Google, Samsung, and Facebook slowly realised that big ideas typically occur during impromptu dialogues between co-workers, and not necessarily between those within the same area of expertise. Yahoo was reported to be re-evaluating their mobile work schemes as a way to gather employees and have them work together in the same space to create the chance for impromptu discussions to happen.

Organisations nowadays strive for creativity among its employees, and this is true for any type of work out there. Creativity is a crucial element for both problem solving and innovations. Hence offices are designed to encourage coincidental collisions (Waber et al., 2014). Roth and Mirchandani (2016) stated that co-working would bring people from various knowledge niches to work together in a common shared space.

2.4 Acoustical Environment in the Workplace

There are two categories in which noise is referred to when assessment on noise exposure is being done: environmental noise and occupational noise. Environmental noise referred to noises from settings such as community, residential, and domestic; while occupational noise referred to noises, which occurred in the workplaces (Concha-Barrientos, Campbell-Lendrum, & Steenland, 2004).

As workplaces, in general, refer to places where people work, this definition put the classification of workplaces in a wide range of places from indoor to outdoor areas. However, when the term occupational noise is being applied, it usually refers to workplaces with a high risk of hazardous noise exposure such as factories, mining sites, and construction sites; or in summary: industrial workplaces.

Noise exposure in the workplace has been said to influence employees' health, performance, and productivity. It was also reported to create physical health problems such as cardiac problems, sickness-related absenteeism, and self-reported fatigue. The poor acoustic environment would not only cause harm to occupants' physical health, but also on their psychological health (Leather, Beale, & Sullivan, 2003).

2.4.1 Acoustical Environment in Industrial Workplaces

Noise is infamous for being the most frequent forms of threat in the industrial workplace. Modern machinery utilised for physical production in industrial workplaces have been proven to reduce employees' work burden. However, the sound generated by these types of machinery was, unfortunately, a detrimental one (Shaikh, 1999). Previous studies showed that more than 30 million employees in America are exposed to high level of occupational noise (Rabinowitz, 2000; McReynolds, 2005), and four to five million people in Germany were reported to be exposed to a hazardous level of noise in their workplaces (Concha-Barrientos et al., 2004). Veitch (2012) stated that effects of workplace's poor setting on human health are interactive.

Due to the harmful effect of occupational noises, departments associated with safety and health of workers such as US's OSHA (Occupational Safety and Health Administration) and Malaysia's DOSH (Department of Occupational Safety and Health) have expressed their concern on occupational noise exposure.

OSHA which was established under the United States Department of Labor, recommended that the workplace noise level to be kept below 85 dB(A) in an eight-hour time-weighted average (USA, Occupational Safety and Health Administration, 2013). Meanwhile, DOSH which is a department established under the Ministry of Human Resources Malaysia stated in its Factories and Machinery Act 1967 (Act 139) under Factories and Machinery (Noise Exposure) Regulations 1989 (Department of Occupational Safety and Health, 1989); the permissible exposure limit should not exceed 90 dB(A) for the duration of eight hours per day. This is higher than OSHA's recommended exposure limit.

Nevertheless, Malaysia's standard MS ISO 9241-6:2005, Ergonomic requirement for office work with visual display terminals (VDTs) – Part 6: Guidance on the work environment (ISO 9241-6, 1999) has placed a section on sound and noise. This article was referred from ISO 11690-1:1996(E) Acoustics – Recommended practice for the design of low-noise workplaces containing machinery – Part 1: Noise control strategies

(ISO 11690-1, 1996), which recommended that the noise exposure in workplaces not to exceed 70 dB(A) for industrial workplaces.

2.4.2 Acoustical Environment in Offices

Earlier discussion has outlined how the office is one of the most prominent types of workplace. Nevertheless, because of the absence of high noise level exposure in the office, it is often uncared for from any departments concerning workers' safety and health.

However, there is a guideline released by the Ministry of Human Resources Malaysia on occupational safety and health in the office (Department of Occupational Safety and Health, 1996). This guideline stated that the elements that create an office environment are the combination of lighting, temperature, humidity, air quality, and decorations. The guideline, unfortunately, failed to recognise the issue of acoustics or noise exposure.

Acoustics is an important element in creating a workable office environment. Acoustics relates closely with human wellbeing by its influence on human stress level, motivation, and productivity (Evans & Johnson, 2000; Bradley, 2003; Salter et al., 2003; Singh et al., 2010). One significant characteristic an office must possess is the ability to provide a calm and quiet ambience in which the occupants could work and concentrate in (Brennan et al., 2002; Sundstrom et al., 1994).

Noise exposure in the office environment has been said to give harmful impacts on human health physically and psychologically (Bluyssen, Aries, & van Dommelen, 2011; Leather et al., 2003; Veitch, 2012; Sundstrom et al., 1994). Navai and Veitch (2003) defined acoustic satisfaction in office space as:

> "…a state of contentment with acoustic conditions; it is inclusive of annoyance, loudness, and distraction – all concepts used by one another researcher in this area to assess subjective experiences associated with the acoustic environment in offices." (p. 2).

A person's work productivity will decrease when they are working in a noisy office environment (Venetjoki et al., 2006; Hodgson, 2008). The important point to be deliberate from the previous sentence is 'productivity'. Many definitions of productivity were discussed in Tangen (2005). Some were simple definition like "faculty to produce" (Littre, 1883), and some were more elaborate like "relationship between output such as goods and services produced, and inputs that include labour, capital, material, and other sources" (Hill, 1993). Based on the various definitions, Tangen (2005) then concluded that the definition of productivity could vary depending on the context in which it is referred to. However, there are some common characteristics on which the term stands on. They are 'use and availability of resources' and 'the creation of value'.

Productivity is what every organisation strive to achieve. However, productivity depends highly on performance (Danielsson, 2010; Tangen, 2005). The capability of employees' performance will determine the amount of productivity for the organisation.

Nevertheless, both Stansfeld and Matheson (2003) and Veitch (2012) stated that the main disturbance to office work is unwanted noise, or in another word, bad acoustic environment. According to the survey done by The Center for the Built Environment (CBE) at the University of California, Berkeley; over 50% of occupants working in cubicles feel that the poor acoustics in their offices distract them from getting their work done (Jensen et al., 2005). Sundstrom et al. (1994) stated that noise and unwanted sound is a problematic issue for employees working in an office mainly due to its effect on job-related stress.

Veitch (2012) elaborated that the nature of the perceived sound is more influential in the disturbance of cognitive processes than its level. Within office environment context, the range of noise level between 48 dB(A) to 80 dB(A) is considered typical. Although, a repeated sound is found to be less disturbing than sounds which include acoustic changes in pitch and tempo. The changing condition of the sound attracts attention while disrupting attention from the task at hand. Nonetheless, when the ambient sound level exceeds above 45 dB(A), acoustic satisfaction still bound to decrease (Navai & Veitch, 2003).

Louis Harris and Associates (1978) stated that employees identified the 'ability to concentrate without noise and other distractions' as the most crucial feature of an office environment (as cited in Sundstrom et al., 1994 and Leather et al., 2003). However, through surveys done by The Centre for the Built Environment (CBE) at University of California, Berkeley; when having to rate their office environment, employees tend to rate acoustics as being the most unsatisfactory, compared to other elements such as thermal comfort and IAQ (Abbaszadeh et al., 2006). Hodgson (2008) on the other hand validated this through his finding. He found that the reason might be because acoustic environment has always been given minimum consideration during the design stage of any building development.

Muehleisen (2010) listed three types of acoustical problems that typically occurred in buildings: excessive noise, poor speech privacy, and poor speech clarity. In this study, these three issues will be discussed as two items: excessive noise, and speech noises; within office environment context.

(a) ***Excessive noise***

'Excessive noise' is when the background noise level is higher than it is supposed to be (Muehleisen, 2010). In an office context, it is considered as an annoyance, especially when it interrupts with verbal communication (Hodgson, 2008). As mentioned earlier, acoustic satisfaction decreases once the background noise level exceeds 45 dB(A), and working environment with an ambient noise of 55 dB(A) may cause health problems to employees especially when they need to deal with complex jobs and tasks (Veitch, 2012). Excessive noise has also been associated with the decreased in occupants' performances (Muehleisen, 2010).

This type of acoustic problems happened in the office environment due to various factors such as occupants' activities, noise from ventilation system and office equipment such as photocopy machines, printers, etc., and noise from exterior sources (Muehleisen, 2010; Hodgson, 2008). Muehleisen (2010) also argued that the issue of excessive noise originated from the problem of poor sound isolation. Poor sound isolation is when the building design failed at separating noises from going into unintended areas. Excessive reverberation in a room might also be one of the main causes of this acoustical hindrance (Hodgson, 2008).

(b) ***Speech noises***

Speech noises could bring about two problems: poor speech privacy, or poor speech clarity. However, this depends on the occupants' perception of the noise. Meaning that if the occupants expect to perceive the sound and they couldn't, they are experiencing a condition of poor speech clarity. On the other hand, if they do not expect to perceive it or the speech sound they heard is irrelevant to them, it means they are experiencing a poor speech privacy situation (Schlittmeier et al., 2008; Muehleisen, 2010; Hodgson, 2008). The appropriate term to describe this issue of speech privacy/clarity is *speech intelligibility.*

Speech sounds have been considered to be the most distracting or unwanted type of sound in the office environment (Venetjoki et al., 2006; Navai & Veitch, 2003; Veitch, 2012; Hongisto, Haapakangas, & Haka, 2008). This happens as cognitive performance, which is essential for typical office tasks, responds negatively towards noises that contain speech and information rather than non-speech noises (Schlittmeier et al., 2008). It was also found that performance loss can increase with high speech intelligibility. Speech noises with high intelligibility effects occupants' concentration as it tends to masks a person 'inner speech'. This 'inner speech' is an essential element in a person memory operation as it helps in cognitive processes of the mind. It was also stated that it is not the level of speech noise that impacts negatively on occupants but it is the intelligibility of the speech noise (Venetjoki et al., 2006; Hongisto et al., 2008).

2.4.2.2 Acoustic Issues in Open-plan Offices

While the various benefits of open-plan offices were discussed earlier, the extent of open-plan offices' charms has its drawbacks. Brill, Keable, and Fabiniak (2000) called the idea of co-workers effortless interaction and creative idea collaboration in open-plan offices as a "seductive myth". As the name implied, the whole concept of open-plan office calls for reduced barriers between the workstations (Brill et al., 2001), and reduced barriers lead to reduced privacy (Veitch, 2012; Hodgson, 2008; Hong et al., 2010; Lee & Brand, 2005).

In contrast to the glorified benefits of open-plan offices, occupants often reported dissatisfaction towards open-plan office on the issue of aural privacy and distraction (Jensen et al., 2005; Muehleisen, 2010). This is not surprising as the primary source of annoyance in open-plan offices is unwanted sound (Navai & Veitch, 2003). Some of the disadvantages of open-plan offices are (Navai & Veitch, 2003; Sundstrom et al., 1982; Brennan et al., 2002; McGuire & McLaren, 2009; Hong et al., 2010; Lee & Brand, 2005; Jensen et al., 2005):

i. Low level of physical and psychological privacy – The occupants' inability to have a private conversation.

ii. Increase noise and aural distraction – Occupants are often distracted by other people private conversation, the sounds of telephone ringing and noises from office equipment and machineries.

iii. Increase disturbances, interruptions, and distractions by others.

Among the aural distraction mentioned above, speech sounds posed the most threat to acoustic comfort in open-plan offices. Speech with substance and information is often found to be more engaging and thus distracting for the unattended listeners compared to sounds or noise with no information such as noises from office equipment and machinery (Navai & Veitch, 2003).

Despite the inevitable disadvantages of privacy loss and distraction in open-plan offices, it remains as the preferred workplace design concept for most offices. A study done by BOSTI Associates stated that:

> "The two workplace qualities with the strongest effects on performance and satisfaction are those *supporting distraction-free work* and *supporting interactions with co-workers* (especially impromptu ones). Both of these top workplace design priorities must exist without compromising the other." (Brill et al., 2001, pp. 20).

This shows that good open-plan office design should while providing space for interaction between co-workers; also deliver a distraction free environment when needed be. The middle ground between spaces for productive social interactions and productive private working areas should be discovered to provide both workplace needs without compromising the other.

2.5 Acoustic Design in Open-plan Offices

As discussed previously, the most prevalent and distractive type of sound in an open-plan office is *speech sounds*. Speech sound contains information that could disrupt the cognitive performance, which is an essential instrument for occupants working in an office environment (Navai & Veitch, 2003; Andersson & Chigot, 2004; Venetjoki et al., 2006; Hongisto et al., 2008; Schlittmeier et al., 2008; Hellström & Nilsson, 2009; Veitch, 2012; Keränen & Hongisto, 2013; Haapakangas et al., 2017).

In open-plan offices, the specific problem related to speech sounds can be referred to as the lack of speech privacy (Bradley, 2004; Kim & de Dear, 2013; Danielsson & Bodin, 2009; De Croon et al., 2005). There are two ways in which the lack of speech privacy can happen. The most common way is the lack of privacy from other people speech noises. This happened when an occupant's workspace was intruded by the sounds of other people intelligible conversations which could impair his or her concentration. The second way is when an occupant feels like they are unable to have a private conversation without being overheard (Navai & Veitch, 2003; Sundstrom et al., 1982; Brennan et al., 2002; McGuire & McLaren, 2009; Hong et al., 2010; Lee & Brand, 2005; Jensen et al., 2005).

Warnock (2004) stated that speech intelligibility and privacy depends on three elements in the office: the people (talker), the background noise (BN) level, and the sound propagation paths.

The people or occupants play an important role in controlling the speech intelligibility and privacy in an open-plan office. Common office etiquettes suggested that occupants should keep their chatter to a minimum and that extended meetings should be held in meeting rooms or a designated area where their discussions would not be distracting to other occupants in the office (Hellström & Nilsson, 2009). Even though occupants are more likely to talk quietly in open-plan offices (Bradley, 2004), this "people" element of the office is unpredictable and often subjected to individual occupants characteristics (Herman Miller, Inc., n.d.).

Background noise (BN) level relates to speech intelligibility by its role as a masking sound. In an open-plan office, if the BN level is too low (lack of masking sound), it would be impossible to obtain speech privacy as the level of speech intelligibility would be high, despite how quiet the talker is being. However, if the BN level is too high, it would cause displeasure and henceforth resulted in the occupants talking a little louder than they need to (Bradley, 2004; Bradley & Gover, 2004; Warnock, 2004; Schlittmeier et al., 2008).

On the other hand, the sound propagation path refers to the open-plan office itself and the physical elements that make up the room. Besides controlling the BN level to achieve speech privacy in open-plan offices, the acoustic design strategies of using the element of absorption and screenings can also be applied (Haapakangas et al., 2017; Keränen et al., 2008).

Previous literature that exclusively discussed about the acoustic design in open-plan offices proposed on using absorption on large surfaces in the open-plan offices such as the ceiling, wall, and floors as a way to control the sound propagation path. The application of screenings and the design of workstation sizes and layout arrangements is also a common strategy to be used in open-plan offices (Bradley, 2004; Warnock, 2004; Hellström & Nilsson, 2009; and Virjonen et al., 2009). Table 2.3 summarised the strategies proposed for the design of speech privacy in open-plan offices.

Table 2.3: Design strategies for regulating the sound propagation paths in OPO

Design strategies	**Bradley (2004)**	**Warnock (2004)**	**Hellström & Nilsson (2009)**	**Virjonen et al. (2009)**
Ceiling absorption	o	o	o	o
Wall treatment	o	o	o	
Floor treatment	o		o	
Screen height	o	o	o	o
Screen material/absorption	o	o	o	o
Workstation size	o	o		o
Workstation layout arrangement	o	o	o	o

Other literature such as Bradley & Gover (2004) and Keränen et al. (2008) suggested that the design of room acoustic for open-plan offices to be done by achieving the target values of relevant acoustic parameters such as the speech transmission index (STI), distraction distance (r_D), A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\ m}$) spatial decay rate of speech ($D_{2,S}$) and etc.

2.5.1 Acoustic Parameters

Acoustic parameter is an essential indicator in the measurement of acoustic quality. Introduction on essential acoustic parameters utilised in this study are discussed below.

2.5.1.1 Background Noise (BN) Level

Background noise (BN) level is measured to establish the ambient noise level of the selected spaces. Background noise (BN) can generally be defined as the ambient noise, or sound available in a room. In term of measuring BN level in an office environment, human sound and speech noises are not considered to be as part of the BN (ISO 3382-3, 2012). Other types of noises coming from basic office equipment such as the air-conditioning, lightings, computers, and other constantly operating machinery such as the printers or sound masking systems, and environmental traffic noises can be considered as part of BN (ISO 3382-3, 2012).

Background noise (BN) level is an important parameter in any room acoustic measurement work as it stands as a reference value in analysing any intrusive sound in the space. Also, it works as a reference value for the determination of the additional level of noise needed for the measurement of other parameters such as reverberation time (RT) and speech transmission index (STI).

Through the BN level collected, another acoustical quantity can be obtained to facilitate in determining the acoustical performance of the room. It is called noise criteria (NC). NC deals with noises originated from the air-conditioning systems. NC data can be attained by plotting the octave band level acquired from the BN level measurement, on an NC curves. Figure 2.8 shows the NC curves graph used for the derivation of noise criteria (NC).

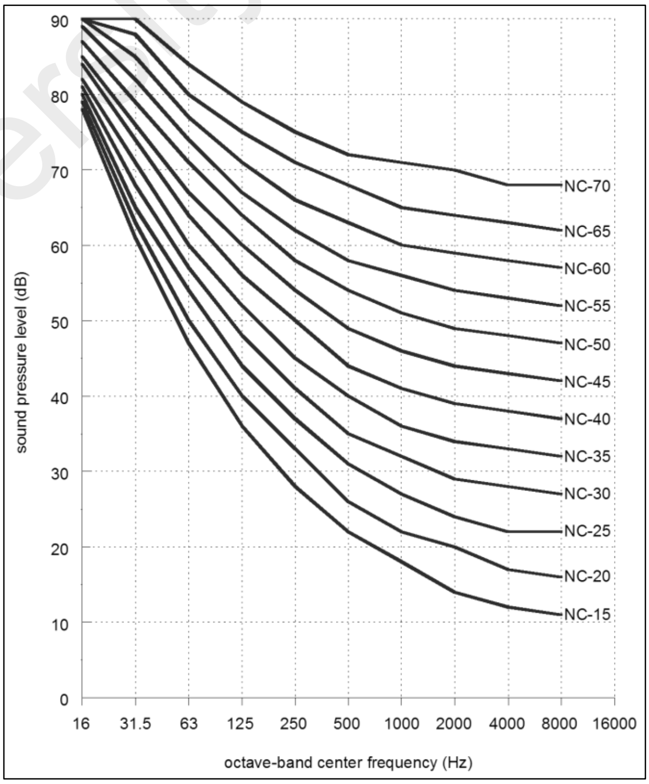


Figure 2.8: Noise criteria (NC) curves

There were a few acoustical standards and acceptability criteria proposed to assist in determining if the measured BN and NC for each open-plan offices are within the acceptable range for occupants' comfort and satisfaction. Although each standard was not quite alike, they seem to be within the same range of value. Table 2.4 summarised the range of acceptability criteria for offices, specifically open-plan office taken from various sources related to the study.

ANSI/ASA S12.2 (2008) listed quite a few types of workspaces from small private executive offices to large offices such as open-plan offices. Background noise (BN) level recommended by ANSI/ASA S12.2 (2008) for private offices ranges from 35 to 48 dB(A) depending on its type. As for open-plan offices, the recommended BN varies between 44 to 48 dB(A). On the other hand, recommended NC ranges from NC-25 to NC-40 for private offices and NC-35 to NC-40 for open-plan offices.

Table 2.4: Range of BN and NC acceptability criteria for office spaces from various standards

Standard	**Type of Space**	**BN in dB(A)**	**NC**
ANSI/ASA S12.2-2008	Executive offices	35 – 44	25 - 35
	Small, private offices	44 – 48	35 – 40
	Large offices, with conference table	38 – 44	30 – 35
	Open-plan areas	44 – 48	35 – 40
ISO 11690-1:1996(E)	Multi-person offices	35 – 45	-
Cavanaugh (1999)	Large offices	42 – 52	35 – 45
Beranek (as cited in Maekawa et al., 2011)	Large offices	43 – 53	-
Hodgson (2008)	Workspaces	-	35 – 40
Green Building Index (2009)	Closed offices	< 40	-
	Open-plan offices	< 45	-

Meanwhile, ISO 11690-1 (1996) indicated that the recommended BN for multi-person offices (open-plan offices) to be within 35 to 45 dB(A). Cavanaugh (1999) recommended that large offices should maintain a background noise level of between 42 to 52 dB(A) and noise criteria (NC) of between NC-35 to NC-45.

Beranek (as cited in Maekawa et al., 2011) recommended that the optimum BN level for large offices to be between 43 to 53 dB(A). Hodgson (2008) in the other hand only listed the recommendation for NC level, which was between NC-35 to NC-40 for workspaces.

Despite being less invested in acoustic comfort compared to other indoor environmental quality (IEQ) elements, Green Building Index (GBI) did recommend the maximum BN level for both private offices and open-plan offices. GBI recommended that closed offices should not exceed the maximum BN level of 40 dB(A) and open-plan office's BN level should not exceed 45 dB(A). However, this was the only requirement made by the GBI regarding acoustic comfort for non-residential development (Green Building Index, 2009).

2.5.1.2 Reverberation Time (RT)

ANSI S1.1 (1994) defined reverberation as "Sound that persisted in an enclosed space, as a result of repeated reflection or scattering, after the sound source has stopped." (p. 3). Reverberation time (RT) on the other hand refers to the time, which is typically conveyed in seconds (*s*); it takes for the sound level to drop (decay) by 60 dB after the sound has been turned off (ISO 3382-2, 2008). RT has also been referred to as RT60 due to the nature of its measurement.

However, in normal room condition with a BN level between 40 to 50 dB, achieving the total sound decay of 60 dB is quite impossible. Thus it is common practice to measure the RT in smaller decay range of 20 dB and 30 dB (taken during the decay between 5 to 25 dB, and 5 to 35 dB respectively). The value would then be extrapolated to 60 dB. These extrapolated RT are labelled as T_{20} and T_{30} according to its decay range (ISO 3382-2, 2008).

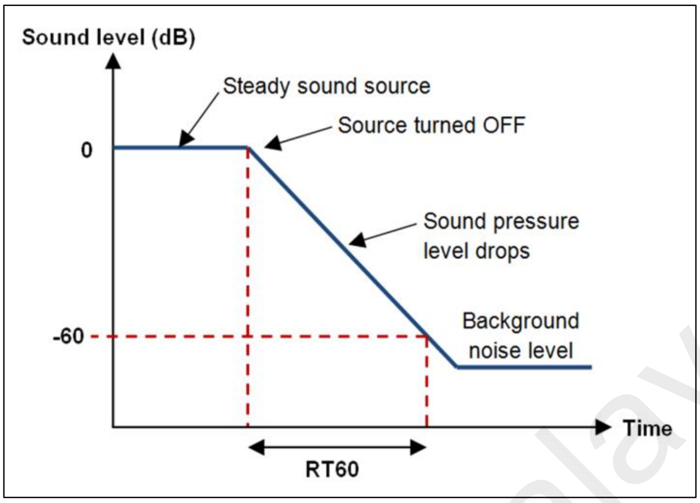


Figure 2.9: Basic diagram of RT measurement

It is essential to measure the RT of selected open-plan offices as it affects the speech intelligibility and perception of privacy in the space. The reverberation time of a space depends on the size and shape of the room, the building materials, and all objects within the room, including the humans. RT is also measured to determine the total sound absorption in the room. Figure 2.9 illustrates the basic diagram of how reverberation time in *s* is obtained during an ideal RT60 measurement.

RT was often considered as the primary descriptor of the acoustic environment. An optimum RT depends highly on the function of the space. In this case, the purpose of the measured rooms can be concluded as workrooms which need an RT level that could provide a comfortable environment that could contribute to easy verbal communication.

According to ISO 11690-1 (1996), RT for workrooms depends on the volume of the room. If the room size is less than 2000 m^3, the RT should be below 0.5 to 0.8 secs. Meanwhile, if the room volume is between 200 m^3 to 1000 m^3, the recommended RT is between 0.8 to 1.3 secs. Hodgson (2008) on the other hand stated that it is preferable that workplaces and offices to have an RT of below 0.75 secs to assure comfortable and easy communication between occupants.

Table 2.5: Summary of recommended reverberation time (RT) level

Standard	Volume of room (m^3)	RT in seconds
ISO 11690-1:1996(E)	Less than 200	< 0.5 – 0.8
	Between 200 -1000	0.8 – 1.3
	Greater than 1000	-
Hodgson (2008)	Not specified	< 0.75

2.5.1.3 Speech Transmission Index (STI)

Speech transmission index (STI) is a "physical quantity representing the transmission quality of speech with respect to intelligibility." (ISO 3382-3, 2012, p.2). STI is used to measure the speech transmission quality using a quantifiable number between zero and one, zero being as the poorest in intelligibility and one as the most excellent.

STI values are mainly subjected to the BN level of the room. The higher the BN level of the room is, the lower the STI value would be, as the speeches were unable to be transmitted well. Although, the basic rule of STI is that it decreases with distance. Normal room condition would always allow for this basic rule to be applied. While the STI value for each receiver points alone can be utilised to analyse the acoustic quality of a room, two important and useful derivative parameters can also be obtained through the decay rate of the STI values. They are the distraction distance (r_D) and privacy distance (r_P).

Distraction distance (r_D) and privacy distance (r_P) are determined through the linear regression line formed using the plotted STI values of each receiver points in the measured room or space. Distraction distance (r_D) and privacy distance (r_P) are the distance where STI falls on STI values of 0.5 and 0.2 respectively (ISO 3382-3, 2012).

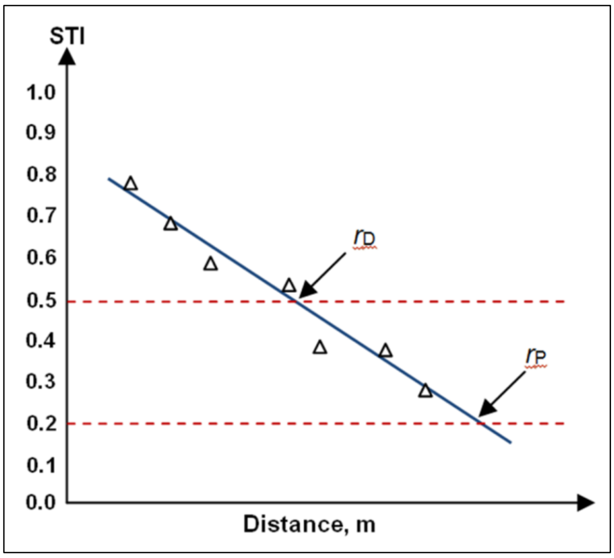


Figure 2.10: The determination of r_D and r_P

As speech is the most prevalent type of noise in offices, it is essential to measure the speech transmission index (STI) of selected open-plan offices. STI helped in determining the privacy level of selected open-plan offices. Figure 2.10 illustrates the derivation of distraction distance (r_D) and privacy distance (r_P) through the decay rate of multiple STI values plotted together in a graph.

Table 2.6: Relation between STI and the perception of speech intelligibility (SI) and speech privacy

STI	Speech Intelligibility (SI)	Speech Privacy
0.00 – 0.05	Very Bad	Confidential
0.05 – 0.20	Bad	Good
0.20 – 0.40	Poor	Reasonable
0.40 – 0.60	Fair	Poor
0.60 – 0.75	Good	Very Poor
0.75 – 0.99	Excellent	None

(Source: Hongisto, 2005)

While high speech intelligibility is needed in spaces such as classrooms for better lesson delivery throughout the entire classroom (Wróblewska, 2010), offices required moderate speech intelligibility. High intelligibility would cause distraction towards the occupants of the office space. Table 2.6 shows how STI is perceived in term of speech intelligibility (SI). It shows that the higher the STI level is, the excellent the SI of the space is. This, however, contradicts with the rule of speech privacy. This means that the higher the STI level is, the lower the speech privacy is going to be.

2.5.1.4 Sound Pressure Level (SPL)

The measurement of sound pressure level (SPL) is primarily done to determine the spatial decay rate of speech ($D_{2,S}$). ISO 3382-3 (2012) defined spatial decay rate of speech ($D_{2,S}$) as the "rate of spatial decay of A-weighted sound pressure level of speech per distance doubling." (p.2). It is previously described as DL_2 in ISO 14257 (2001). The value of $D_{2,S}$ helps characterised the sound propagation of the room through the decrease in sound pressure level. $D_{2,S}$ is highly affected by the availability of partitions between the workstations and the finishes of the ceilings (Passero & Zannin, 2012). Measurement of $D_{2,S}$ is done to determine how much the sound decreases with distance from the sound source, within the context of the room which has different levels of sound absorption in various parts of the room. Figure 2.11 shows how spatial decay rate of speech ($D_{2,S}$) is obtained through the decay rate of SPL.

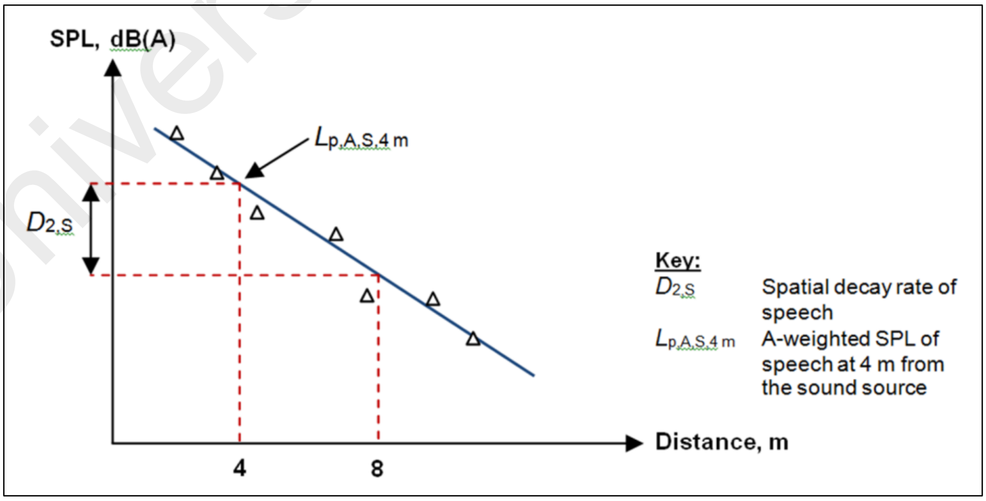


Figure 2.11: The determination of $D_{2,S}$ through decay rate of SPL

2.5.2 Green Building Design Strategies and Acoustic Problems

Green building rating tools (GBRT) outlined many requirements, which would have to be considered for a building to achieve green building ratings. However, in order to improve on other requirements such as energy efficiency, sustainability, and other indoor environmental qualities such as thermal comfort and natural lighting; design strategies and elements utilised have unfortunately intensified the existing acoustic defects (Muehleisen, 2010; Hodgson, 2008).

2.5.2.1 Ventilation System

Review of previous literature revealed that the more common ventilation system adapted into green building design was identified to be ‘natural ventilation’ (Hodgson, 2008). However, that does not seem to be the case for green office buildings in Malaysia. Through initial review of selected green office buildings, it is identified that two out of the three green office buildings studied adapted the radiant cooling system (chilled slab system) as their way of cooling and ventilating the building specifically the open-plan offices.

One of the reasons ‘natural ventilation’ was rarely utilised for office spaces in green office buildings (or office buildings in general) in Malaysia is because of the hot and humid weather experienced all year round. Being located within the equatorial doldrums area, Malaysia is a tropical country with a climate consisting of uniform temperature, high humidity and copious rainfall (Malaysian Meteorological Department, n.d.). Due to these climate conditions, the utilisation of natural ventilation would not be ideal as it would make it tough to regulate the internal thermal condition to a perfect level that would suit the occupants' thermal comfort need in the long run. Although, it should be noted that natural ventilation strategy is still being utilised in green office buildings in Malaysia. A typical example of naturally ventilated spaces in green office buildings would be in non-working or secondary spaces with high volumes such as the atrium, where thermal comfort is not a long-term issue for the building occupants.

The utilisation of radiant cooling system as one of the green design strategy could assist in achieving many green building requirements. While conventional air-conditioning system would result in massive amount of energy consumption especially in buildings in tropical country like Malaysia (Cui, Kim, & Papadikis, 2017), radiant cooling system is found to be an effective way to regulate the indoor temperature and still be energy efficient (Karmann, Schiavon, & Bauman, 2016; Kulhari, Singh, & Goyal, 2016; Rhee, Olesen, & Kim, 2017).

Radiant cooling system is not only benefitting towards the building's energy consumption, it would also helps in human health and productivity. Improved IAQ and themal comfort are delivered by radiant cooling system through regulated indoor temperature and minimal air draught (Karmann et al., 2016; Rhee et al., 2017). IAQ could affect occupants' health condition and eventually affect their performance. Thus, improved IAQ and thermal comfort will help in reducing poor health conditions and increase occupants' productivity (Field & Digerness, 2008; Kamaruzzaman & Sabrani, 2011).

While, natural ventilation would lead to the increase of noise level in the building due to the external noise ingress through the openings and windows (Coudriet, 2009; Field & Digerness, 2008; Field, 2008; De Salis et al., 2002), radiant cooling system is otherwise. The system produces less noise due to the lack of fan and blower and hence leads to the issue of low background noise level (Rhee et al., 2017; Kulhari et al., 2016).

2.5.2.2 Lighting System

Green building promotes the exploitation of daylight as a mean to improve the lighting quality in the building, and at the same time minimise the energy consumption used for indoor illumination (Muehleisen, 2010).

The chief design strategy for daylight harvesting is to provide a huge number of windows to allow daylight to penetrate into the building interior. At present, this prerequisite is in line with the current architectural trends, which are the practice of having curtain wall systems and glass façades as the building's exterior treatment (Muehleisen, 2010).

In the effort to maximise the utilisation of daylight, the uses of elements such as low height partitions, light shelves, and interior glazing or glass partitions are applied and multiplied. These elements are implemented as a way to allow daylight to infiltrate further into the interior spaces of the building and furthermore reduce the dependency on electric lightings to light up the interior spaces (Coudriet, 2009; Field, 2008; Muehleisen, 2010).

While the use of glasses is justified as a way to maximise daylight harvesting, acoustic problems would respectively take their place in its presence, as glass has a significantly low sound isolation capability. Moreover, glass has very low acoustic absorption quality (Coudriet, 2009; Field, 2008; Muehleisen, 2010). Also, light shelves installed to spread daylight into the interior spaces are made of materials with hard reflective surfaces (Field, 2008). Low isolation capability of glass would assist in the transmission of noise from the exterior into the interior spaces, and also the transmission between the adjacent spaces indoor (Muehleisen, 2010). On the other hand, low acoustic absorption of glass would contribute to excessive reverberation in the interior spaces and consequently lead to the issue of speech clarity (Coudriet, 2009; Muehleisen, 2010).

Poor speech clarity would interfere with the flow of communication in the interior spaces.

2.5.2.3 Internal Building Finishes

Green buildings have a unique characteristic of having an exposed interior aesthetic, which featured its raw building materials (Coudriet, 2009). Some of the reasoning behind this design move was that architects tried to utilise the thermal mass and radiant heating and cooling for better control of the thermal environment of the building, thus minimising the energy consumption. Exposed aesthetic also minimises the usage of natural resources. The elimination of carpeting, for example, is considered essential because of its chemical composition, adhesive off-gassing, and also for its short life-cycle (Coudriet, 2009). The general reason for having minimum finishes and more exposed surfaces is to achieve better IAQ and also because it requires less maintenance (Muehleisen, 2010).

Although removal of finishes are convincing for environmental benefits as it provides better IAQ; with fewer finishes, acoustical problems are more likely to happen. The apparent reason was that the eliminated finishes such as the acoustical ceilings and carpeting were previously the main features that provided the interior space with acoustic absorptions (Coudriet, 2009; Field, 2008; Muehleisen, 2010).

Coudriet (2009) stated that finishes such as acoustical ceiling managed the acoustic environment of a room by controlling reverberation and noise levels which were the main contributor of distraction and annoyance to building occupants. With its absence, acoustic problems such as excessive reverberation and poor speech intelligibility are more likely to occur.

Table 2.7: Summary of four green building design strategies and their cause and effect on acoustic comfort

Building Element	**Ventilation system**	**Lighting system**	**Internal building finishes**	**Workspace design and configuration**
Green building design strategies	Radiant cooling system /	Daylighting	Reduced finishes	Open-plan office layout
Design methods	Chilled floors (embedded pipes)	Curtain / glass wall, reflective light shelves, light trough	Bare (reflective ceilings)	Minimal solid partitions between workspaces, low height and glass partitions
IEQ positively affected	Thermal comfort & IAQ	Visual comfort	Thermal , visual comfort, & IAQ	Visual comfort & IAQ
Other / green outcome	Reduce energy consumption on A/C systems	Reduce energy consumption on artificial lighting	Less maintenance	Promote interaction between co-workers
Influence on acoustic parameters	**BN**: Low BN level	**BN**: External noise ingress **RT**: Excessive reverberation	**BN**: Low noise control **RT**: Excessive reverberation	**STI**: Reduce isolation between workspace
Causes	Low noise from ventilation system to act as BN or masking sound	Low sound isolation capability of glass, low acoustic absorption of glass	Lack of acoustic absorptive ceiling finishes to control noise	Low / no barrier between the workspaces

2.5.2.4 Workspace Design and Configuration

Open-plan office is closely related to the maximisation of natural ventilation and daylighting. Open-plan office is considered as a modern design trend and has become a typical format for office space (Bradley, 2003). Moreover, it has also become a part of green design elements that are highly influential in making sure other design strategies such as natural ventilation and daylighting to work splendidly (Coudriet, 2009).

Open-plan offices usually use a limited number of solid partitions and utilised low height partitions or glass partitions as a mean of separation between the workstations. This, as mentioned earlier, was to cater for green building requirements which are to achieve better indoor air quality (IAQ), thermal comfort, and lighting; by relying on natural ventilation and daylight harvesting as much as possible. On the contrary, open-plan office layout would result in acoustic problems such as reduced sound isolation and eventually poor speech privacy (Field, 2008).

2.6 Computer Simulation for Acoustic Design

Architecture uses visuals as its ‘tools of the trade’ to express ideas (Schroeder, Martin, & Lorensen, 1996). Visualisation has been the most practical approach of presenting imaginary spaces (Koutamanis, 2000). Initially, visual communication in architecture was delivered through hand-drawn sketches and drawings. However, this process demands meticulous effort, and the process of producing aesthetically appealing visuals is often time-consuming.

Nowadays, through the aid of computer technology, architects and designers migrated towards producing their ideas digitally (Akin, 1990). Using computers, 2D design sketches of preliminary ideas can turn into 3D models in a short amount of time. Besides having the advantages of viewing the space in a 3D viewpoint, these modelling tools can also be used as a medium to explore ideas, forms, shapes, spaces, and function (Koutamanis, 2000; Yin, Wonka, & Razdan, 2009; Oxman, 2008).

In addition to being a medium for architectural visuals, these models can also be utilised for the prediction of building performances (Yin et al., 2009; Yezioro, Dong, & Leite, 2008). The ability to predict building performance is a potent instrument in the construction industry. Successful planning of building performance can potentially lead to sustainable energy conservation (Hong, Chou, & Bong, 2000).

One element in building performance that can benefit from these 3D models is acoustics. In the past decades, the process of transforming 2D architectural drawings into digital formats for room acoustics evaluation was described as tedious and laborious work. As a result, establishing assessments toward these processes took a lot of time and effort (Oldham & Rowell, 1987). However, with today's thriving technological development in computer graphics and modelling tools, those stages would be considered as the easy ones as 3D models would be readily available since the beginning of the preliminary design stages.

Like other building performance prediction work, acoustic prediction is an essential element in the field of built environment (Hornikx, 2015) as it can save time, cost, energy, and resources (Hong et al., 2000; Hensen & Lamberts, 2001; Hensen, 2004; Augenbroe, 2002). These savings can especially be achieved when the prediction work takes place during the early stages of the design work (Siltanen et al., 2008).

2.6.1 Development of Acoustic Simulation Methods

As mentioned previously, the early study in architectural acoustic was more concerned towards the acoustical conditions in auditoriums and concert halls (Rossing, 2007). Thus, it is only natural that the development of acoustical simulation technique began with acousticians attempts in designing the acoustic in auditoriums and concert halls. Rindel (2002) discussed in detail the history of the development of acoustic simulation starting from the use of physical models by Sabine in 1913, to the application and development of scale models throughout the 1930s to 1970s, and the latest technique of acoustical simulation using computer models.

The primary concern and use of physical models in acoustic simulation focused on analysing the first reflection of wavefronts or rays through a 2D section of a room. Scale models, on the other hand, concentrated on reducing the scale of models from 1:5 to 1:50 for practical design purposes. Subsequently, the introduction of computer models provided a speedy and more reliable acoustical simulation results (Rindel, 2002). Figure 2.11 illustrated the development of the three methods of acoustical simulation arranged by the earliest report of the methods.

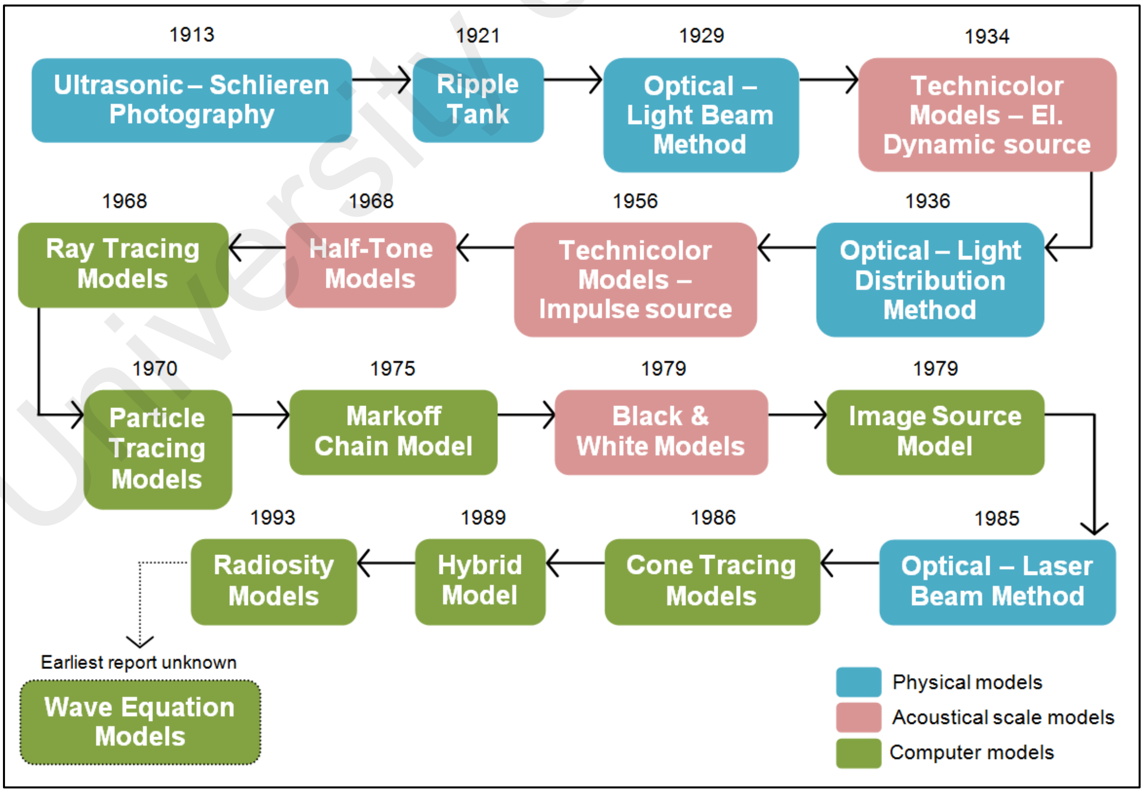


Figure 2.12: Timeline of the development of the acoustical simulation methods. (Adapted from Rindel, 2002).

The ability to simulate the acoustic environment of open-plan office can make a huge impact on the acoustic quality of the space. Through computer simulation, the design of open-plan office can be used to predict the acoustic quality of the space. Using the initial predictions, the acoustic design of the open-plan office can be manipulated to suit the specific purpose of the space.

Previously the design of architectural space, including open-plan offices, only concern with the calculation and prediction of reverberation time (RT) using the Sabine formula. However, the acoustic performance of open-plan offices cannot be characterised using RT alone. This is due to the many irregular features and designs that make up the room such as the amount of uneven distribution of absorptive surfaces, the furniture layouts, etc. (Rindel & Christensen, 2012). It is also crucial to note that as speech noise is the main issue in open-plan offices, using RT to describe the acoustic quality of the space would be unsuitable.

Through computer simulation using the many acoustic prediction tools commercially available today, the more appropriate acoustic parameters can be easily predicted (Pelzer, Aretz, & Vorländer, 2011). ISO 3382-3 (2012) outlined the methods to measure the appropriate acoustic parameters in open-plan offices. These acoustic parameters can be translated to forecast the speech intelligibility and privacy of the open-plan offices.

Spatial quality is an essential element in architectural design. Spatial quality can be achieved by creating the ideal IEQ condition. As acoustic quality is one of the elements that make up the IEQ, it is important that this element to be designed accordingly, parallel to other IEQ elements. Using computer simulation tools available, designers and architects can estimate the acoustic quality of the space early on in the design stage.

2.7 Summary

In this day and age, the importance of workplaces in people’s everyday lives is indisputable. With the amount of time people spend in their workplaces, it is paramount for a workplace to be a place where people can find comfort, as well as a place that can ensure their health and well-being. At the beginning of the research, it was established that acoustic comfort has always been problematic in the workplace. With the ever-growing workplaces concept and designs, acoustic comfort continued to be an issue.

While green building as a concept “offered” to resolve the issue of acoustic comfort along with other environmental issues in the workplace, somewhere along the way, acoustic always gets left behind. Often because it was overlooked or seen a trivial matter as the effect of acoustic discomfort is gradual and unnoticeable.

Hence, this chapter elaborated on the main topics on which this research was built on. The fundamentals of the three topics (acoustic, workplace, and green building), its objectives and purpose, and relation to human comfort were discussed. Furthermore, tying the elements together assisted in the understanding of why acoustic comfort is still an issue.

Also, deliberation of the three elements together assisted in the quest to find the best solution to cater for the acoustic issue. Nevertheless, consideration of their objectives and purpose helped draw the line in which they overlapped. This understanding also helped in discovering the particular design direction which can and should be taken so that the limitation of each element would not be jeopardised.

CHAPTER 3: RESEARCH METHODOLOGY

This chapter explicates in detail the research methods carried out to achieve the aim and objectives developed in Chapter One. The research is done through three approaches: case studies in selected green office buildings, acoustical measurement in selected open-plan offices, and computer modelling and acoustical simulation using selected simulation tool.

3.1 Research Design

Research design is the sequential steps mapped out in the early stage of the research work in order to achieve the research aim and objectives. Yin (2009) defined research design as "*a logical plan for getting from here to there*, where *here* may be defined as the initial set of questions to be answered, and *there* is some set of conclusions (answers) about these questions." (p.26).

To achieve the research objectives procured in Chapter One of this thesis, the research design is roughly divided into two phases. The first phase is designed to respond to the first two research objectives, which is to understand the actual acoustical quality of existing green office buildings in Malaysia and further comprehend the underlying reasons behind the acoustics performance. On the other hand, the second phase is designed to counter the third and furthermore fourth objective which is to come up with design measures and considerations for an acoustical design that would specifically suit the design elements in green office buildings. The second phase is a continuation of the first phase as the data collected and analysed in the first stage are utilised for the second stage to ensure workability of the second stage in this research work. Figure 3.1 illustrates the three methodologies utilised in the research design.

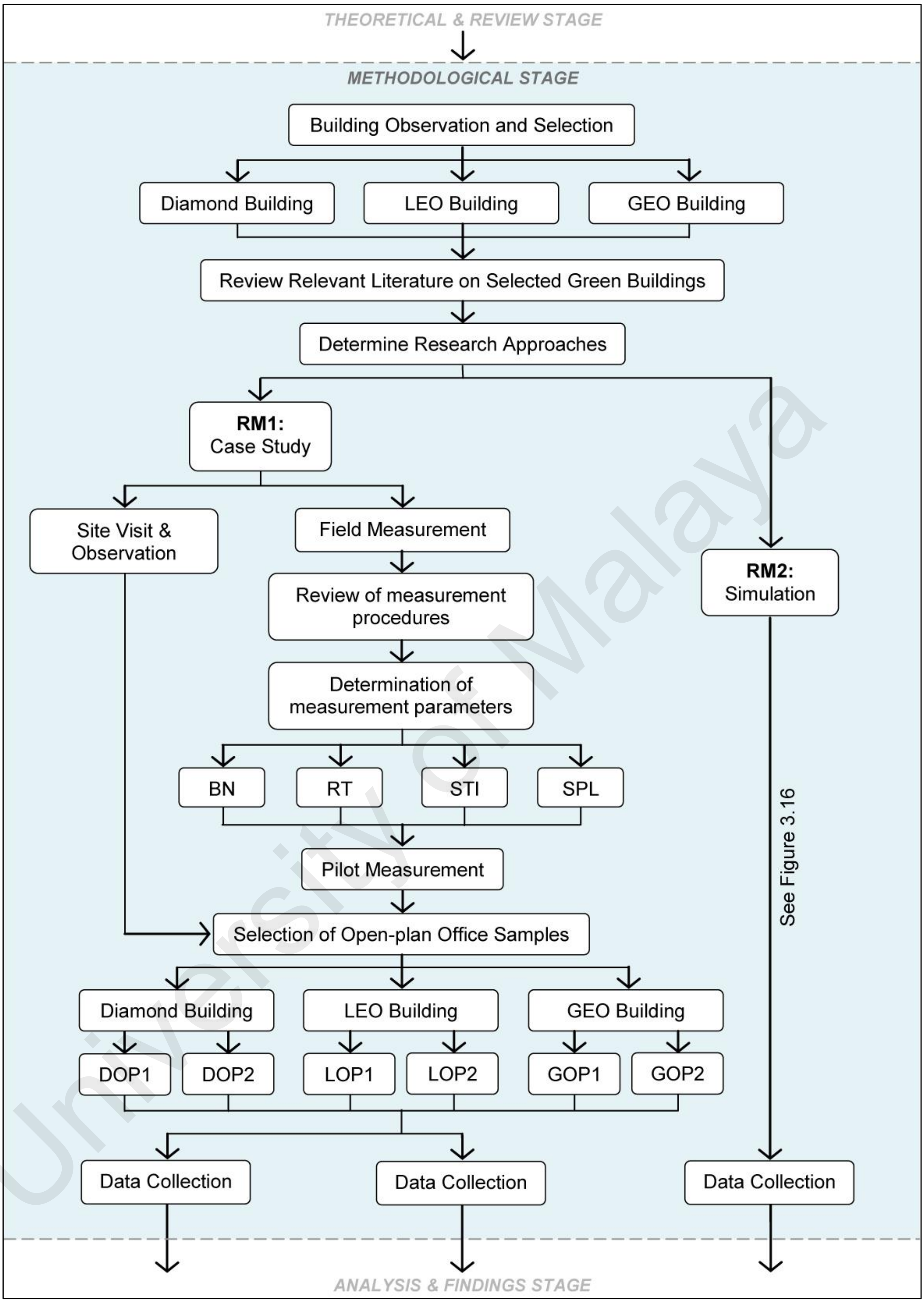


Figure 3.1: Research design workflow

In the study, the data are collected by way of case study through site visits, observations, and field measurements. The idea is that data collected during the field measurements would provide figures that would be equated with existing acoustical standards and subsequently showcase the level of acoustic performance of selected open-plan offices. This research approach merely achieves the first research objective which is *'to evaluate the level of acoustic quality in selected open-plan offices'*. By having a case study research approach through site visits and observations, the data collected during the field measurements can be analysed together with the data collected in the site visits and observations. This way of analysis would assist in achieving the second research objective which is '*to identify the green design elements which influence the acoustical quality in selected open-plan offices.*'

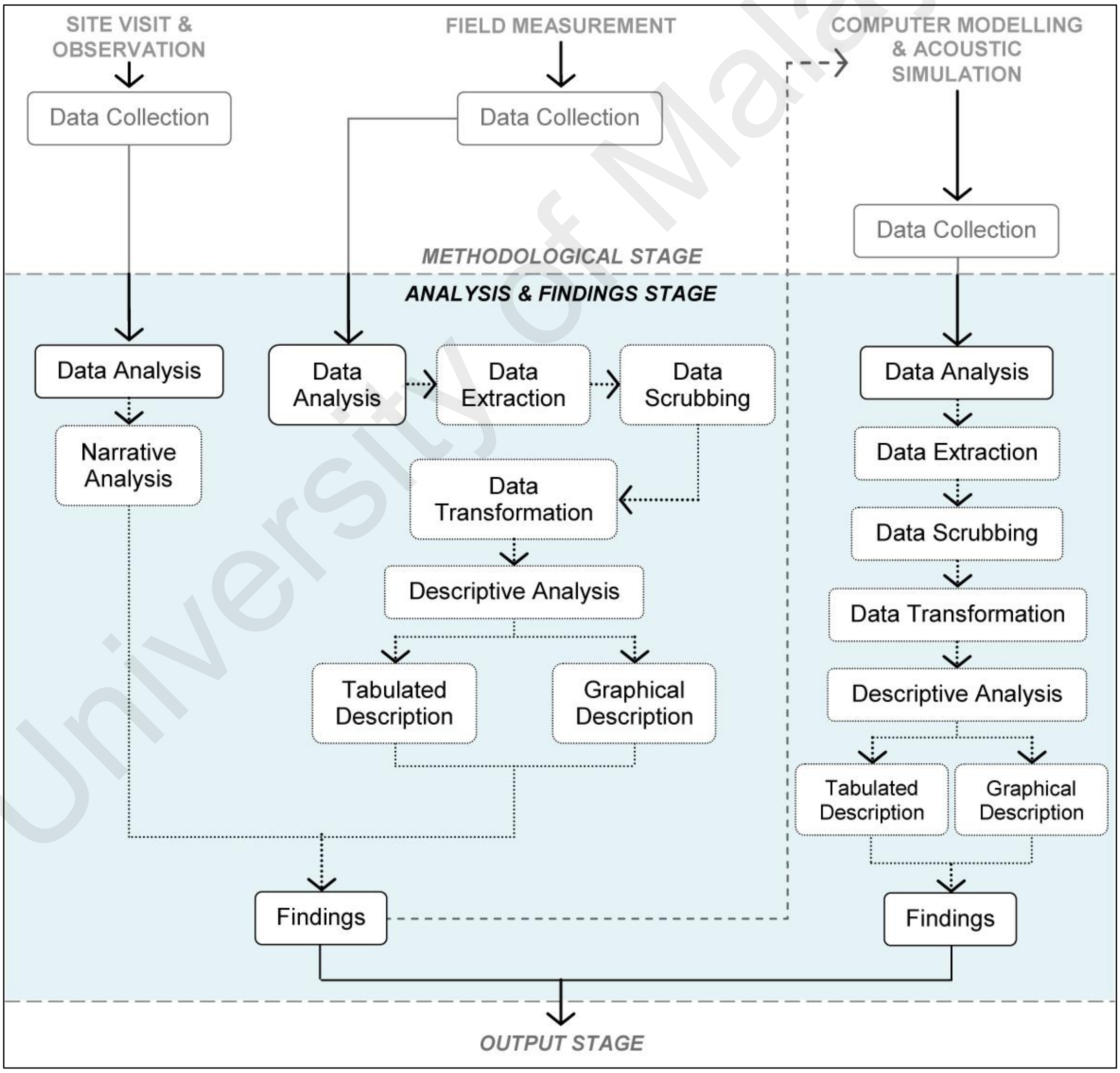


Figure 3.2: Analysis stage workflow

Furthermore, by analysing the site visits, observations, and field measurements data together and analysing it with the findings obtained from previous literature, the preliminary conclusions would help in determining the essential acoustical parameters relevant for good acoustic design in open-plan offices. This understanding is use for the third research method, which is an experimental research method through the utilisation of computer modelling and acoustic simulation tool. Figure 3.2 demonstrates how the data collected from each method were analysed and how the data processes interconnected with each other.

3.2 Building Observation and Selection

The selection of green office buildings as the subject for the case study and acoustical measurement started with the observation of Malaysia's current green building movement. At the beginning of the research work in 2012, the green building movement was a relatively a new thing in Malaysia. The Malaysia's green building rating tool initiative, the Green Building Index (GBI) was just launched in 2009 (Green Building Index, n.d.) and Malaysia's building industry was just warming up to the idea of building *green*.

The observation and selection process started with online web searches for the list of green office buildings that can be used as potential subjects for the study. The main criterion for the selection is that the building must be a GBI-certified green building. As the research scope is to study office buildings, specifically open-plan offices; only the Non-Residential Certified Building list was attained from GBI official website. The list was then analysed and narrow down to find the office buildings that have been built and occupied.

During the selection process, three GBI-certified green office buildings were observed to be a suitable case study for the research. The three green office buildings are:

1. *Diamond* building (Headquarter building of Malaysia's Energy Commission)
2. *LEO* building or the Low Energy Office building (Head office for the Ministry of Energy, Green Technology and Water (KeTTHA) Malaysia)
3. *GEO* building or the Green Energy Office (Headquarter building for GreenTech Malaysia).

These three green buildings are one of the first green office buildings ever built in Malaysia. In the preliminary building observation, previous literatures related to the three buildings are reviewed to understand the building background, systems, and elements. It should be noted that the three green office buildings are designed by the same green building consultants namely IEN Consultants; which means that they have similar green design fundamentals. As the buildings are pioneer green office buildings in Malaysia, they have been studied extensively on its energy consumption, building energy index (BEI), lighting, thermal comfort, and IAQ (Yau, Ding, & Chew, 2011; Nikpour et al., 2012, Hong, 2009). The studies show that they are exemplary green buildings with excellent BEI readings and exceptional indoor air quality (IAQ), thermal and visual comfort. However, research regarding the acoustical performances of the selected buildings was very scarce.

After the statuses of the three buildings were verified, initial permission and confirmation for the research work were obtained through phone calls made to the buildings' management. Official letters from the University of Malaya were then requested from the office and sent out to the selected green office buildings.

It should be noted that initially, there were a few more green building approached for the study. However, only these three green office buildings gave positive feedbacks and permission for the research work and acoustical measurement to be carried out. Table 3.1 shows the building selection criteria for the three green office buildings selected.

Table 3.1: Criteria for building selection

No.	Selection Criteria	Diamond	LEO	GEO
1.	Certified Green by GBI	✓ (Platinum)	✓ (Silver)	✓ (Certified)
2.	Located in the Klang Valley	✓	✓	✓
3.	Built as green / sustainable building from the beginning	✓	✓	✓
4.	Fully occupied *office* building	✓	✓	✓
5.	Main nature of work: administrations and mild research	✓	✓	✓
6.	Accessible at the time of research work	✓	✓	✓

3.3 Case Study

Case study is a standard research method practised in several areas of social science when the need to understand an intricate social condition arises (Yin, 2009). Among other research methods available for the application of research work, Gillham (2000) described case study research method as something that lies within 'the qualitative dimension'. Qualitative methods often deal with descriptive and inferential elements in research. Although it is referred to as 'soft' method, its content is crucial in interpreting data and facts obtained from quantitative methods (Gillham, 2000).

Groat and Wang (2002) defined case study in architectural context as "an empirical inquiry that investigates a phenomenon or setting." (p. 346). 'Setting' in this context included both historical and contemporary situations. According to Groat and Wang (2002), there are five prominent characteristics of an architectural case study. There are:

i. A case study can either choose to focus on one or multiple cases which are studied in its real-life context.

ii. It should have the capacity to explain causal links between elements in the study. It can be either explanatory, descriptive, or/and exploratory.

iii. It should guide by theory or hypothesis that should control the type of data that needs to be collected.

iv. Data collected in a case study should be backed by multiple sources of evidence.

v. The data collected in a case study should have the ability to function into a generalised theory that can be applied in other similar cases.

3.3.1 Case Study Design

The case study is designed according to Groat and Wang (2002) five principal characteristics. The case study's whats, hows, and whys are determined through the theory developed from the findings in literature reviews which is; 'the acoustics quality in green office buildings was unsatisfactory in comparison to acoustics quality in non-green office buildings' (Abbaszadeh et al., 2006). This was puzzling as green building design elements are suppose to improve and enhance the components of indoor environmental quality (IEQ) including acoustic comfort. Hodgson (2008) then explained that the negative acoustical phenomenon reported occurred as the results of green building design elements itself.

Thus the initial theory developed is that these issues could be applied to any green office buildings. It should be noted that the green buildings covers in the literature reviews (Abbaszadeh et al., 2006; Hodgson, 2008) are built in four seasonal countries tackling different weather conditions and thus the green building design strategies tend to differ from green designs for buildings in a tropical country like Malaysia. Thus it is determined that there would be some inconsistencies and to apply the theory literally on green office buildings in Malaysia would be improper.

Thus, the case study aims to answer similar questions probed in previous literature reviews by identifying the design elements and strategies of the three selected green office buildings; which would be backed up by the acoustical measurements. This should help in determining the acoustical conditions in the open-plan offices in the three green office buildings. The data collected in the case study would be descriptive which should explain the cause and effect of the acoustic measurement data collected. Figure 3.3 illustrates the procedures of data gathering for the case study work.

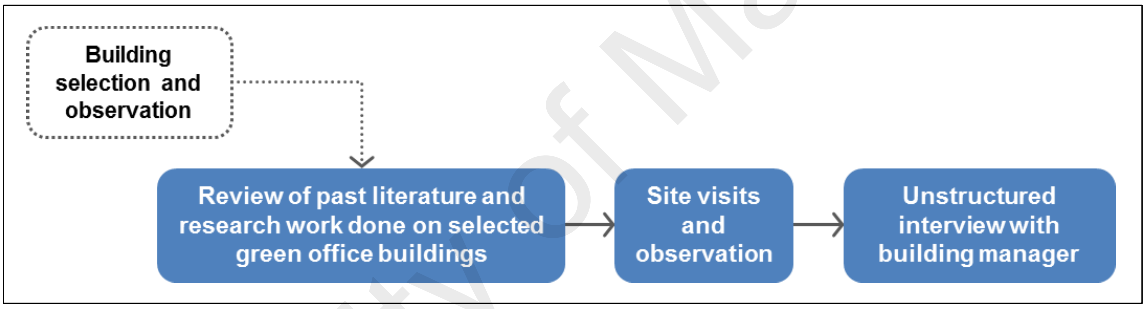


Figure 3.3: Procedures of case study data gathering

3.3.1.1 Review of Past Literature

Before site visits at selected green office buildings, preliminary researches on the green office buildings are carried out. The literature search work includes reviews of previous journal papers, dissertation works, textbooks, and internet web pages related to the selected green office buildings. Essential information related to the study, i.e. architectural information; are collected for the case study.

3.3.1.2 Site Visits and Observation

Site visits are done during office hours by appointment. Information gathered throughout the literature reviews are verified during the visits. Photographs of the buildings are also taken during the site visits. Three main elements that are observed during the visits are:

i. Site location, planning, and external components of each buildings.
ii. Design elements of the entire building; internally, externally, and any other special features.
iii. Acoustic quality in the building, open-plan office spaces, and any prominent exterior sources of acoustic problems.

3.3.1.3 Unstructured Interview with Building Manager

The building managers of the three green office buildings are informally interviewed (during the building tour) for information regarding the building systems and unique green building features.

3.4 Field Measurement

To investigate the acoustic performances of open-plan offices in the selected green office buildings, acoustical measurements are carried out. However, due to the time constraint and limitation of building access, it is determined that only two open-plan office spaces would be chosen as sample spaces to represent the buildings for this study.

Measurement quantities or parameters are determined by referring to previous literature reviews and acoustical Standards. Significant measurement parameters are selected so that the measurement data collected would assist in verifying the acoustical performance of the selected open-plan offices. The Standards referred to in determining the measurement quantities are:

1. ANSI/ASA S12.2-2008 – American National Standard – Criteria for Evaluating Room Noise.

2. ISO 3382-2:2008(E) – Acoustics – Measurement of room acoustic parameters – Part 2: Reverberation time in ordinary rooms.

3. ISO 3382-3:2012(E) – Acoustics – Measurement of room acoustic parameters – Part 3: Open plan offices.

3.4.1 Measurement Parameters

There are four acoustical parameters measured in the selected open-plan offices from all three green office buildings. They are:

1. Background Noise (BN) Level, measured in A-weighted decibel or dB(A)
2. Reverberation Time (RT), which is in the unit of second (s)
3. Speech Transmission Index (STI)
4. Sound Pressure Level (SPL), measured in dB(A).

3.4.2 Measurement Procedures

Measurement work is carefully planned to ensure the right spaces and measurement points are selected, the right acoustical measurement apparatuses are used, and the right measurement procedures are followed. Figure 3.8 below mapped out and summarised the measurement procedures of field measurement work carried out in this thesis.

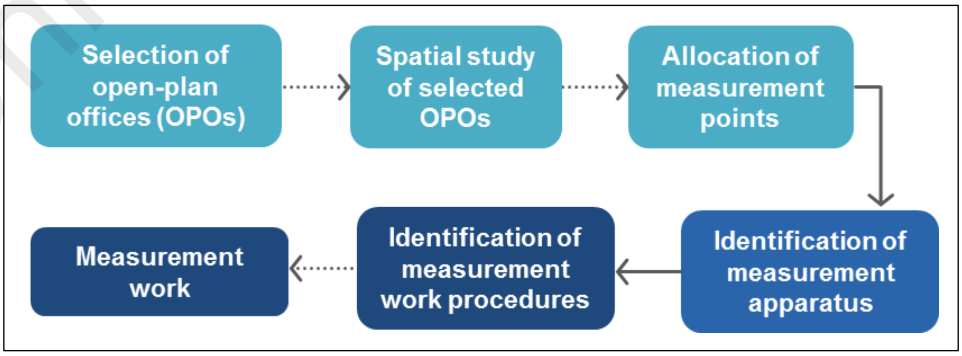


Figure 3.4: Framework of measurement procedures

3.4.2.1 Selection of Sample Spaces and Measurement Points

Among the green office building selected for the study, two open-plan offices are selected from each building. The two open-plan offices are taken as representative spaces to be acoustically measured. The open-plan offices represent the general working areas of the buildings. The limitation of space selection is due to the restraint of time for the measurement work and building accessibility issues.

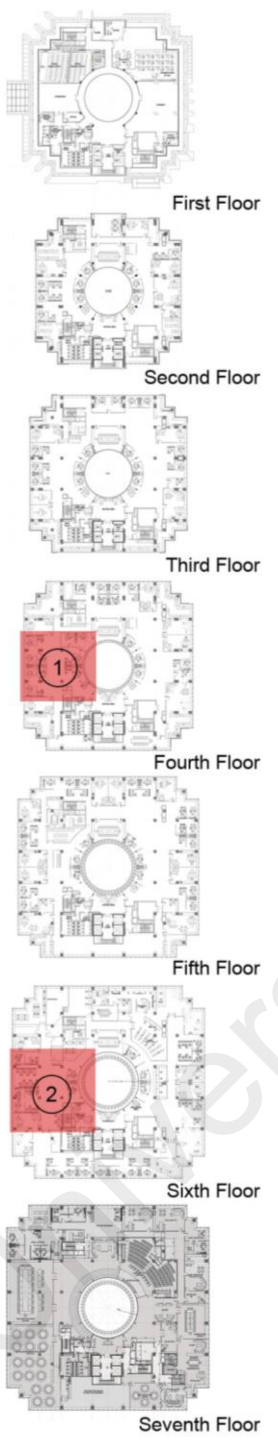
Table 3.2: Summary of selected OPO in the three green office buildings

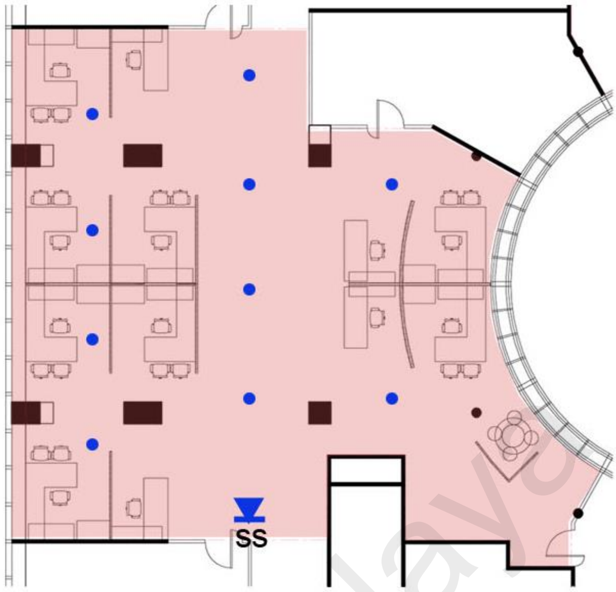
No.	**Building / measured open-plan offices (location in building)**	**Code**	**Dimension of room (*m*)**			**Calculated parameter of room**	
			L	**W**	**H**	**Volume (m^3)**	**Arranged capacity**
Diamond Building							
1.	Open-plan Office 1 (L.4)	DOP1	16.8	15.1	3.5	887.9	12 (+16)*
2.	Open-plan Office 2 (L.6)	DOP2	16.6	17.0	3.5	987.7	17 (+9)*
LEO Building							
3.	Open-plan Office 1 (L.2)	LOP1	13.6	13.7	2.7	503.1	13
4.	Open-plan Office 2 (L.3)	LOP2	29.0	11.9	2.7	931.8	26
GEO Building							
5.	Open-plan Office 1 (L.2)	GOP1	8.0	12.0	3.75	360.0	10
6.	Open-plan Office 2 (L.2)	GOP2	30.5	8.0	3.75	915.0	35

*maximum guests capacity

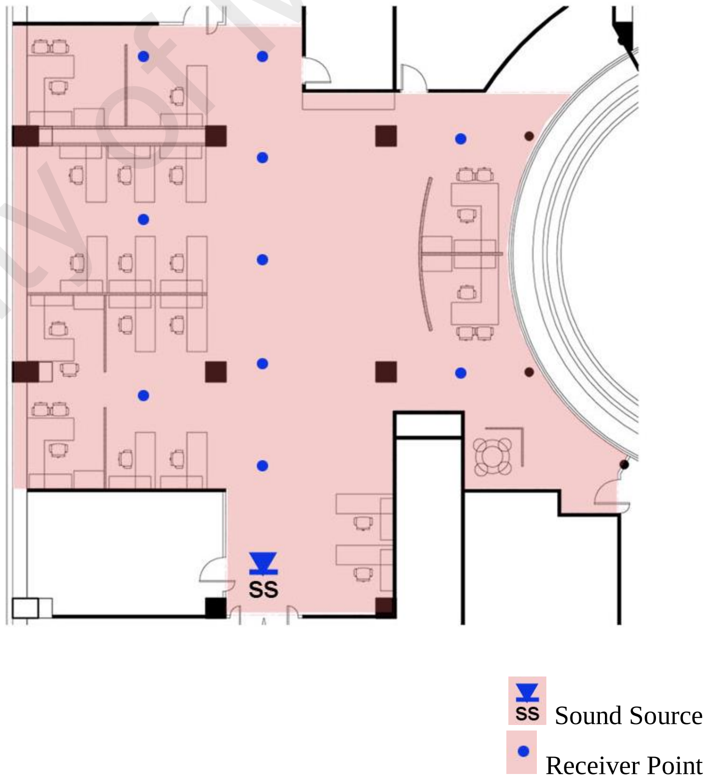
Figure 3.5, 3.6, and 3.7 show the layouts of all the selected spaces. The location of the sound sources and receivers are also annotated in the layout plans. Table 3.2 summarises the sizes, volumes, and the arranged capacity of permanent occupants (plus the maximum guests) of all the selected open-plan offices.

Diamond building floor plans





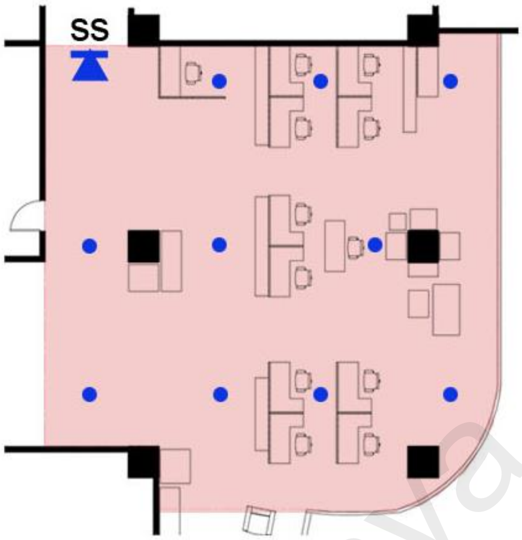
(1) DOP1: Open-Plan Office 1 (Level 4)



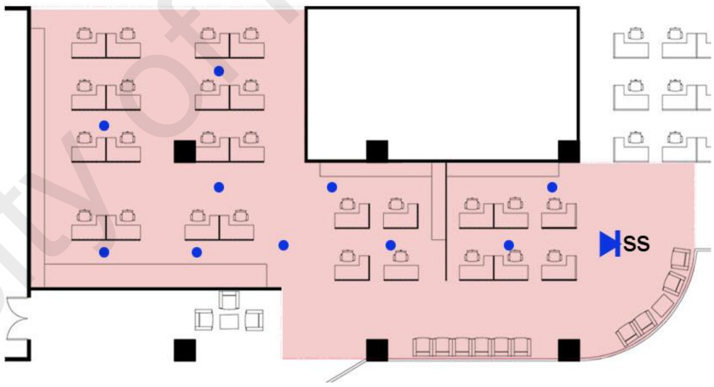
(2) DOP2: Open-Plan Office 2 (Level 6)

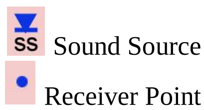
Figure 3.5: Diamond building's OPO layout plans and locations in the building

LEO
building floor plans



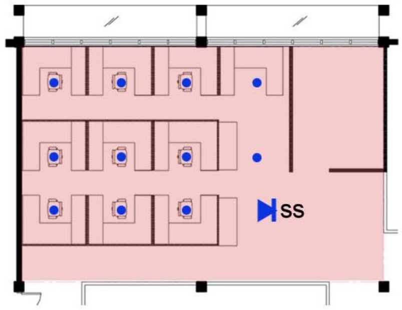
(1) LOP1: Open-plan Office 1 (Level 2)

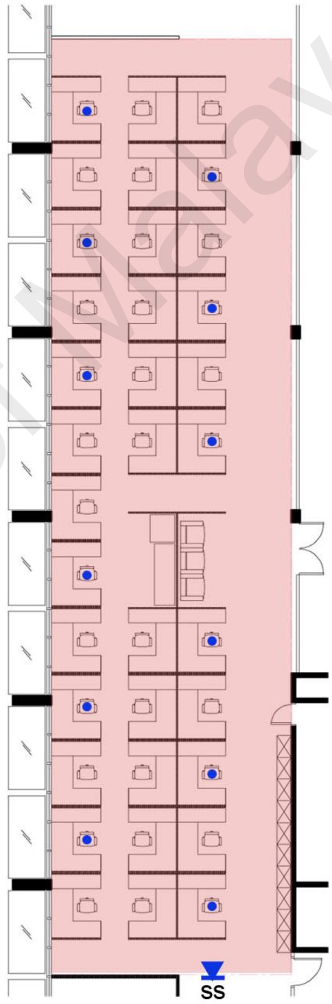


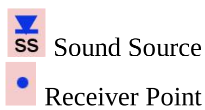


(2) LOP2: Open-plan Office 2 (Level 3)

Figure 3.6: LEO building's OPO layout plans and locations in the building

<table>
<tr><td>GEO
building floor plans</td><td rowspan="2">

(1) GOP1: Open-plan Office 1 (Level 2)




(2) GOP2: Open-plan Office 2 (Level 2)</td></tr>
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Figure 3.7: GEO building's OPO layout plans and locations in the building

3.4.2.2 Measurement Apparatus

(a) ***Sound level meter (SLM)***

There are two sound level meters (SLM) utilised for the measurement work. The first one is the 01dB Metravib Blue Solo (Blue Solo) and the second one is the Cirrus Research CR:172B Optimus Green SLM (Cirrus). Both Blue Solo and Cirrus are designed to meet the requirement of IEC 61672-1:2002 (BS EN 61672-1:2003) class 1 (01dB, n.d.; Noise Measurement Instruments, n.d.). Each SLM is occupied with a ½-inch free-field microphone.

Blue Solo (Figure 3.8) is a sound level meter developed by 01dB, which specialised in noise monitoring and vibration. The Blue Solo is built to measure the equivalent continuous sound level of pressure levels or peak levels. Blue Solo allows for measurements of low noise level in quiet conditions, as low as 30 dB. The SLM allows for the measurement of both 1/1 and 1/3-octave band frequencies. However, both octave bands cannot be measured simultaneously.

For this study, Blue Solo accuracy and the system’s sensitivity were verified through a calibration process. The calibration was done before the measurement work using an acoustic calibrator. The Blue Solo was calibrated according to the calibrator reference level of 94 dB at one kHz test tone.

Unlike Blue Solo, Cirrus (Figure 3.9) has the advantages of measuring all the BN and SPL acoustic measurement functions at the same time. For example, it allows simultaneous 1/1 and 1/3-octave bands to be measured concurrently. Even though Cirrus is designed to cater more towards the measurement of environmental noise, it allows for other types of measurement conditions such as occupational and general noise measurement. However, it does not allow for the measurement of specific indoor acoustic parameters such as RT and STI.

Data collected using Cirrus is extracted using NoiseTools, a software specifically designed for Cirrus Research-made SLMs. The software provides quick analysis and reports for the extracted data. However, for this study, the data collected from the selected measurement points would be analysed manually.

During the measurement work, the ½-inch microphones of both SLM are covered with a protective windscreen. The windscreen is a porous sphere material used to protect the microphone from damage, keep the microphone's capsule clean, and most importantly reduce the effect of wind-generated noise on the microphone.

Figure 3.8: 01dB-Metravib Blue Solo SLM (Blue Solo)

Figure 3.9: Cirrus Research CR:172B Optimum Green SLM (Cirrus)

(b) ***Sound generator (Minirator MR2) and amplifier (Crown XLS 1000)***

The Minirator MR2 is an audio generator and an impedance meter developed by NTi Audio AG. The audio generator provides the sine wave, sweep signal, and pink noise needed for the measurement of reverberation time (RT), speech transmission index (STI), and sound pressure level (SPL) respectively. The audio generator also provides other types of signals such as white noise, delay test signal, and polarity test signal. Additionally, the Minirator MR2 supports the application of user WAV-files using the apparatus.

During the measurement sessions, the Minirator MR2 (Figure 3.10) was connected to the Crown XLS 1000 amplifier (Figure 3.11) to augment the sound signals to suitable sound levels and frequencies through the omnidirectional loudspeaker.

Figure 3.10: Minirator MR2

Figure 3.11: Crown XLS 1000 Power Amplifier

(c) ***Omnidirectional loudspeaker***

For the field measurement work, an omnidirectional loudspeaker was used as the sound source for the measurement of RT, STI, and SPL. The speaker encompassed of 12 loudspeakers that are configured in a dodecahedral shape, which allows for sound to be spread evenly in a spherical distribution. The usage of a dodecahedron loudspeaker is crucial in architectural acoustic measurement, especially in this study of office acoustics as the sound needs to be radiate evenly in all directions for reliable acoustical measurement results.

During the measurement work, the loudspeaker was connected to the amplifier to emit the intended signals according to the type of parameters being measured (RT, STI, or SPL).

Figure 3.12: Omnidirectional loudspeaker

3.4.2.3 Measurement Work

To evaluate the acoustical quality of selected open-plan offices, field measurements were carried out. In order to achieve comparable results between all the spaces, the conditions of the spaces during the measurement were controlled by reducing the human and weather factors. Human factors refer to any acoustical influence created by human presence such as sounds from human activities and absorption. On the other hand, weather factor refers to any external noise caused by thunderstorm, raining, and etc. The measurement work started in November 2012 and completed in January 2013. The measurements were conducted during non-office hours on weekdays between 6 p.m. to 8 p.m. During the time of the measurement, the office spaces were unoccupied except for one or two building personnels (for security reasons). In addition, to reduce the weather factor, no measurements were done during irregular weather conditions. The physical environment of the open-plan offices was kept similar to the environment during office hours by ensuring that the basic building services such as the air-conditioning and lightings for all the spaces were in operation at the time of measurement as per how they would operate during regular working hours. Measurements were carried out in fully furnished open-plan offices.

(a) ***Background noise (BN) level***

In determining the selected open-plan offices' BN level, measurements were done by selecting measurement points at which the measurement would be taken. Measurement points' selection was made based on the geometry and floor area of the room. The sufficient numbers of measurement points or in this case 'listener positions' were chosen to assure sufficient coverage of the floor area. Selected listener positions for all selected spaces are as marked in Figure 3.5, 3.6, and 3.7.

After the selection of measurement points, the BN level was measured using Cirrus. The SLM was positioned at the height of 1.2 meters above finish floor level, to achieve the height of a person sitting on an office chair. At every selected point, the BN level was measured for two minutes with the data recorded at every one second. The A-weighted BN data collected from each measurement point were calculated and averaged to simplify the data presentation. Noise criteria (NC) were achieved by plotting the averaged BN data in the frequency range of 63 Hz until 8000 Hz into the NC curved graph. Figure 3.13 shows the condition and positioning of Cirrus Optimum Green during BN measurement.

Figure 3.13: The Cirrus in position during BN level measurement

(b) ***Reverberation time (RT) and speech transmission index (STI)***

To obtain data for reverberation time (RT) and speech transmission index (STI) of the selected open-plan offices, a loudspeaker are used as the sound source. Since it is impossible to determine which direction a person would face when they are talking, especially in an open-plan office; an omnidirectional loudspeaker is utilised (ISO 3382-3; 2012). The sound source is positioned at the height of 1.2 meters above finish floor level to achieve the height of a sitting person (ISO 3382-3; 2012). For RT and STI data gathering, a PC-based acoustic measuring system and analyser is utilized. The measuring software, dBBati32; is integrated with the Blue Solo as the analyser. Figure 3.14 illustrates the basic equipment setup during the measurement of RT and STI.

During RT measurement, the sound source is set to radiate a sine-wave signal at four specific frequencies which are at 250 Hz, 500 Hz, 1000 Hz, and 2000 Hz. The measurements are taken separately in each frequency at selected measurement points. Each measurement is taken in a five-second range.

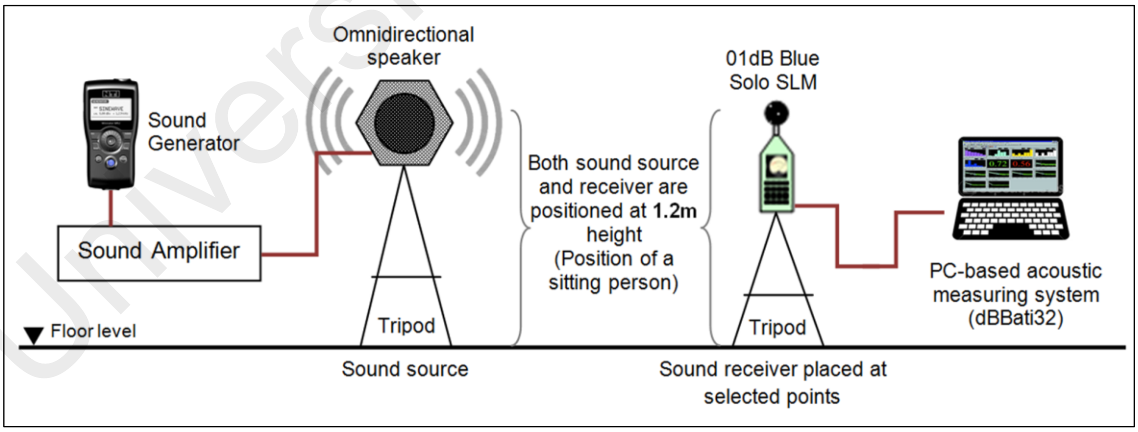


Figure 3.14: Basic equipment setup during the measurement of RT and STI

Before the measurement work for RT started, the rough BN level is surveyed through the display on the computer using the dBBati32 software. The sound source is then adjusted to exceed at least 30 dB from the surveyed BN level. This adjustment is made as such so that the automatic RT adjustment done by the software would consistently obtain a T_{30} range of RT. However, it should be noted that the differences between a T_{20} and T_{30} RT do not have any significant impact on the final RT results as the differences were not that substantial.

As for the STI measurement, the same equipment setups are repeated. However, instead of using sine-wave signal, sweep signal is projected from the sound source at the level of 68 to 70 dB(A), measured at a one-meter distance from the sound source; to represent raised human talking voice level. Measurements of STI are taken in two seconds' range at every receiver points.

It should be noted that the results of RT and STI are obtained automatically from the dBBati32 software. However, the measurement settings are verified a few times beforehand, and the measurement of the first few measurement points are done twice to ensure precise results. The software's calculations of RT and STI are attached in Appendix D.

(c) ***Sound pressure level (SPL)***

As previously discussed, the SPL is taken to measure the spatial decay rate of the open-plan offices, or in other words; to identify how much the sound level drops with distance from the point of its emission. The measurement of SPL is done according to ISO 3382-3 (2012). The sound source was fixed to emit pink noise at the level of raised human talking voice which is between 68 to 70 dB(A), measured at a one-meter distance from the sound source. Cirrus is used as the sound receiver for SPL measurement. The measurements are done at selected receiver points, which are linear with the sound source. Figure 3.15 illustrates the basic equipment setup during the measurement of SPL. It should be noted that for this study, the measurement data of SPL would only be use for the purpose of model verification for the computer simulation stage of the study.

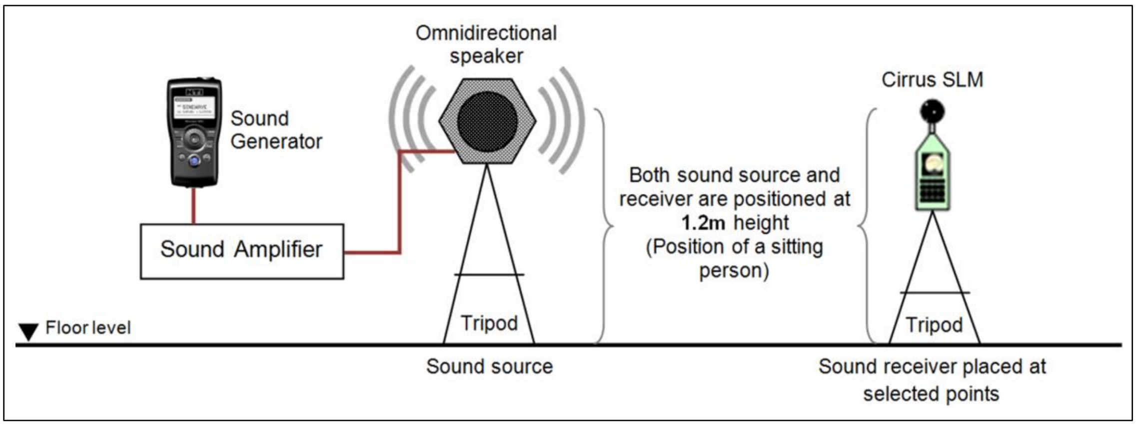


Figure 3.15: Basic equipment setup during the measurement of SPL

3.5 Computer Simulation for Acoustical Design in Open-Plan Offices

As discussed earlier, open-plan offices have always been about flexibility, flexibility in term of economical space manipulation and flexibility in term of work collaborations between co-workers (Veitch, 2012). However, this concept of space which can induce and enhance work collaboration between co-workers depends heavily on the 'nature-of-work' carried out in the office. Different types of work require different levels of cognitive concentration. Open-plan office in the type of bullpen office (open-plan office with no partitions or barriers between workstations) would be ideal and practical for work such as advertising, marketing, design studios, or large control room where people need to share information all the time (Veitch, Charles, & Newsham, 2004). These types of work do in fact require more work collaboration and discussions, as they need to develop ideas together for better work outcome and a borderless office is a crucial medium in this ‘nature-of-work’.

However, for work such as administrative or research work (as carried out in the three green office buildings studied), occupants require significant personal spaces in which they can concentrate in, to get their work done, but at the same time still be accessible to colleagues for a minimal amount of discussions and also for social interaction purposes. The best type of office would be open-plan office, equipped with separate workstations with some barriers or partitions for privacy and concentration.

The detail findings and data for field measurement and case study would be discussed later in Chapter 4 and 5. However, through the process of understanding the choices of design strategies, an understanding was established that these design decisions were made to cater green building concerns such as energy efficiency (EE) and indoor environmental quality (IEQ). As far as EE goes, it can be seen that the green building design elements and strategies implemented in the three green office buildings were successfully achieved. The three buildings have solid records that showcase how they achieved their EE goals throughout their years of operations.

In term of IEQ, external and major design elements used in the green office buildings focused more on tackling issues regarding indoor air quality (IAQ), thermal comfort, and visual comfort. Acoustic comfort usually comes within the package unintentionally. While these external design elements work well in addressing other issues of IEQ, the modification of external design elements cannot directly affect the acoustical parameters which can re-establish acoustic comfort in the buildings.

Internal design elements such as the air conditioning system used in the three green office buildings are undoubtedly very responsive towards the IAQ and thermal comfort in the buildings, besides assisting heavily on the buildings' EE goals. However, these A/C systems are the primary contributor towards the low BN level. Nevertheless, such internal design elements are considered as permanent design variables. Tempering or modification of such elements might create other problems, not just towards IAQ and thermal comfort, but also towards acoustic comfort in the buildings.

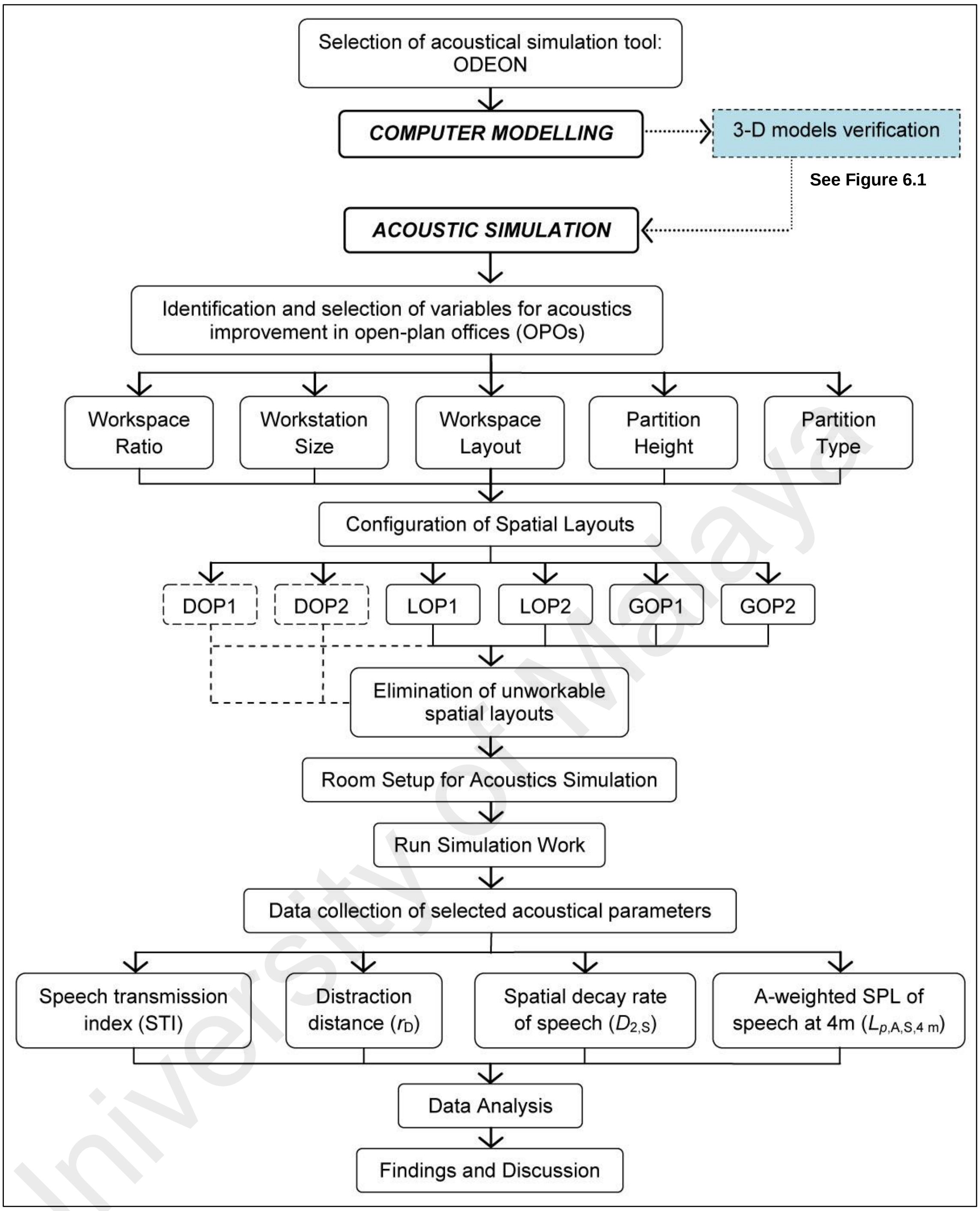


Figure 3.16: Computer modelling and simulation workflow

Thus, it was identified that the design elements that can and should be manipulated for this experimental simulation work to achieve an acoustically comfortable open-plan offices are the internal offices' spatial layout elements and configurations. Careful selection of open-plan office design elements and its variables would be discussed thoroughly in the next subchapters. Figure 3.16 illustrates the simulation workflow starting from the identification and selection of open-plan office internal design elements to the selection of relevant acoustical parameters, which will be used to test the applicability of the design variables.

3.5.1 Selection of Design Strategies for Spatial Layout Configuration

The path towards spatial layout configuration and modification for acoustically comfortable open-plan offices begin by identifying the 'live' design strategies within the open-plan offices. These elements should be flexible and modifiable for diverse layout configurations intended for the simulation. Five design strategies are identified as elements that could conceivably influence the acoustical environment in open-plan offices. The design strategies identified are: *workspace density ratio, workstation size, workspace layout arrangement, partition height,* and *absorptive partition type*. The first three variables are identified and configured simultaneously as the elements depended on each other throughout the design configuration stage. Meanwhile, the latter two variables are configured into the layouts later in the design variable development. These strategies are selected as they play an important role in the acoustical design of open-plan offices as per discussed previously in the literature review.

3.5.1.1 Workspace Density Ratio ($W_{DENSITY\_RATIO}$)

Workspace density ratio is the first variable identified for the purpose of acoustically comfortable open-plan office design configuration. Workspace density ratio would help in determining the spatial density of an office, which refers to the average spatial provision per employee or occupants in an open-plan office space (Oldham, 1988). The density ratio would influence the number of employees sharing the open-plan office space. Similar to any other physical elements in a workplace, workspace density ratio has a significant psychological effect on the occupants. Workspace density can influence the physical characteristic of the office environment, which in turn contributes to occupants' satisfaction and frustration towards their work environment, and furthermore towards their job satisfaction (Duval et al., 2002).

Oldham (1988) discussed that lower density offices would buffer employees from overstimulation and provide a more peaceful work environment. Previous studies have reported on the effects of workspace density on employees' environmental well-being. While Szilagyi and Holland (1980) (as cited in Charles & Veitch, 2002) reported positive effects of increased office density such as improved communication, friendship prospects, and work satisfaction; others, as cited in Charles and Veitch (2002), have reported otherwise. High office density may deter occupants' work and environmental satisfaction as it touches on occupants' perception of privacy and office crowding (Duval et al., 2002).

Besides the psychological effects on occupants, workspace density ratio can also influence other physical design elements of the workspace. The density of an open-plan office would not only influence the suitable and allowable workstation sizes, but it could also influence on the distance between the workstations, and hence the distance between the office occupants (Duval et al., 2002; Charles & Veitch, 2002). In theory, these discrepancies would, in turn, stir the acoustical conditions of the office space.

Table 3.3: Minimum space requirement per employee for open-plan offices

Area per employee	References
8 – 10 m^2 (Old guideline) 12 – 15 m^2 (New guideline)	Neufert & Neufert (2000), Architects' Data (3rd Ed.).
6.25 m^2	Department of Occupational Safety and Health (1996), Guidelines on Occupational Safety and Health in the Office.
11 m^3	UK, Health and Safety Executive (2013), Workplace (Health, Safety and Welfare) Regulations 1992 (2nd Ed.).
10 – 14 m^2	Worksafe Victoria (2006), Officewise - A Guide to Health & Safety in the Office.

There are no definitive or standardise minimum-floor-area-per-employee requirements. However, some office planning guidelines have suggested on the comfortable spatial requirement per employee for open-plan office. The recommendations and ‘requirements’ are as presented in Table 3.3.

Even though there are guidelines for minimum spatial area required to be provided per employee, a definite space requirement depends on the type of work conducted in the office, the usage of machines and equipment, the degree of privacy needed for that particular type of work, the frequency of outside visitors, and the level of storage space needed (Neufert & Neufert, 2000).

As for the three green office buildings studied, the nature of work for the occupants in the open-plan offices are mainly administrative and mild research work. As the guidelines for spatial requirement varies between the mentioned references, two levels of spatial requirement would be taken as the first variable in this simulation work. The two types of workspace density ratios would be calculated as below. The two ratios would be referred to as S1 and S2 respectively.

S1: Total Floor Area (of OPO) / (*x*) no. of workstations = <12 m²

S2: Total Floor Area (of OPO) / (*x*) no. of workstations = >12 m²

The calculations would provide the number of individual workstations that would be use for the spatial layout configuration of each workspace density ratio. However, it should be noted that the final number of workstations provided depends on the spatial accessibility of the open-plan offices. The density ratio of S1 (<12 m²) and S2 (>12 m²) are defined as such to provide a range of ratio, as the spatial quality and geometry of the actual open-plan offices would influence the number of workstations that could be arranged in the space. It is important to note that these workspace density ratios are not directly translated into the sizes of individual workstations as these ratios are inclusive of not only the work surfaces and cabinets, but also the circulation area in the office; including the primary and secondary circulation space, and shared storage spaces.

Table 3.4: Number of workstations provided in each OPO according to the two $W_{DENSITY\_RATIO}$

No.	**OPO**	**Usable Office Area (m²)**	**No. of workstations**			
			<12 m² (S1)		**>12 m² (S2)**	
1.	DOP1	237.7	*24	(9.9 m²/pax)	*18	(13.2 m²/pax)
2.	DOP2	297.0	*32	(9.3 m²/pax)	*22	(13.5 m²/pax)
3.	LOP1	176.7	18	(9.8 m²/pax)	14	(12.6 m²/pax)
4.	LOP2	281.8	30	(9.4 m²/pax)	22	(12.8 m²/pax)
5.	GOP1	81.4	8	(10.2 m²/pax)	*6	(13.6 m²/pax)
6.	GOP2	245.7	26	(9.5 m²/pax)	20	(12.3 m²/pax)

Table 3.4 illustrates the number of workstations configured for each open-plan office according to earlier discussed calculations. It should be noted that the number of workstations provided in each open-plan office is rounded to even numbers for more natural spatial layout arrangements. The intention for this would be discussed and shown in subchapter 'Workspace Layout Arrangements (WLA)'. Discrepancies shown in Table 3.4 (See * in DOP1, DOP2, and GOP1) would also be discussed in the next subchapters.

3.5.1.2 Workstation Size (W_{SIZE})

Through the calculation of workstation density ratios, the number of workstations to be provided in each open-plan office is established. Similar to the previous variable, as workstation sizes depend on the nature of work, there is no absolute workstation sizes requirement found in any workplace safety guidelines. However, workstation designs need to be physically ergonomic to ensure employees health, comfort, and furthermore productivity (Openshaw & Taylor, 2006). Work surfaces need to be large enough for all tools and equipment typically used in office settings. It should also allow for easy repositioning should there be any changes in tasks (Back Design Inc., n.d.).

The basic rule of thumb for ergonomic workstation design specified the ‘preferred and permitted area of reach for work surfaces’ in an office setting as a guide for comfortable work surface design and tools arrangement (See Figure 3.17). Frequently used tools should be placed within the primary (usual work) and secondary (occasional) work zones to avoid strenuous movement while reaching for the work tools or items, and less frequently used tools should be placed at the tertiary (non-working area) work zone (Neufert & Neufert, 2000; USA, Occupational Safety and Health Administration, n.d.; Canadian Centre for Occupational Health and Safety, n.d.).

As it is already established, the nature of work carried out in the studied open-plan offices was administrative and mild research work. These works required a mixed balance of computer-related work and writing or reading tasks. There are many types of workstation designs available such as the L-shaped desk, U-shaped desk, body pocket shaped desk, and cockpit desktop; just to name a few (Back Design Inc., n.d.). Although, as this research focused mainly on the acoustic part of the office ergonomic, basic workstation and work surface shape and sized were employed as part of the experimental variable. A basic L-shaped work surface is considered suitable for the mixed-work tasks, as the computer or laptop can be placed on one side, and paper-related tasks can be carried out at the perpendicular work surface. Figure 3.18 illustrated the basic ergonomic reachability of the L-shaped workstation.

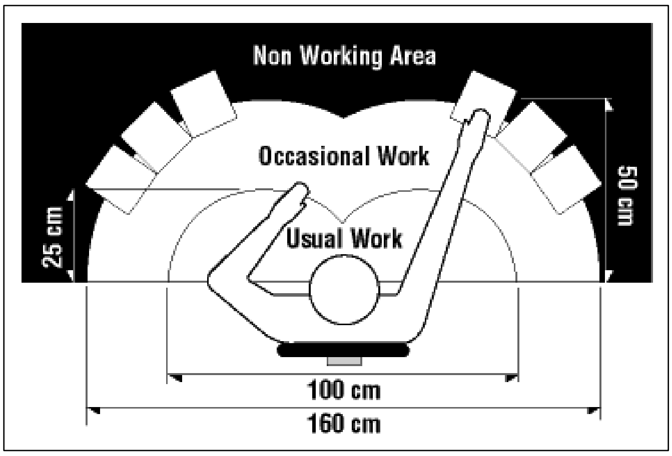


Figure 3.17: Preferred and permitted area of reach for workstation design
(Source: Canadian Centre for Occupational Health and Safety, n.d.)

The study applies two types of L-shaped workstation size variations. A difference in workstation sizes i argued to have an impact on occupants' satisfaction in term of privacy (Veitch et al., 2003). In term of spatial layout, different sizes in workstation would increase the spatial distance between the occupants (Charles & Veitch, 2002). This might help in providing better acoustical isolation between the office occupants. Bradley (2003) reported an encouraging increase in speech privacy with the increase of workstation size. The finding suggested that workstation size as an important design variable to achieve good acoustic in an office environment. Nevertheless, workstation size needs to be controlled, as a too-large workstation size can lead to occupants' dissatisfaction in term of resources handling efficiency as well as social isolation (Veitch et al., 2004); which is against open-plan office's purposes.

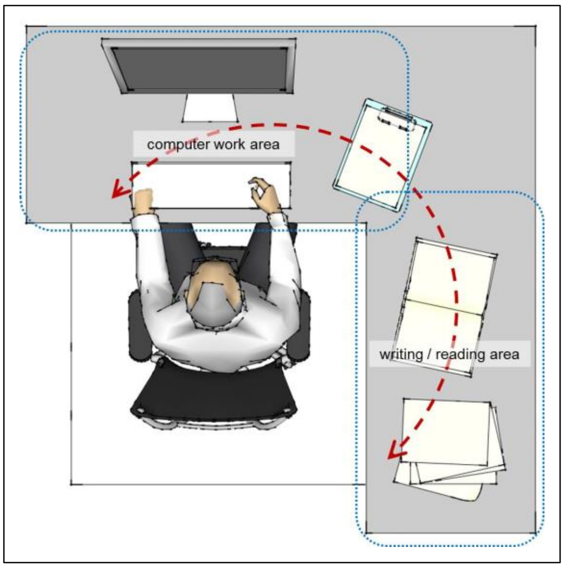
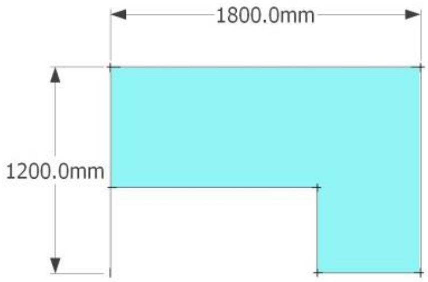
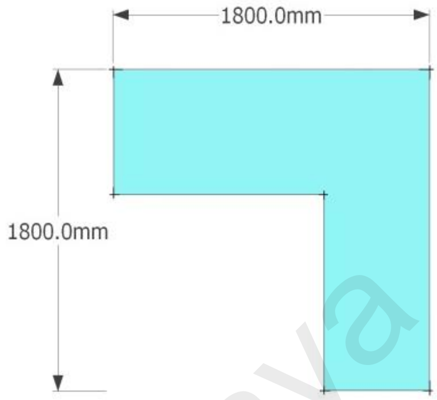
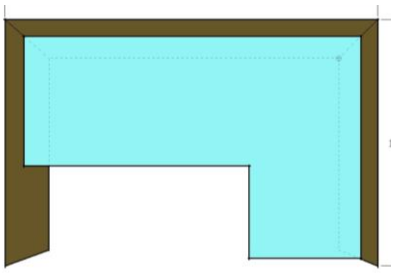
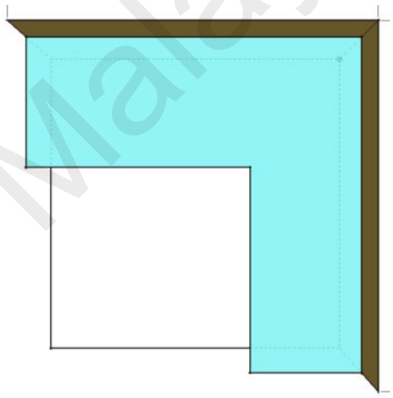
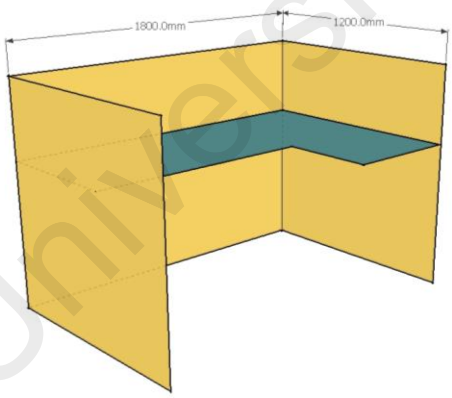
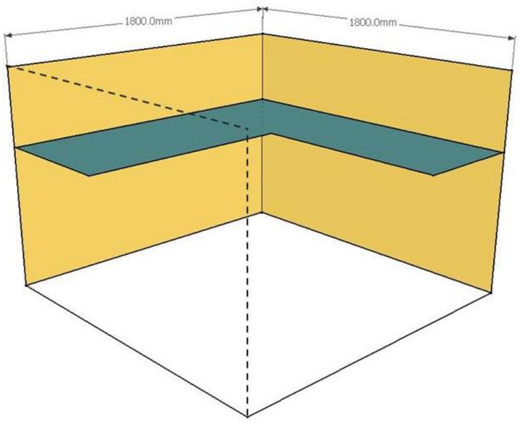


Figure 3.18: Example of L-shaped workstation spatial tasks division

Table 3.5 illustrates the two variations of workstation size that are applied in the study. Workstation A (wsA) and workstation B (wsB) are an 1800 mm x 1200 mm and an 1800 mm x 1800 mm workstation respectively. The two sizes are standard workstation sizes available in the current market, and it should be adequate for the purpose of administrative and research type work.

It should be noted that the experimental simulation work concentrated on using two size L-shaped workstations for better control of layout variations. Other elements such as the status hierarchy of the office would not be considered in the experiment, as it would lead to uncontrollable selections of workstation sizes and layout configurations. However, there would also be a few types of wsA and wsB variations, which will be discussed in the next subchapter.

Table 3.5: Two types of basic workstation variations used for the simulation work

wsA **(Workstation A)**	**wsB** **(Workstation B)**
1800 mm x 1200 mm (6' x 4')	1800 mm x 1800 mm (6' x 6')
	
	
	

3.5.1.3 Workspace Layout Arrangement (W_{LA})

The workspace layout arrangements (W_{LA}) are configured using the number of workstation required according to the workspace density ratio calculations and the two L-shaped workstation sizes discussed previously. There are two basic layout arrangements applied in the study. The first is the "linear W_{LA}", and the second is the "cluster W_{LA}". Through these two basic arrangements, several types of W_{LA} are use as the workspace layout designs for the simulation work.

The W_{LA} for each open-plan office begins with the two workspace density ratios S1 and S2 as identified previously. Subsequently, each workspace ratio is developed into two W_{LA} using the two workstation types; wsA and wsB respectively. Another four different W_{LA} are then derive from the linear and cluster workstation arrangement setting. Figure 3.19 shows the development of W_{LA}, and the number and type of workstation layout arrangements available for each open-plan office are as illustrated in Table 3.6.

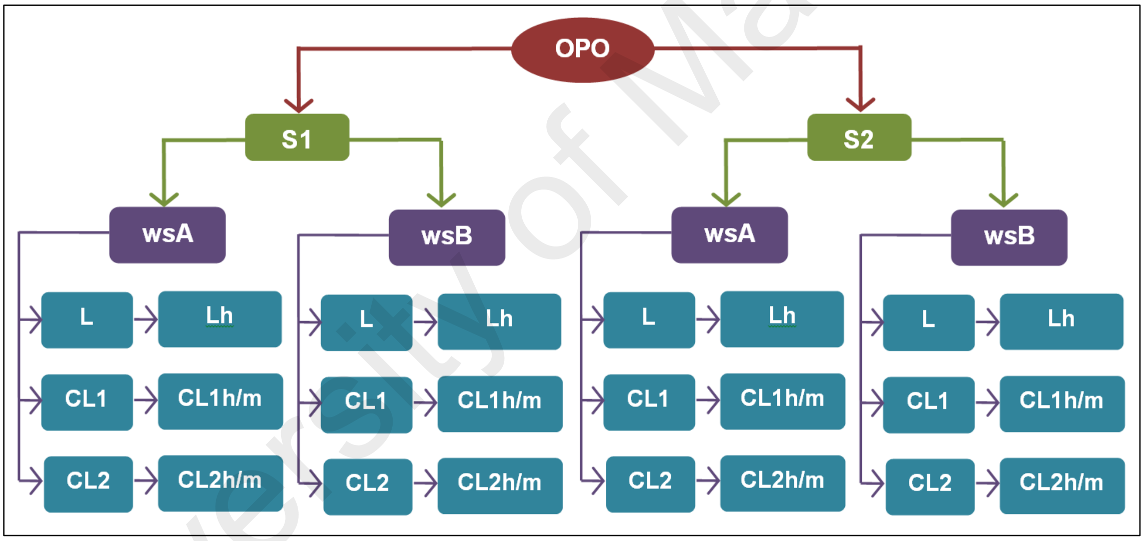


Figure 3.19: Development of workspace layout arrangements (W_{LA})

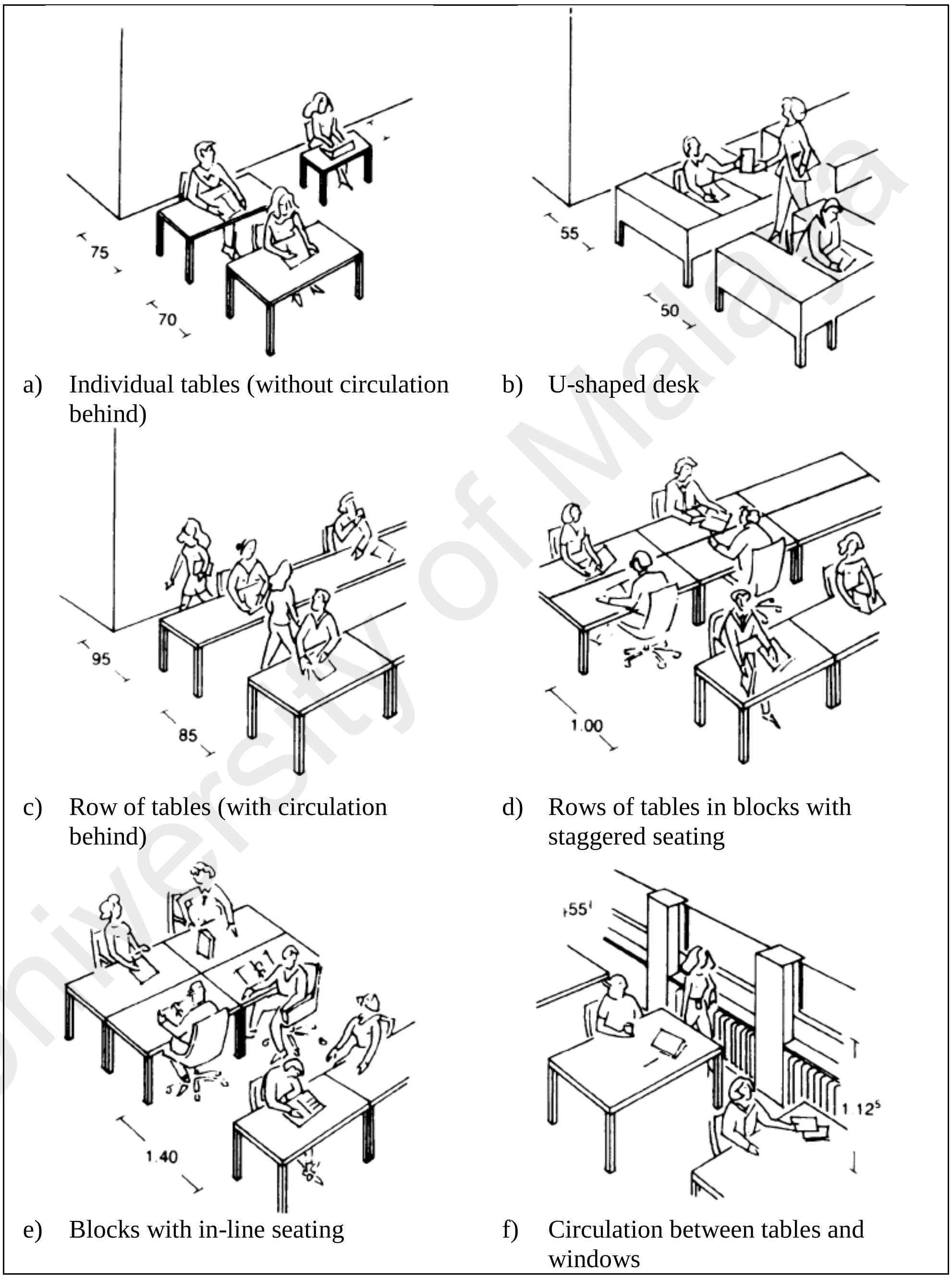
The UK, Health and Safety Executive (2013) prescribed that workstations in an office should be arranged accordingly to assist safe and comfortable work environment. Boutellier et al., (2008) identified office layouts as a backbone for effective office environment, which would assist in efficient work productivity. Safe and supportive office layouts and spatial arrangements would foster an ideal work environment and employees' satisfaction and in turn expedite productivity (Wineman, 1982; Francis et al., 1986; Leaman & Bordass, 1999; Haynes, 2008; Sailer & McCulloh, 2012). Samani, Abdul Rasid, and Sofian (2014) discussed the role of creativity as a valuable instrument in the workplace and how elements in the workspace including the office design and spatial arrangement can either cultivate or damage it.

Besides the ergonomic needs for individual workstations, the interactions between workstations and the surroundings need critical consideration, especially in an open-plan office setup. Open-plan office layout offers employees with the liberty to roam around freely in the office space. Thus, a clear primary and secondary circulation path need to be specified. Neufert & Neufert (2000) provided the minimum distance of clearance between workstations and the surrounding area. This distance of clearance would ensure employees working at the workstations can retain sufficient personal space with a little spatial stretch, and at the same time still provide comfortable unobstructed space for others to pass by if needed, or even for easy interaction between colleagues.

Figure 3.20 illustrates the basic minimum clearance adhered to in the workspace layout configuration work. Although the actual clearance provided in the layouts are decided according to the amount of space available, all the minimum requirements are accordingly met.

The standardised list of workspace layout arrangements for each OPO would consist of one *Linear* (L) arrangement and two types of cluster arrangements, *Cluster 1* (CL1) and *Cluster 2* (CL2). Consequently, modified versions of the three arrangements are derived through either the changing of workstation orientation and/or minor workstation modifications. The layout arrangements would be identified by its modification processes accordingly.

It is crucial to note that there would be no workspace layout arrangement for DOP1 and DOP2. The reason behind this is because after identifying the standard workspace density ratios and workstation sizes; due to the irregular geometry and columns positioning of the two open-plan offices, arranging the workstations according to the standardised layout arrangements while trying to adhere to the minimum clearance prerequisite; are quite impossible.



a) Individual tables (without circulation behind)
b) U-shaped desk
c) Row of tables (with circulation behind)
d) Rows of tables in blocks with staggered seating
e) Blocks with in-line seating
f) Circulation between tables and windows

Figure 3.20: Minimum clearance between workstations according to its arrangement and surroundings
(Source: Neufert & Neufert, 2000)

Since the results of measured acoustical parameters would be analysed and compared according to each group of standardised arrangements, open-plan offices from Diamond building would not be simulated.

Subsequently, through the layout arrangement process of LOP1 and LOP2, and considering the minimum clearance requirements (Neufert & Neufert, 2000); it is found that it is not possible to assemble the layouts for both open-plan offices using workspace density ratio S1 with workstation wsB. As for the discrepancy in GOP1, there would be no layout arrangement for both workstation sizes wsA and wsB due to the small number of workstations to be provided using the density ratio S2. This is because data collected from a measurement line with less than four workstations would not be sufficient and this would affect the acoustical parameter results later in the simulation work (ISO 3382-3, 2012).

Table 3.6: List of workspace layout arrangements (W_{LA}) for the simulation

LOP1				**LOP2**			
S1		**S2**		**S1**		**S2**	
wsA	**wsB**	**wsA**	**wsB**	**wsA**	**wsB**	**wsA**	**wsB**
L		L	L	L		L	L
Lh		Lh	Lh	Lh		Lh	Lh
CL1		CL1	CL1	CL1		CL1	CL1
CL1h		CL1h	CL1m	CL1h		CL1h	CL1m
CL2		CL2	CL2	CL2		CL2	CL2
CL2h		CL2h	CL2m	CL2h		CL2h	CL2m
GOP1				**GOP2**			
S1		**S2**		**S1**		**S2**	
wsA	**wsB**	**wsA**	**wsB**	**wsA**	**wsB**	**wsA**	**wsB**
L	L			L	L	L	L
Lh	Lhm			Lh	Lh	Lh	Lh
CL1	CL1			CL1	CL1	CL1	CL1
CL1h	CL1m			CL1h	CL1m	CL1h	CL1m
CL2	CL2			CL2	CL2	CL2	CL2
CL2h	CL2m			CL2h	CL2m	CL2h	CL2m

LEGENDS:

L : Linear
Lh : Linear (Horizontal)
Lhm : Linear (Horizontal / modified)
CL1 : Cluster 1
CL1h : Cluster 1 (Horizontal)
CL1m : Cluster 1 (Modified)
CL2 : Cluster 2
CL2h : Cluster 2 (Horizontal)
CL2m : Cluster 2 (Modified)

Table 3.6 shows the list of workspace layout arrangements (W_{LA}), which are simulated in the study. For easy viewing of the layout arrangements, Table 3.7, 3.8, 3.9, and 3.10 shows the thumbnail layout plans of the W_{LA} of LOP1, LOP2, GOP1, and GOP2 accordingly (Refer Appendix E for larger visuals of the workspace layout arrangements).

Table 3.7: Workspace layout arrangements (W_{LA}) for LOP1

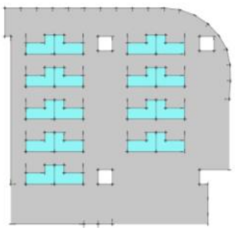
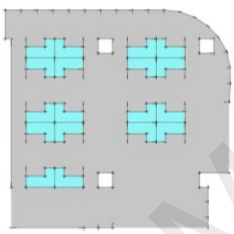
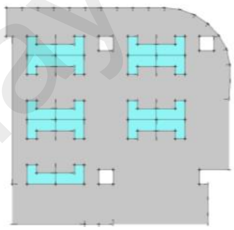
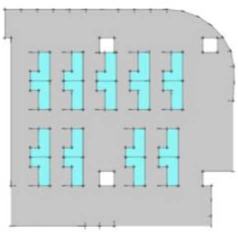
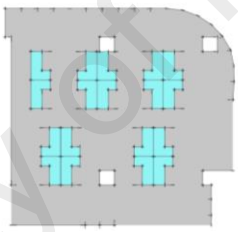
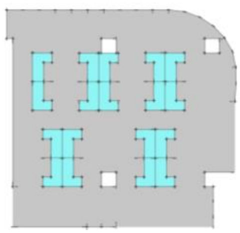
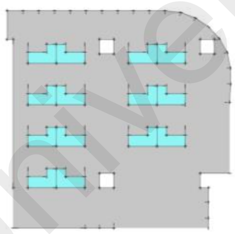
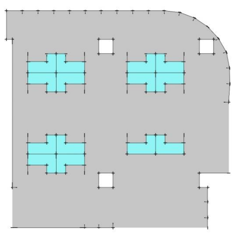
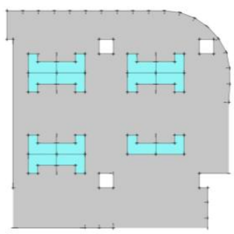
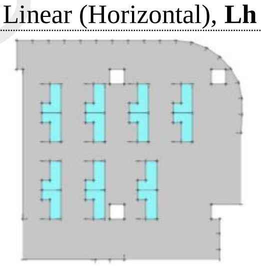
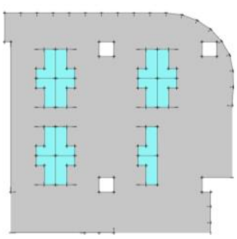
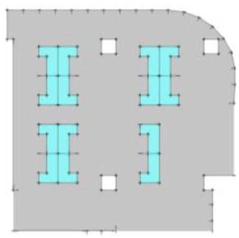
LOP1_S1_wsA		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Horizontal), **CL1h**	Cluster 2 (Horizontal), **CL2h**
		
LOP1_S2_wsA		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Horizontal), **CL1h**	Cluster 2 (Horizontal), **CL2h**
		

Table 3.7, Continued

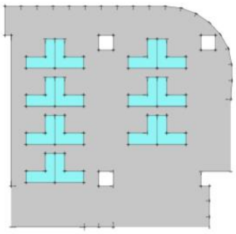
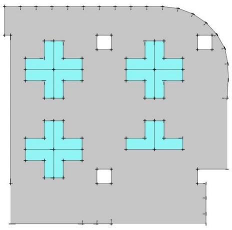
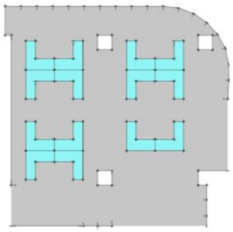
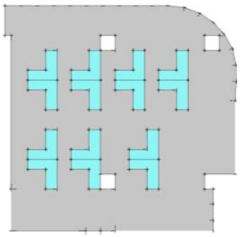
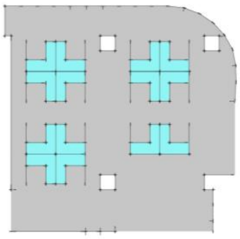
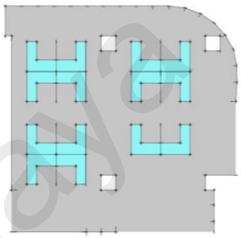
LOP1_S2_wsB		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Modified), **CL1m**	Cluster 2 (Modified), **CL2m**
		

Table 3.8: Workspace layout arrangements (W_{LA}) for LOP2

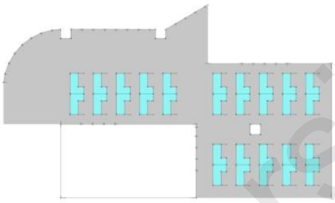
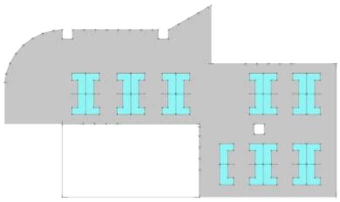
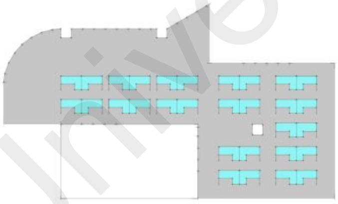
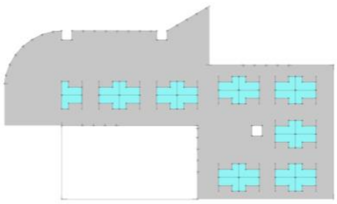
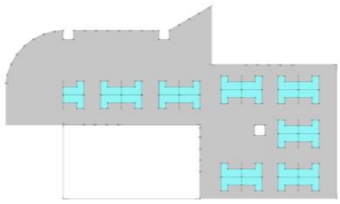
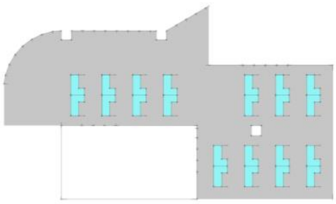
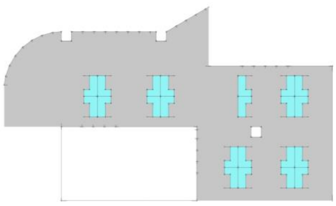
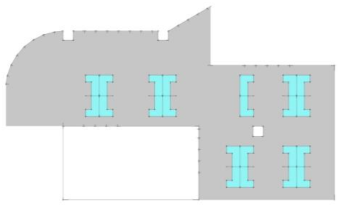
LOP2_S1_wsA		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Horizontal), **CL1h**	Cluster 2 (Horizontal), **CL2h**
		
LOP2_S2_wsA		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		

Table 3.8, Continued

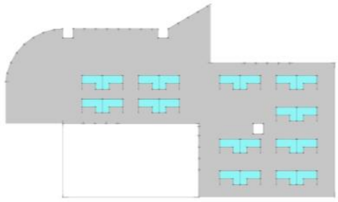
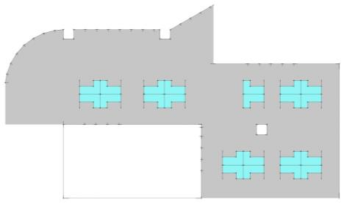
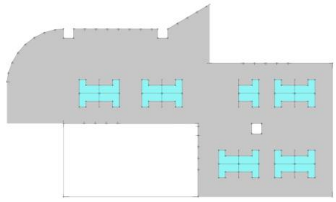
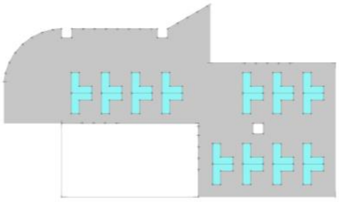
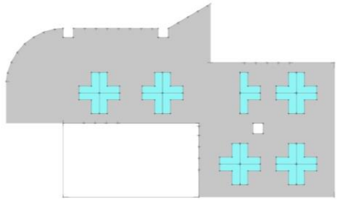
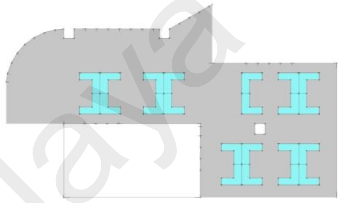
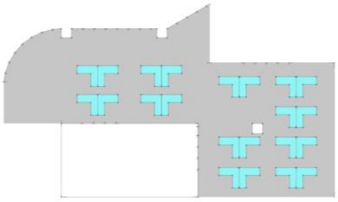
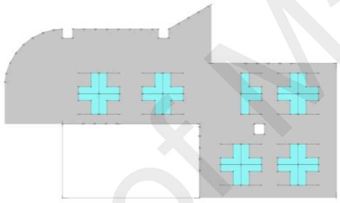
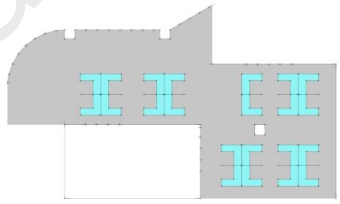
LOP2_S2_wsA (continued)		
Linear	**Cluster 1**	**Cluster 2**
Linear (Horizontal), **Lh**	Cluster 1 (Horizontal), **CL1h**	Cluster 2 (Horizontal), **CL2h**
		
LOP2_S2_wsB		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Modified), **CL1m**	Cluster 2 (Modified), **CL2m**
		

Table 3.9: Workspace layout arrangements (W_{LA}) for GOP1

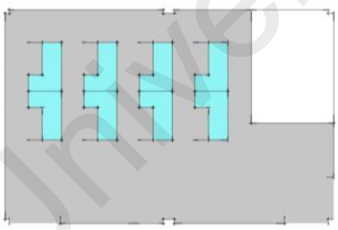
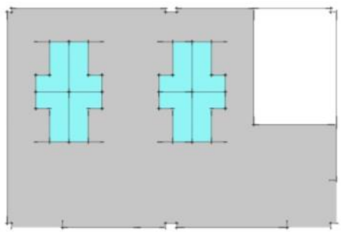
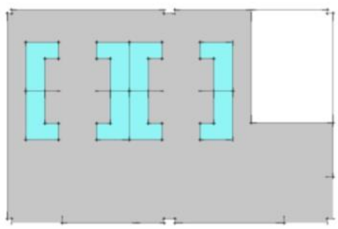
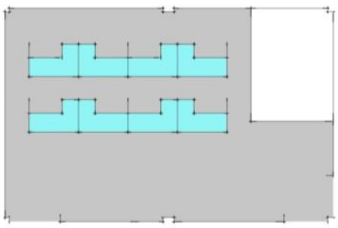
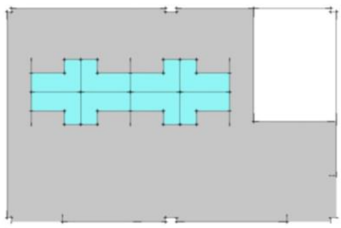
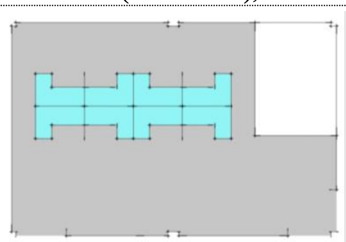
GOP1_S1_wsA		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal), **Lh**	Cluster 1 (Horizontal), **CL1h**	Cluster 2 (Horizontal), **CL2h**
		

Table 3.9, Continued

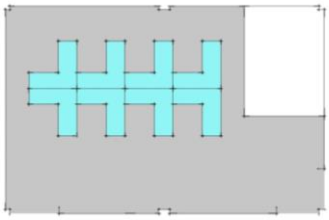
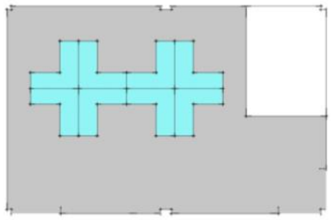
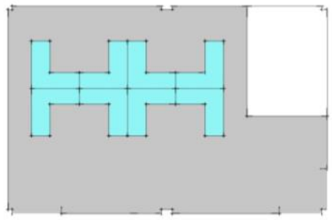
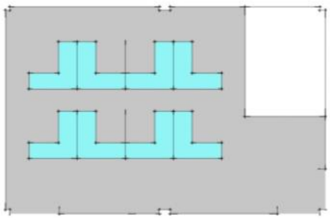
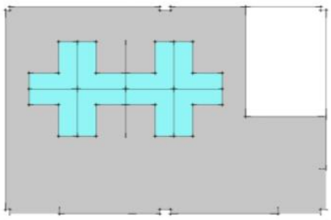
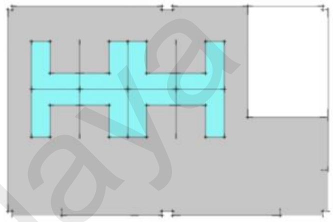
GOP1_S1_wsB		
Linear	**Cluster 1**	**Cluster 2**
Linear, **L**	Cluster 1, **CL1**	Cluster 2, **CL2**
		
Linear (Horizontal/modified), **Lhm**	Cluster 1 (Modified), **CL1m**	Cluster 2 (Modified), **CL2m**
		

Table 3.10: Workspace layout arrangements (W_{LA}) for GOP2

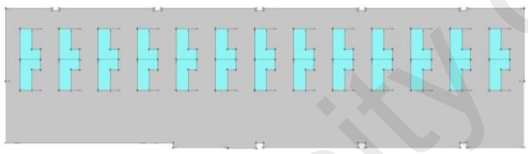
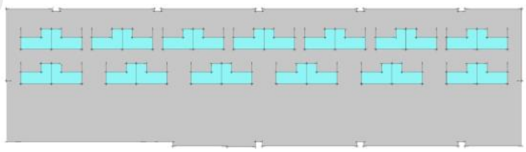
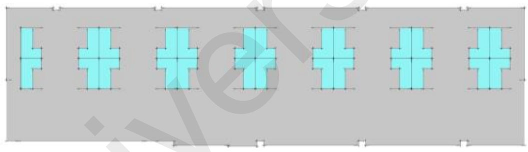
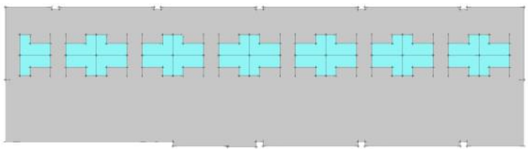
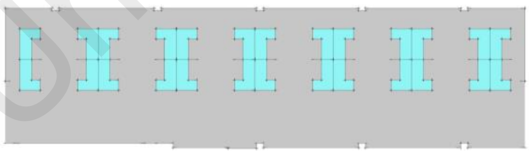
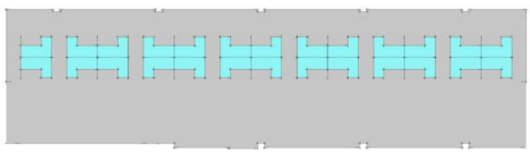
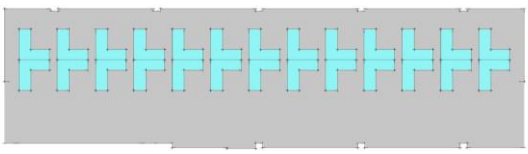
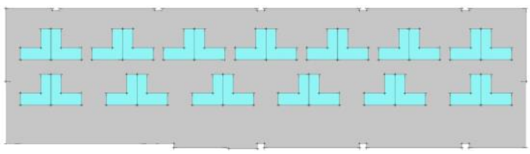
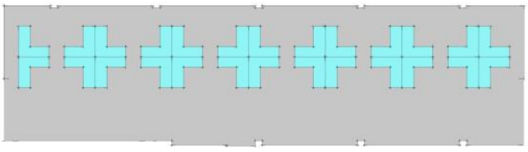
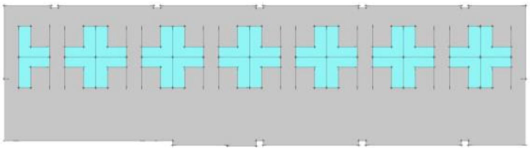
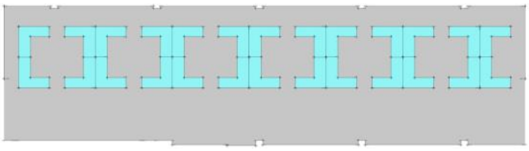
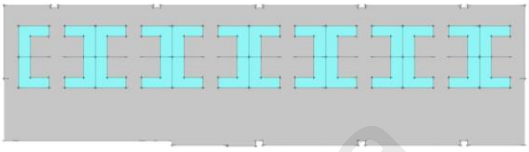
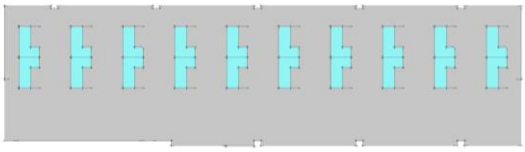
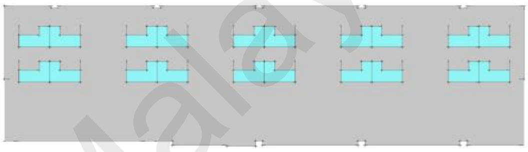
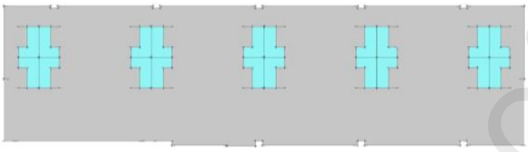
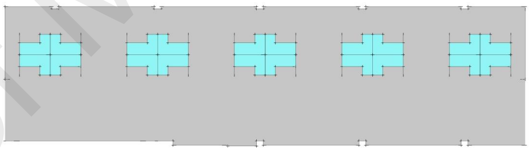
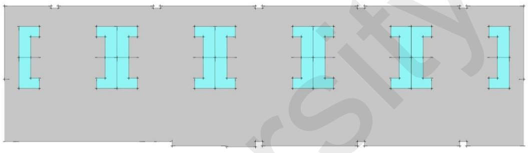
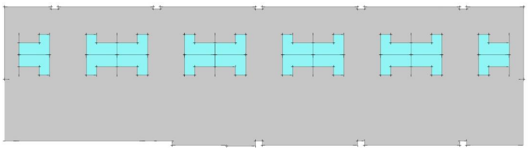
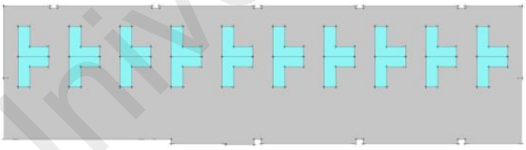
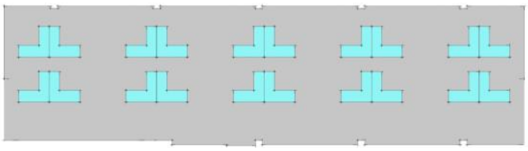
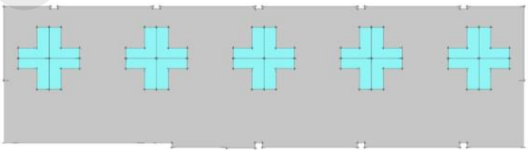
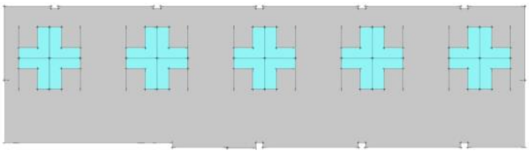
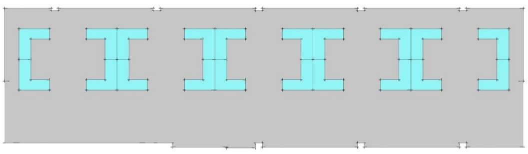
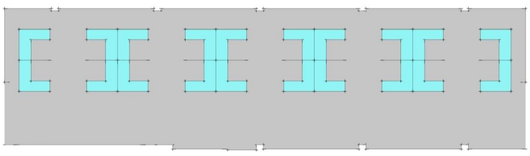
GOP2_S1_wsA		
Linear	Linear, **L**	Linear (Horizontal), **Lh**
		
Cluster 1	Cluster 1, **CL1**	Cluster 1 (Horizontal), **CL1h**
		
Cluster 2	Cluster 2, **CL2**	Cluster 2 (Horizontal), **CL2h**
		
GOP2_S1_wsB		
Linear	Linear, **L**	Linear (Horizontal), **Lh**
		

Table 3.10, Continued

GOP2_S1_wsB (continued)		
Cluster 1	Cluster 1, **CL1**	Cluster 1 (Modified), **CL1m**
		
Cluster 2	Cluster 2, **CL2**	Cluster 2 (Modified), **CL2m**
		
GOP2_S2_wsA		
Linear	Linear, **L**	Linear (Horizontal), **Lh**
		
Cluster 1	Cluster 1, **CL1**	Cluster 1 (Horizontal), **CL1h**
		
Cluster 2	Cluster 2, **CL2**	Cluster 2 (Horizontal), **CL2h**
		
GOP2_S2_wsB		
Linear	Linear, **L**	Linear (Horizontal), **Lh**
		
Cluster 1	Cluster 1, **CL1**	Cluster 1 (Modified), **CL1m**
		
Cluster 2	Cluster 2, **CL2**	Cluster 2 (Modified), **CL2m**
		

3.5.1.4 Partition Height (P_{HEIGHT})

One of the most important characteristics of open-plan offices is the barriers or partitions separating the individual workstations (Duval et al., 2002; Charles & Veitch, 2002). Partitions between individual workstation provide a visual and acoustical barrier between employees working in the same open-plan office. Oldham (1988) discussed the advantages of screenings and partitions in an open-plan office and how it should impact office occupants positively in term of privacy, satisfaction, and performance. Previous studies have reported a corresponding increase in perception of privacy and work satisfaction, with the increased height of partitions (Sundstrom et al., 1982; O'Neill & Carayon, 1993). On the other hand, another study by O'Neill (1994) found that the discrepancies in workstation measures including the partition height did not play any significant role in employees' work satisfaction and performance. Subsequently, research finding in Charles & Veitch (2002) and Veitch et al. (2003) reported that occupants' feel more satisfied with their work environment by having lower partition heights rather than higher partition heights.

There is no standard specification for the ideal partition heights that could provide idyllic acoustical isolation between workstations. However, it is commonly accepted that partition heights should attain some degree of visual privacy which is to be higher than a seated person head-level (Newsham, 2003; Veitch et al., 2004). Veitch et al. (2004) suggested in their study that the 1.37 m high partition provides an excellent visual privacy for a workstation design.

In the physical measurement and simulation work in this study, the height of 1.2 m is taken as a standard height for a sitting person ear or 'sound receiver'. As there are discrepancies in the findings between partition height and employees' satisfaction as found in the literature, three partition height levels would be taken on for experimentation. The three variables of partition heights applied in the simulation work would be 1.0 m, 1.2 m, and 1.4 m. The three heights signified low, average, and high partition level. This is done to identify if partition heights play any substantial influence on the acoustical parameters concerned with speech privacy and acoustical isolation.

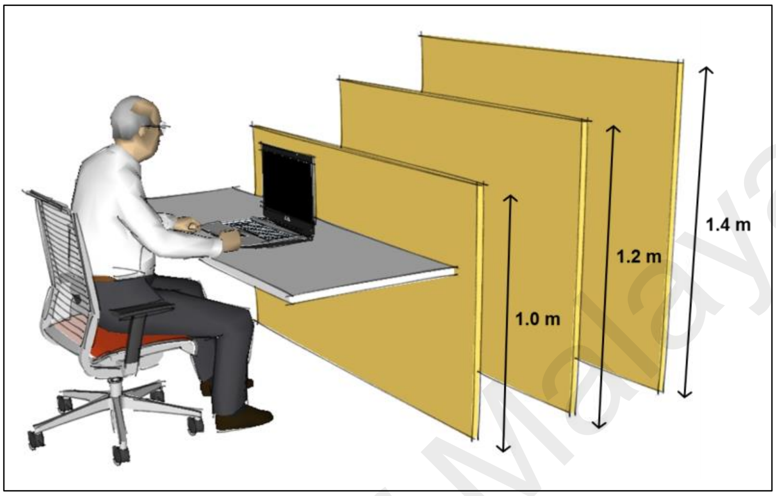


Figure 3.21: Three partition heights applied as the workspace variables in the study

3.5.1.5 Absorptive Partition Type (P_{TYPE})

While the height of partitions surrounding a workstation might have a prominent effect on communication and privacy, another critical characteristic of workspace partition is the design of the partitions (O'Neill, 2008). A previous study (O'Neill, 1994) defined partition types by its designs such as "single-piece partition" and "stackable-frame-and-tile partition". O'Neill (1998) studied the effect of the two partition designs and found that the frame-and-tile partition effected positively on office occupants' communication and privacy.

Nonetheless, Wang and Bradley (2002) in their study of sound propagation between two adjacent rectangular workstations stated that there are many office elements that could influence the speech propagation in an open-plan office. Although, the study specified on three design variables that need to be exploited and associated together to achieve high speech privacy between adjacent workstations. The three design variables are partition heights, ceiling absorption, and partition absorption.

As this research focused on the acoustics design of green buildings, ceilings in general automatically became an inapplicable design variable. This is because two out of three green office buildings studied omitted ceilings from being part of their open-plan office design elements. Thus, the last design element which became part of the experimental variable is the partition type in term of absorption coefficient (α).

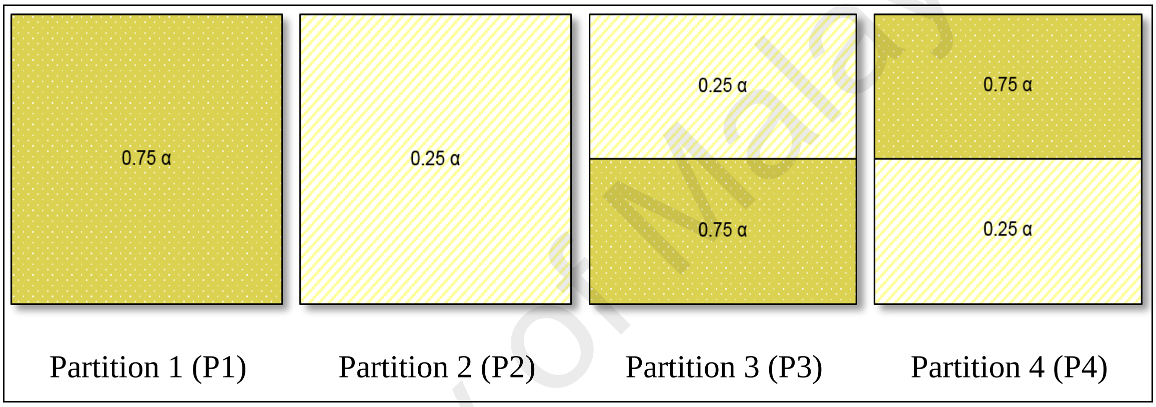


Figure 3.22: Four absorptive partition types (P_{TYPE}) applied in the simulation work

Four absorptive partition types are used as the variable in the experimental simulation work. The absorption coefficient (α) used is: 0.75 to represent high absorption material, and 0.25 to represent low absorption material. The two absorption coefficient values are composed into four absorptive partition types as illustrated in Figure 3.22. The four absorptive partition types represent the different design of partitions with different types of materials.

3.5.2 Simulation Work

After the process of identifying the most optimum 3D model through the model verification stage (See results in Chapter 6), the experimental simulation work for acoustically comfortable open-plan offices begins.

The simulation work commenced with the construction of models using the five different design variables as discussed previously. Similar to the steps taken during the 3D model construction and verification stage, during the layout configuration in computer modelling tool SketchUp, all the necessary setup such as the model setting-out and surface layering are completed during the model construction phase. Afterwards, the 3D models with the configured layouts and variables are exported into ODEON for the next step of the simulation work.

Similarly to the material assignment procedures done during the model verification stage (See Chapter 6), the material assignment for this stage of the study is done in ODEON as well. Identical materials and surfaces such as the floor, walls, tables, windows, etc. were assigned with the same type of materials according to each open-plan office settings. The only dissimilar material was the partitions, which were assigned with new materials that are created using the new absorption coefficient (α). It should be noted that each partition materials (P1, P2, P3, and P4) created are assigned with an equivalent absorption coefficient (α) at the middle frequencies (250 Hz, 500, 1000, and 2000 Hz) only, which should represent the normal human voice range.

3.5.2.1 Allocation of Sound Sources and Receivers

The allocation of sound sources and receivers are done according to the positioning recommended in ISO 3382-3 (2012). The recommendation stated that the measurement should be carried out over a line which crosses over a minimum number of four workstations. Hence, for all simulated open-plan offices, sound sources and receivers are allocated at every workstation at the height of 1.2 meters above the floor level. However, only one sound source would be active during each simulation sessions.

Afterwards, the data of selected acoustic parameters are collected from four different simulation sessions with four different sound source locations and four measurement paths. This is done as per recommended in ISO 3382-3 (2012), which is to have at least two sound source positions for a simulation work. Although, it is important to note that the two sound sources (at two different locations) should not be active at the same time during a simulation session. Figure 3.23 illustrates the example of four measurement paths from one of the 3D model in open-plan office GOP2 layout.

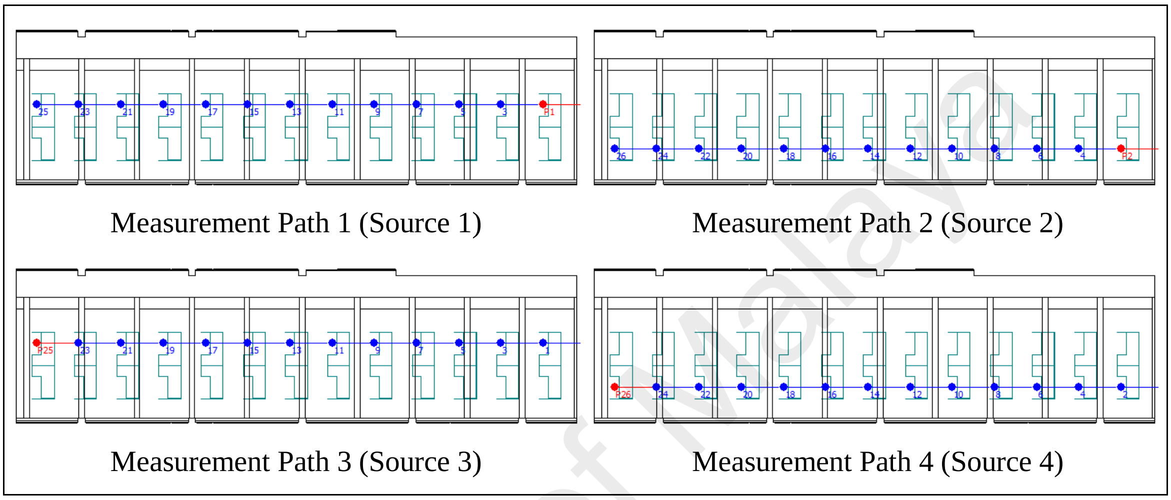


Figure 3.23: Example of the four measurement paths in GOP2 model layout

The sound source type used in this experimental simulation stage is different from the sound source used during the 3D model verification stage. For this stage, the sound source utilised was a pre-set ISO 3382-3 sound source input readily available in ODEON labelled ISO3382-3_OMNI.S08. The sound source selected is an omnidirectional sound source with a total power of 68.4 dB(A) which is equivalent to a normal talking voice of a person. Meanwhile, the sound receiver type used is similar to the sound receiver setting as per 3D model verification stage. Both of the sound sources and receivers are omnidirectional as recommended in the ISO 3382-3 (2012).

3.5.2.2 Model Debugging and Room Background Setup

The model debugging and room background setup for this stage are basically the same as the setup employed in the model verification stage. The background noise (BN) levels input in the background setup for LOP1, LOP2, GOP1, and GOP2 for this stage are as specified in Table 6.1. Table 3.11 below illustrates the models' simulation settings and input in ODEON.

Table 3.11: Simulation settings and input in ODEON

<table>
<tr><td>Sound source type</td><td>: ISO3382-3_OMNI.S08 (Total power: 68.4 dBA)</td></tr>
<tr><td></td><td><table>
<tr><td>Freq (Hz)</td><td>63</td><td>125</td><td>250</td><td>500</td><td>1k</td><td>2k</td><td>4k</td><td>8k</td></tr>
<tr><td>Sound power</td><td>0.0</td><td>60.9</td><td>65.3</td><td>69.0</td><td>63.0</td><td>55.8</td><td>49.8</td><td>44.5</td></tr>
</table></td></tr>
<tr><td>Calculation setup</td><td>: Precision</td></tr>
<tr><td>Impulse response legth</td><td>: 2000 ms</td></tr>
<tr><td>Temperature input</td><td>: 24° celcius</td></tr>
</table>

3.5.2.3 Simulated Acoustics Parameters

The acoustic simulation work using ODEON would simulate most of the basic and essential acoustical parameters. However, for the purpose of figuring out the best design solutions that would contribute towards an acoustically comfortable open-plan office design for green office buildings, four acoustical parameters would be extracted and analysed. These acoustical parameters are important in measuring speech privacy in the open-plan office environment (ISO 3382-3, 2012). The acoustical parameters selected are:

i) Speech transmission index (STI) in the nearest workstation

ii) Distraction distance (r_D) in meter

iii) A-weighted SPL of speech at a distance of 4m, $L_{p,A,S,4\,m}$ in dB(A)

iv) Spatial decay rate of speech ($D_{2,S}$) in dB(A)

While reverberation time (RT) has been a staple acoustical parameter in room acoustics, it is not pertinent to characterise the acoustical conditions of open-plan office using RT. This was due to the fact that RT only describes the temporal decay of sound, and did little to predict the spatial attenuation; which is important in determining speech privacy in open-plan offices (Virjonen, Keränen, & Hongisto, 2009).

STI and r_D are the two acoustic parameters that relate directly to the level of speech intelligibility and privacy in open-plan offices (ISO 3382-3, 2012; Haapakangas et al., 2017). While the importance of STI and r_D in speech intelligibility of open-plan offices has been discussed earlier, the other two acoustic parameters which are $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$ control a different aspect of acoustic quality.

A-weighted SPL of speech at a distance of 4m ($L_{p,\mathrm{A,S,4\ m}}$) is basically the level of A-weighted SPL recorded at the distance of 4 meters from the speaker. Meanwhile, spatial decay rate of speech ($D_{2,\mathrm{S}}$) serves to describe how much the level of A-weighted SPL has reduced when the distance from the speaker has doubled. These two acoustic quantities relate to each other as the $D_{2,\mathrm{S}}$ was derived from the identification of $L_{p,\mathrm{A,S,4\ m}}$ and SPL at 8 meters.

Haapakangas et al. (2017) specified r_D as the most relevant acoustic parameter for measuring intelligibility and privacy in open-plan offices. r_D takes into consideration all the combined effect of acoustic factors between the sources and the receivers. On the other hand, the measurement of $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$ are not at all affected by BN level which is an essential element in determining the STI and the r_D. The two parameters depended on the effect of elements in open-plan offices such as the room absorption, volume, geometry and screens (Hongisto, 2005). However, Virjonen et al. (2009) argued that considering only r_D or $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$ alone to determine the acoustic condition of open-plan offices might not be sufficient and could even be a little bit misleading. Thus, an equivalent deliberation of all four acoustic quantities is a vital step.

The simulated data for each acoustic parameter namely r_D, $D_{2,S}$, and $L_{p,A,S,4\text{ m}}$; from each open-plan office would be collected from four measurement paths respectively. The data from the four measurement paths would be averaged to get a single number data which could be used in the analysis process. Meanwhile, the data for STI in the nearest workstation would not be averaged as it would be an inaccurate way to present an STI data.

3.6 Summary

The chapter discussed the research approaches of the study thoroughly. Every step taken starting from the design of research to the work procedures is deliberated to ensure the correct research methodologies are chosen. Each methodology chosen and carried out is done to answer each of the objectives made for the research.

The research method *Field Measurement* is chosen to answer the first objective of the research which is "To evaluate the level of acoustic quality in selected open-plan offices". Acoustic quality is a quantifiable element which can be physically measured, thus; the correct acoustic parameters that should be measured, the precise manner of which the acoustic measurement work should be done, and the right tools to be used were deliberated comprehensively.

The research method *Case Study* and *Observation* is done to understand the physical design of the selected green office buildings. The appropriate steps and information to be gathered are itemised to ensure the correct elements are analysed. The findings of the design elements are then analysed with the acoustic measurement data to answer research objective number two which is “To identify the green design elements that influence the acoustic quality in selected open-plan offices”.

The final method which is *Computer Simulation* is done to answer the research objective “To investigate a workable alternative of design elements that could assist in achieving an acoustically comfortable open-plan office”. Experimental open-plan office designs that are constructed using selected design elements are simulated using selected acoustic simulation software. Analysis of the simulated data would help in answering the final research objective, which is “To recommend relevant acoustic parameters and design strategies to be considered for the design of acoustically comfortable open-plan offices”.

The relevance of every so-called “selection” in this study such as the methods, tools, procedures, and parameters is clarified throughout the chapter. Justification of the research work was done through the extensive study of previous literature and works, and also from established acoustic standards available.

CHAPTER 4: CASE STUDY

This chapter presented the case study data collected from the three green office buildings. Brief introduction about the buildings' proprietor will be presented. This follows by detail narrative analysis on the buildings' background, as well as minor and major architectural design features. The analysis of each building will be done separately, and the analysis of field measurement and data presented in this chapter will be done at the end of Chapter Five.

4.1 Case Study 1: Diamond Building

4.1.1 Introduction to Malaysia's Energy Commission

Diamond building is a headquarter building for Malaysia's Energy Commission (Suruhanjaya Tenaga Malaysia). The Energy Commission is a statutory body in charge of regulating the energy sector mainly the electricity supply and piped gas supply industries throughout Peninsular Malaysia and Sabah. The Energy Commission was established on 1st May 2001 under the Energy Commission Act 2001 in the effort to enhance the performance of the energy supply industry in Malaysia. The Commission began its operation on 1st January 2002 and continued all responsibilities which were previously under the Department of Electricity and Gas Supply after the department was dispersed on the same day.

The vision of the Energy Commission is to be a highly effective energy regulators as well as the authority on energy matters. The Commission aim is to ensure safe and reliable energy supply at a reasonable price, protect the interest of the public, and foster economic development and competitive markets in an environmentally sustainable manner. Roles and functions of the Commission include economic, technical and safe regulation, and also consumer protection (Energy Commission, 2013).

4.1.2 Background of Diamond Building

Figure 4.1: Exterior view of Diamond building

Diamond building is located at Precinct 2 Putrajaya, the central hub of government buildings in Malaysia. The building is situated at a road junction right across from Malaysia's Immigration Department building. The site is islanded by roads, and adjacent sites are currently vacant and being utilised as parking lots.

The construction of the building commenced on 13th September 2007 and ended on 15th March 2010. The building was awarded with green building certifications from Malaysia's Green Building Index (GBI) and Singapore's BCA Green Mark; both on 27th April 2011 (Mohd Yusof, 2012). It is the first office building in Malaysia to obtain Platinum rating from the GBI and also the first building outside of Singapore to receive Platinum rating from the BCA Green Mark (Mohd Yusof, 2012; Koay, 2011). In 2012, Diamond building was named the most energy efficient building at the 2012 ASEAN Energy Award (AEA). It also won the top prize in the category of 'New and Existing Buildings' in the same event (Koay, 2011; Bredenberg, 2012).

The building aimed to be a landmark building in term of sustainability. The design strategies were designed to reach optimum satisfaction in four aspects in the GBI: energy efficiency, water efficiency, indoor environmental quality (IEQ), and outdoor environmental quality. Two essential elements which were seriously considered during the design stage were energy efficiency, and to rely heavily on the usage of daylight (Koay, 2011). Diamond building's building energy index (BEI) was designed to be 85 kWh/m^2/year, which is a reduction of 65% in energy consumption compared to 210 kWh/m^2/year of BEI reading of typical office buildings in Malaysia. At present, the average BEI reading of Diamond building is around 65 kWh/m^2/year (Mohd Yusof, 2012; Reimann, 2010).

4.1.3 Diamond Building's Architectural Design

4.1.3.1 Site Planning

Figure 4.2: Site plan of Diamond building

The site is situated at a corner of road junctions of Jalan Tun Hussein and Jalan Pembangunan. Although the roads are supposed to be utilised as main roads, minimal traffic is observed throughout the day. The site is fully occupied with the primary structure situated in the middle, surrounded by a sunken garden around the building. The base of the building is a square shape aligned with the site boundary at the west side. The drop-off point is located on the west side, adjacent to the nearest building which is the immigration building, and the services entrance is located on the south side of the building. The site boundary is surrounded by pedestrian walkways which is consistent with the whole town planning of Putrajaya

4.1.3.2 Design Features and Elements

The building is an eight-storey office building with a rooftop level and one and a half storey of basement parking (GFA of 14,000 m²). The site has an almost square shape with each side essentially facing the four cardinal directions, albeit a little tilted towards north-east (See Figure 4.2). Due to the site condition, the options for exploring different shapes of floor plans; to minimise heat gain from the east and west sides; as its passive design strategies were practically limited. However, this shortcoming is compensated by its tilting façade design.

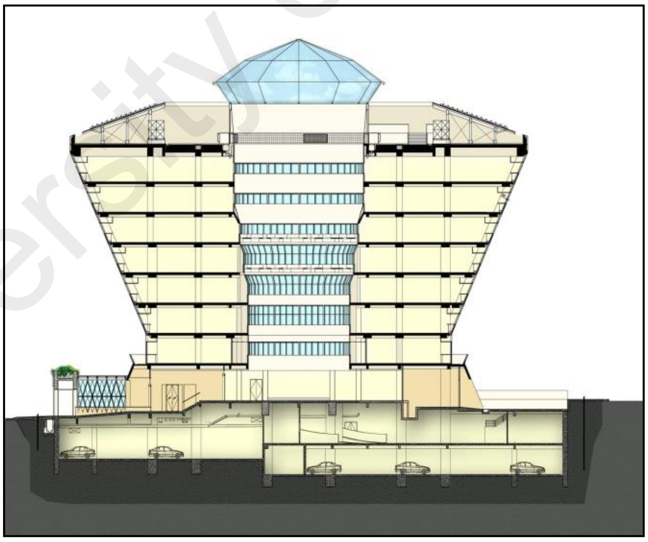


Figure 4.3: Section cut of Diamond building profile
(Source: Malaysia's Energy Commission)

The tilted façade is resulted from the increased floor area in each floor level. The ground floor started small, and each upper floor is designed slightly larger than the previous floors (See Figure 4.3). Besides blocking direct sunlight into the building, the tilting façades also help in minimising the building footprint, which in turn allow for larger landscape area around the site. The landscape area also helps in reducing heat gain into the building. The tilting façades are made up of curtain walls of double-glazing windows. The east and west façades are installed with Low-E glass, which reduces the radiant heat infiltration.

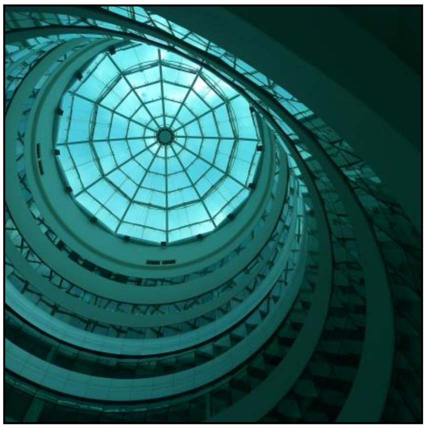


Figure 4.4: Interior view of Diamond building's atrium

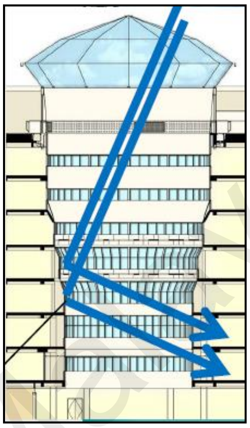


Figure 4.5: Illustration of how the band reflector panels reflect lights into the office space (Source: Mohd Yusof, 2012)

Besides the tilted façades, the main feature of the building is the central atrium (See Figure 4.4). The atrium is top off with a diamond-shaped dome of glass. The combination of tilted façades and the glass dome created a diamond shape building; hence how the name 'Diamond' for the building was derived from. The atrium is illuminated by natural light harvested through the glass dome. However, an automated atrium blind manages and optimises the sunlight intake. The system has different blind assemblages to optimise the daylight harvested by ensuring stable diffuse of daylight into the building. Besides illuminating the atrium, the daylight harvested through the glass dome is also used for lighting up the office areas surrounding the atrium. For maximum use of daylight, band reflectors called the Tannenbaum reflector panels are installed in the fourth and fifth floors to deflect daylight across the atrium towards the first and second floor where daylight levels are the lowest (See Figure 4.5).

Figure 4.6: Windows and the location of mirror light shelf installed above

Figure 4.7: Mirror light shelf and fixed blinds installed above windows (Source: Mohd Yusof, 2012)

Figure 4.8: View of roof light-trough from the interior space

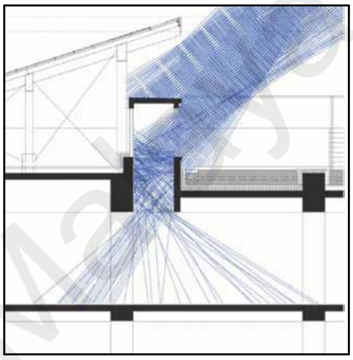


Figure 4.9: Sectional cut to show the mechanics of the roof light-trough (Source: Energy Commission, 2013)

As the building design aimed at maximising the use of daylight, mirror light shelves are installed above the windows to reflect natural light into the building further. This is further reinforced by the high reflective ceiling surfaces which reflected the light throughout the office spaces. The daylight harvested through this mirror light shelf system is coupled with fixed blinds for glare control. Secluded areas on the top floor of the building are illuminated through roof light-trough (See Figure 4.6 and Figure 4.7). On rainy or cloudy days where daylight levels are not enough to illuminate the office spaces, energy efficient electrical lightings are utilised. Individual table lamps are also used at each workstation for optimum illumination.

Air-conditioning system in Diamond building uses the radiant cooling system through floor slab cooling. Chilled water pipes are embedded in the concrete slabs, where the floor slabs would be chilled overnight and would later release cool air into the office spaces during the day. The system is complemented by a conventional cold air supply system. Figure 4.10 and Figure 4.11 shows the cooling system designed in Diamond building.

Figure 4.10: Chilled water pipes for floor slab cooling system

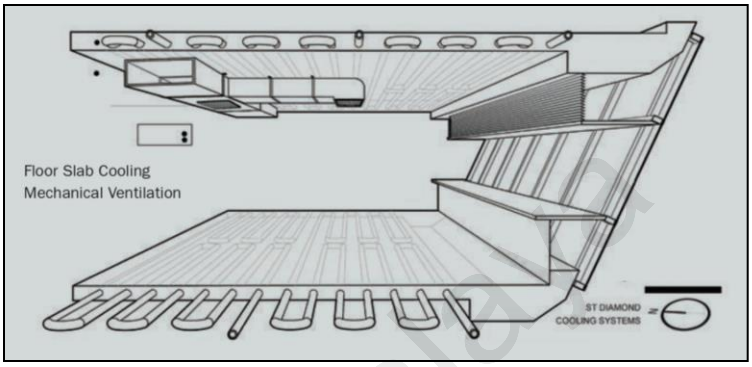


Figure 4.11: Diagram of chilled water pipes embedded into the floor slab
(Source: Chen & Izdihar, 2013)

The Diamond building also adopted the rainwater harvesting system for the use of landscape irrigation and toilet flushing. Also, the building uses water efficient fittings such as the dual flushing toilets, waterless urinals, and taps with aerators to help reduce the annual water consumption of the building. Grey water recycling is also practice by recycling greywater from washbasins and floor traps to water the landscape area.

Figure 4.12: RWH area and photovoltaics panels at the roof area

The Diamond building is also installed with photovoltaics (PV) panels for the purpose of renewable energy. PV panels are installed on the roof area for maximum solar catchment. Figure 4.12 shows photovoltaic panels on the rooftop of Diamond building as well as the rainwater catchment area. Interior fittings in Diamond building used environmentally friendly materials such as recycled plasterboards, low VOC paint for the walls and ceilings, and recycled content carpet materials.

4.1.3.3 Design Elements in Open-plan Offices in Diamond Building

Open-plan office spaces in Diamond building, specifically DOP1 and DOP2 can be categorise as being an irregular-shape space. Even though DOP1 and DOP2 are situated at the same side of the building, due to the tilted façade design, the upper floors are bigger than the lower floors, and thus explained why DOP2 which is located on the sixth floor has much bigger area than DOP1 which is located on the fourth floor. However, all the design elements in both DOP1 and DOP2 are mostly similar to each other as well as other open-plan offices available in the building. The similarities of both open-plan offices are illustrated in Figure 4.13. Figure 4.13 shows the locations, layout plans and interior views of DOP1 and DOP2. Table 4.1 below summarises the physical design elements available in both DOP1 and DOP2 of Diamond building.

Figure 4.13: Locations and interior views of DOP1 and DOP2

Table 4.1: Summary of physical design elements in OPO of Diamond building

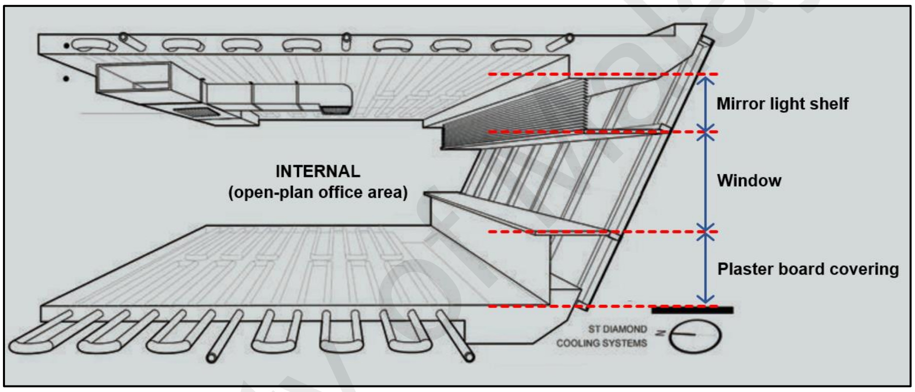
No	Design Element
1.	Exterior wall ▪ The exterior walls of the whole building are made of double-glazing curtain walls (all around) with low E glass (on the East and West façades). ▪ However, the internal area of the building is not fully exposed to the curtain walls. Some part of the window area is covered with plasterboard coverings, and the mirror light shelf area is done to obtain as much indirect sunlight into the office spaces.   
2.	Interior walls ▪ The full height partition walls separating the open-plan offices and the smaller private offices and other rooms such as the printing room and storage are made of lightweight solid wall system and glass walls. 
3.	Floor ▪ The floor is a concrete floor with thin carpeting made of recycled content. 

Table 4.1, Continued

<table>
<tr><th>No</th><th>Design Element</th></tr>
<tr><td>4.</td><td>Ceiling

Major part of the ceiling is basically bare concrete ceiling that works as part of the radiant cooling system.
Some part of the ceiling are boxed up using plasterboards made of recycled materials. These plasterboard boxes are used as channels to carry the mechanical and electrical wirings.
The bare highly reflective concrete ceilings also work as part of the daylight harvesting system.

 
</td></tr>
<tr><td>5.</td><td>Furniture

The workstations in open-plan offices in Diamond building are standardised into few design varieties.
The desks and storage cabinet are made of standard laminated fibreboard material in different sizes depending on the size of the workstations.
The partitions dividing the workstations are standardised into few designs and heights:
i) 1.5 m high semi-transparent polycarbonate or/and fabric panels with steel frames,
ii) Fibreboard floor panels with semi-transparent polycarbonate backing storage shelves (1.5 m total height),
iii) Semi-transparent polycarbonate with steel frames with storage shelf,
iv) 1.1 m high hanging fabric panels with steel frame (in front of desks).

 
 
</td></tr>
</table>

4.2 Case Study 2: LEO Building (Low Energy Office)

4.2.1 Introduction to KeTTHA

LEO building is the head office for Ministry of Energy, Green Technology, and Water (KeTTHA) Malaysia. KeTTHA was established on 9th April 2009 after the restructuring of Malaysia's cabinet in 2009. It was previously known as Ministry of Energy, Water, and Communications (MEWC). The addition of 'Green Technology' in KeTTHA is one of the government's initiatives to address the global issues related to environmental pollution, ozone depletion, global warming and other related issues.

The vision of KeTTHA is to be the industry leader in Sustainable Development of Energy and the National Water and Green Technology. The missions of KeTTHA are to formulate policies and establish the legal framework and effective regulation; to set the direction for the energy industry, green technologies, and water industry in line with national development goals; and to develop an efficient management system and an effective monitoring mechanism, among other things.

Some of the objectives of KeTTHA are to "ensure the implementation of development policies in the power industry, water and green technology effectively; ensure the provision of comprehensive infrastructure"; and "to provide a conducive environment for industrial development and technology" (KeTTHA, n.d.).

4.2.2 Background of LEO Building

LEO building is located in Precinct 1 Putrajaya, Malaysia. The construction of LEO building started in April 2002 and completed in October 2003 and later occupied in 2004 (Danker, 2004).

Figure 4.14: Exterior view of LEO building
(Source: www.greenbuildingindex.org)

LEO building is the first government building in Malaysia built to attain energy efficiency and low environmental impact. It was done in that manner to express the government commitment to 'achieve sustainable development through energy efficiency and conservation'. It was also done with the intention to set an example on energy efficiency for future buildings and dismiss the belief that it is not financially possible to build energy efficient buildings (Danker, 2004; Baird, 2010).

With energy efficiency as the primary focus, LEO building was designed with a target of 50% saving in energy usage, and to reach a benchmark BEI of 100 kWh/m^2/year (Reimann, 2015). LEO building is a first prize winner of 2006 ASEAN Energy Award in "New and Existing Building' category (Baird, 2010) and it received a GBI Silver rating on 1st December 2011 (Green Building Index, n.d.).

4.2.3 LEO Building's Architectural Design

4.2.3.1 Site Planning

LEO building is located at Precinct 1 Putrajaya as part of government building cluster in Parcel E. Surround by other government buildings such as the Ministry of Education (MoE) and Ministry of Higher Education (MoHE) buildings at its west and south side; the building is situated at the corner of the government building cluster. The site is surround by small boulevards at the north, east, and south sides. A Minimal amount of traffic noise is observed coming from these adjacent roads as the roads are small access roads with lines of cars usually parked at the sides. Eventhough the site faces a main highway (Lebuh Perdana Timur), due to the significant distance in between, traffic noise from the highway is not too perceivable from the building. Figure 4.15 shows the location of LEO building among the Parcel E government building cluster.

Figure 4.15: Site plan of LEO building

4.2.3.2 Design Features and Elements

LEO building comprises of six floors including one roof level, and one and a half storey of basement parking with a total built-up area of around 16,000 m². The building has an almost tilted sideways 'L' shape design where each wing is connected to a central atrium. The building entrance is located on the south side of the building in the elongated wing façade. The long façade with many windows are design to face north and south to optimise the usage of daylight while minimising the building's heat absorption. The west-facing façade has no windows as a measure to avoid direct sunlight and to minimise heat gain from the afternoon sun. Windows on east-facing façades are equipped with deep shading to minimise solar gain from the morning sun (See Figure 4.16). Figure 4.17 shows the aerial view of LEO building.

Figure 4.16: East façade view of LEO building
(Source: Roy et al., 2005)

Figure 4.17: Aerial and façades view of LEO building
(Source: http://www.p-perdana.com/)

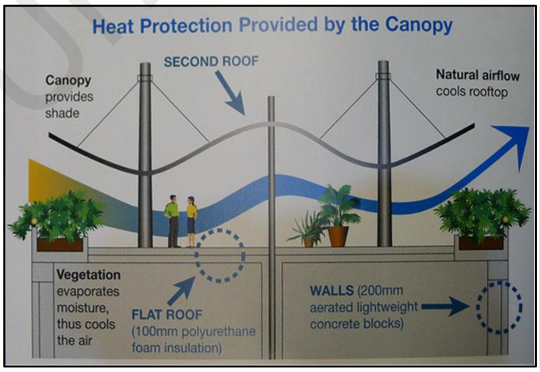


Figure 4.18: Double roof system used in LEO building as a heat reduction strategy
(Source: KeTTHA, n.d.)

Structurally, the building is made of reinforced concrete columns and beams. The walls are made up of 200mm aerated lightweight concrete, painted in light colours to reduce solar heat absorption. The roof uses a double roof system of concrete flat roof and canopy roof. The flat roof is made of 100mm polyurethane foam insulation. The canopy roof acted as a second roof to prevent the sun from hitting the flat roof directly while enhancing the building aesthetic. The flat roof is also furnished with potted plants placed along the boundary of the roof to further minimise heat absorption (See Figure 4.18).

Thermal comfort of the building is controlled using conventional air cooling system which is set to keep a constant internal temperature of 24° Celsius. The air-conditioning system is not design to be centralised, so that manual ON and OFF switch can be set up in individual rooms. The system that detects the CO_2 level of airborne pollutants in the building observes the intake of outside air for air quality control in LEO building.

LEO building maximises the usage of daylight by strategically placing the working spaces at the perimeter of the building. Daylight penetration in the building is maximised using two types of windows: punch-hole façades (on lower floors), and curtain walls (on upper floors) (See Figure 4.19). The exterior louvres control glares that come through the curtain walls. The punch-hole façades system has a double mechanism system, which comprises of deep overhang with complimentary light shelf. Diffusion of light through the punch-hole façade reduces the heat gain while still allowing sufficient light to be harvested (See Figure 4.20). All windows are made of 12mm thick glass with light green tint glazing which allows 65% of daylight in and 49% of heat out. As for spaces that require the assistance of artificial lighting, high-efficiency light fixtures are utilised.

Figure 4.19: Punch-hole windows on the North façade

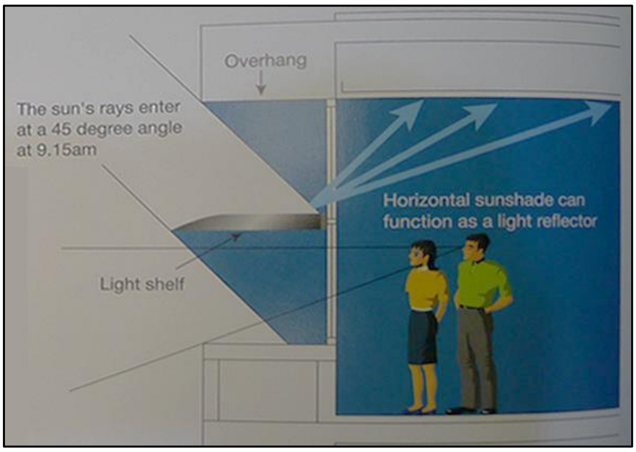


Figure 4.20: The daylight harvesting method using the punch-hole window
(Source: KeTTHA, n.d.)

The atrium that connected the two wings of the building serves as an intermediate space between the hot outdoors and the air-conditioned spaces indoors. Daylight harvested through the skylight illuminates the atrium as well as the open-plan offices adjacent to the atrium (See Figure 4.21). Besides being lit by natural light, the atrium is also ventilated naturally through a thermal flue system at the top of the atrium. The water feature that helps to reduce the temperature in the atrium is powered by the solar panels installed on the roof area. Figure 4.22 illustrates the thermal flue system used in the atrium.

Figure 4.21: View of the middle atrium in LEO building

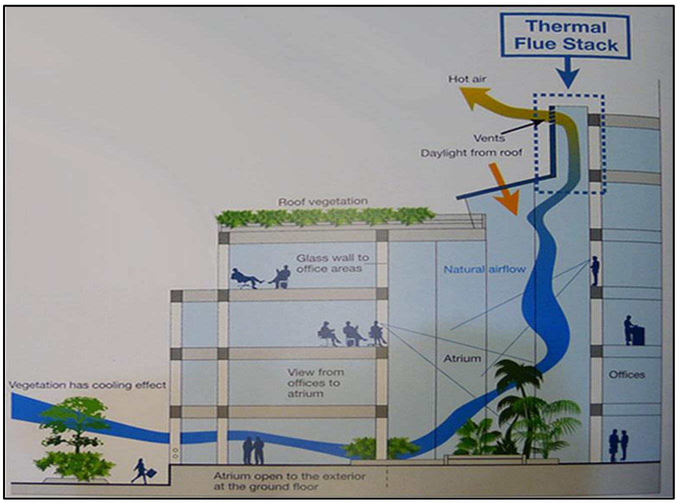


Figure 4.22: The natural ventilation system designed for the atrium
(Source: KeTTHA, n.d.)

To further reduce the energy consumption in LEO building, energy efficient office equipment is used; for example flat screens instead of CRT screens. Building performance of the building is monitored by the energy management system (EMS) to assess the energy usage of the building and to optimise the performance of various mechanical and electrical systems in the building.

4.2.3.3 Design Elements in Open-plan Offices in LEO Building

While personal, closed offices are designed and located at the perimeter of LEO building, open-plan offices in LEO building such as LOP1 and LOP2 are design to be cluster around the central atrium of the building. Due to the irregular shape of the atrium, the open-plan offices are of irregular shapes as well. Much like the open-plan offices in Diamond building, the internal design elements such as the walls, floors, and ceilings of LOP1 and LOP2 are similar to each other. Figure 4.23 shows the locations, layout plans and the interior views of LOP1 and LOP2. Table 4.2 summarises the physical design elements in both LOP1 and LOP2.

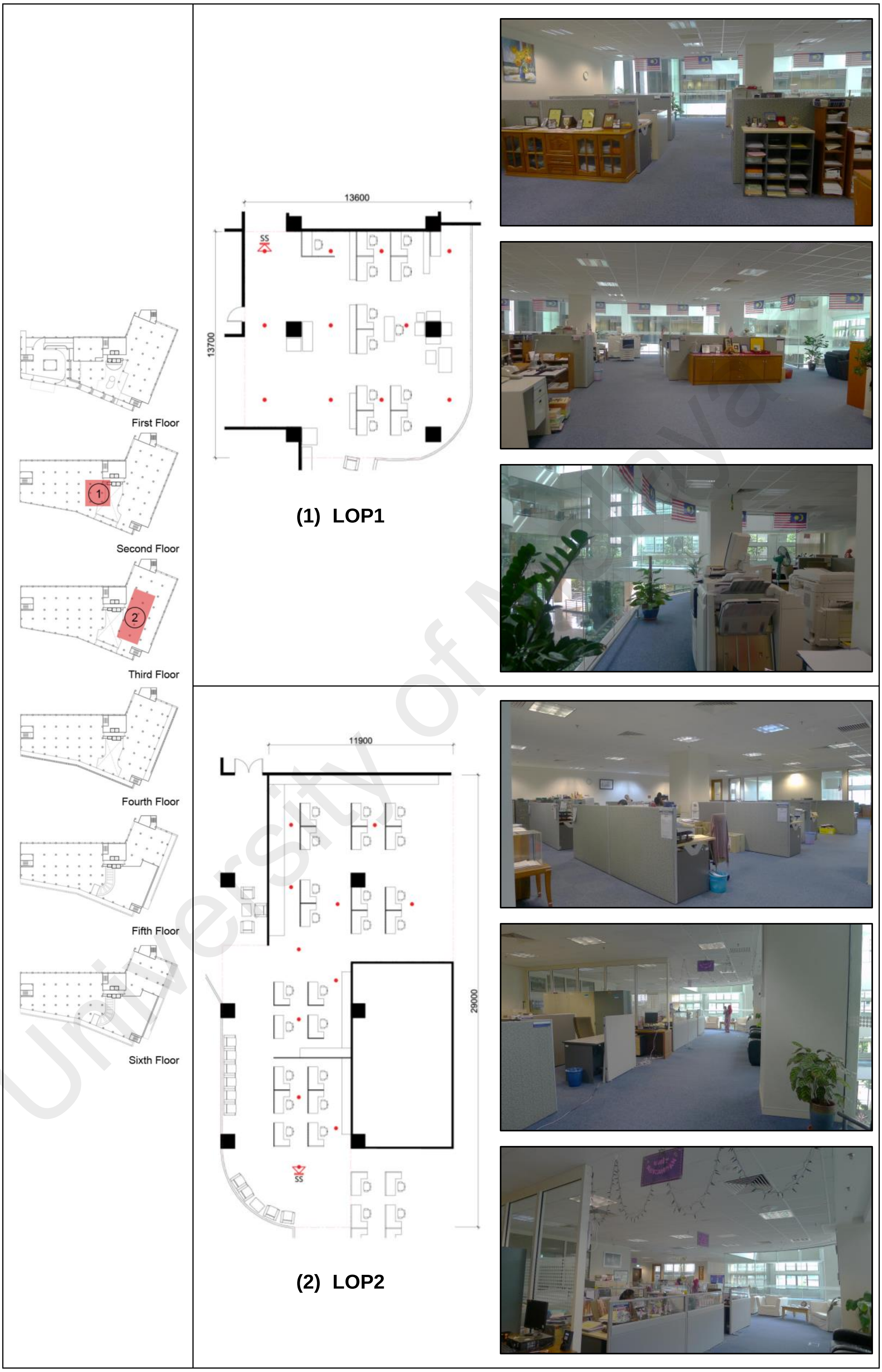


Figure 4.23: Locations and interior views of LOP1 and LOP2

Table 4.2: Summary of physical design elements in OPO of LEO building

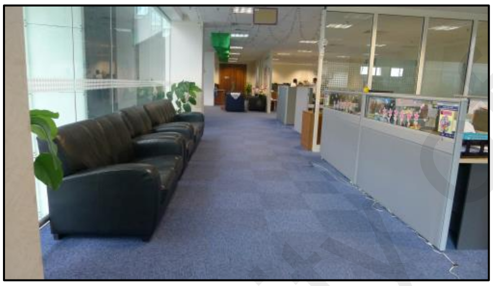
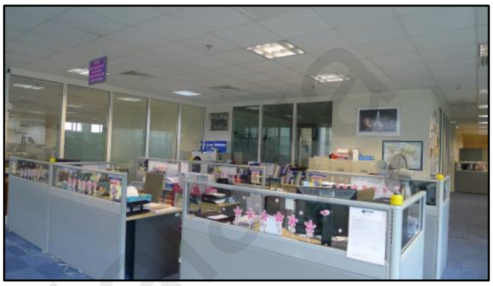
No	Design Element
1.	Exterior walls ▪ Both LOP1 and LOP2 are located within the proximity of the central atrium of LEO building. Both open-plan offices have no direct contact with the external walls.
2.	Interior walls ▪ As mentioned previously, both LOP1 and LOP2 are located adjacent to the atrium. ▪ As the atrium supposedly served to illuminate the open-plan offices with natural daylight harvested in the atrium, the walls separating the atrium and the open-plan offices are made of full heights tempered glass curtain walls. ▪ Internally, the walls separating the open-plan offices and the individual closed rooms are made of lightweight solid wall system with aluminium frame glass panels.    
3.	Floor ▪ The floor system in LEO building uses the raised floor systems with thin carpet coverings. 
4.	Ceiling ▪ All ceilings in workable spaces in LEO building were installed with suspended ceiling tiles. 

Table 4.2, Continued

No	Design Element
5.	Furniture ▪ Furniture in LEO building is standardise into a few variety of designs. ▪ The desks at each workstation are made of laminated fibreboard material (1500 mm x 600 mm). ▪ The partitions dividing the workstations had a consistent height of 1.2 m and standardised into two designs: i) Standard full height (1.2 m) fabric panel with aluminium frame, ii) Standard fabric panel with 1’ top polycarbonate vision screen with aluminium frame.    

4.3 Case Study 3: GEO Building (Green Energy Office)

4.3.1 Introduction to GreenTech Malaysia

GEO building is the headquarter building for GreenTech Malaysia. Formerly known as Malaysia Energy Centre (PTM), GreenTech Malaysia or fully known as Malaysia Green Technology Corporation was established on 12th May 1998. Malaysia Energy Centre (PTM) was first created to assist in the development of the energy sector, particularly on technological research and demonstration of renewable energy and energy efficiency. PTM was restructured into GreenTech Malaysia on 7th April 2010 after the commencement of the National Green Technology Policy in August 2009, with the intention to provide direction towards better management of sustainable environment. The restructuring process also appointed GreenTech Malaysia to assists the Ministry of Energy, Green Technology and Water (KeTTHA).

The goal of GreenTech Malaysia is to develop and establish a conducive environment, which will encourage nationwide acceptance of green technology as a new engine for economic growth, as stated in the policy statement: 'Green Technology shall be a driver to accelerate the national economy and promote sustainable development'. In the effort to promote green technology, GreenTech also provided consultancy and advisory services, secretariat and coordination services, energy audit, study and research, training and certification in any issue regarding green technology and sustainable development (GreenTech Malaysia, n.d.).

4.3.2 Background of GEO Building

GEO building is located on a five-acre site in Seksyen 9 Bandar Baru Bangi, Selangor. The construction of the building began in March 2006 and was completed in October 2007. The building is design to be entirely energy efficient. The concept on which the building was built on focused on the innovation of green technology to minimise energy usage and the usage of fossil fuel for the sake of environmental concern and to actively partake in the usage of renewable energy. Furthermore, this is all to be done without jeopardising the occupants' comfort and well-being.

The building is design to achieve a building energy index (BEI) of 65 kWh/m^2/year (Reimann, 2010). This target BEI value is very low compared to a conventional office building in Malaysia, which on average recorded a BEI of 250 to 300 kWh/m^2/year. This is also an impressive number compared to the Malaysia Standard MS 1525 (2014) which required an energy efficient building to have a BEI of 135 kWh/m^2/year. Since the building adopted the Building Integrated Photovoltaic System (BIPV), the BEI count is further reduced, as the BIPV is able to provide 50% of the electricity supplies the building needs.

Figure 4.24: Exterior view of GEO building
(Source: www.greenbuildingindex.org)

GEO building is the first building in Malaysia to be certified as a green building by the Green Building Index (GBI) on 24th July 2009. It is also the first completed green-rated office building in Malaysia (GreenTech Malaysia, 2010; Yoong, 2008).

4.3.3 GEO Building's Architectural Design

4.3.3.1 Site Planning

Situated on a 5-acre land, the building only occupies less than 50% of the site area. Aside from the building and the parking area, more than 50% of the site is left green and embellishes with grass field and vegetation around the edges of the building and the site perimeter. Along the north perimeter of the site is the main road, which is connected to the site entrance. While residential areas occupy the east side of the site, an office tower building of Lembaga Hasil Dalam Negeri (LHDN) occupies the west.

LEO building was carefully planned and aligned, with the elongated side of the building facing north and south. This building orientation ensured that the majority of its windows do not receive direct sunlight from the east and the west. As the site is situated away from large main roads, the traffic condition at the roads adjacent to the site is observed to be minimal. Residents from the neighbouring residential area as well as lorries from nearby factories are the main user of the road at the north of the site. The considerable distance between the building and the road also filters the traffic noises, if there is any. Figure 4.25 illustrates the location of GEO building and its context.

Figure 4.25: Site plan of GEO building

4.3.3.2 Design Features and Elements

GEO building is a small four-storey office building cum training centre with a total gross floor area of 4,800 m^2. The building has an elongated floor plan with two identical segments. However, while the south segment is a straight rectangular shaped building, the north segment was slightly arched towards the northwest. The two segments are divided by a middle atrium that is naturally lit by daylight through the photovoltaic skylight roof (See Figure 4.26 and Figure 4.27). The building is an airtight building with a self-shading design profile, where the upper floors are cantilevered to shade the lower floors. It is designed as such to maximise daylight harvesting while controlling the amount of glare entering the building. Figure 4.28 shows the sectional cut of LEO building and the cantilevered building profile.

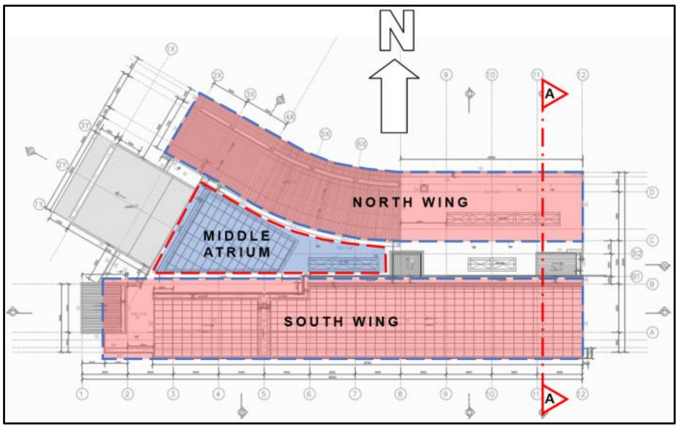


Figure 4.26: Roof plan of GEO building

Figure 4.27: View of the middle atrium
(Source: Yoong, 2008)

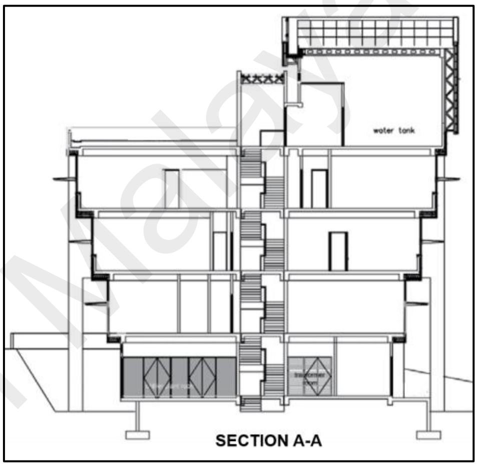


Figure 4.28: Sectional cut of GEO building
(Source: Yoong, 2008)

The building structure consists of reinforced concrete columns and beams. External walls of the building are lightweight wall system installed with rock wool insulation to minimise heat gain into the building. External windows of GEO building use double-glazing windows, which also help in minimising heat gain while maximising daylight harvesting. Air-conditioning system of GEO building utilises the combination of radiant cooling and conventional cold air supply system. The radiant cooling system consisted of chilled floor slabs where the concrete floor slabs are chilled using cold water supplied through the cold water piping embedded in the floor slabs. The chilled slabs are prepared throughout the night, and during the day, the floor slab would radiate cool air into the office spaces below (See Figure 4.29).

As the building has a thin depth, daylight harvesting is possible to all the workspaces in the building. The daylight harvesting system is accompanied by mirror light shelves, which are installed above the windows, to further reflect daylight into the building (See Figure 4.29 and Figure 4.30). While the bare ceilings act as reflective surfaces for daylight penetration in the lower floors, the top floor is equipped with roof light-trough, which collects light through the roof; and reflects diffused daylight into the building. GEO building uses an energy efficient T5 miniature fluorescent tube electrical lighting as a supplement for artificial lighting. Individual workstations are equipped with LED task light to optimise the occupants' visual comfort.

The building is also equipped with rainwater harvesting system that collects rainwater on the roof areas of the building. The rainwater harvested is utilised for cooling system condenser, watering landscape areas, and for general cleaning purposes. Photovoltaic panels are also installed as part of the renewable energy effort, which at the same time act as the atrium's skylight roof.

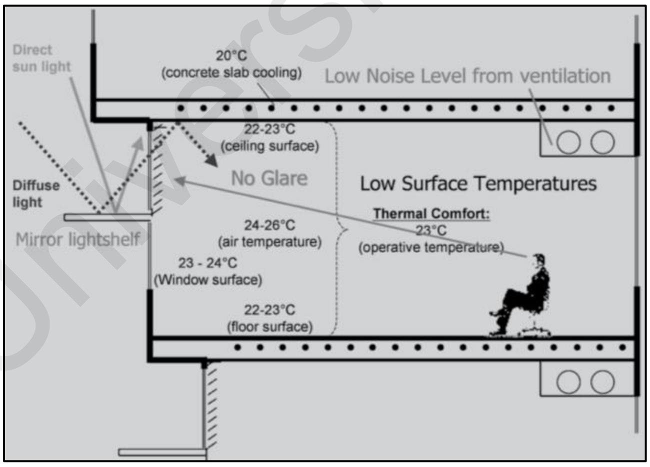


Figure 4.29: Daylight harvesting system in GEO building using the mirror light shelves above the windows
(Source: Yoong, 2008)

Figure 4.30: Location of the mirror light shelves on GEO building's North façade

Figure 4.31: The location of roof light trough system on the flat roof and the interior light diffuser

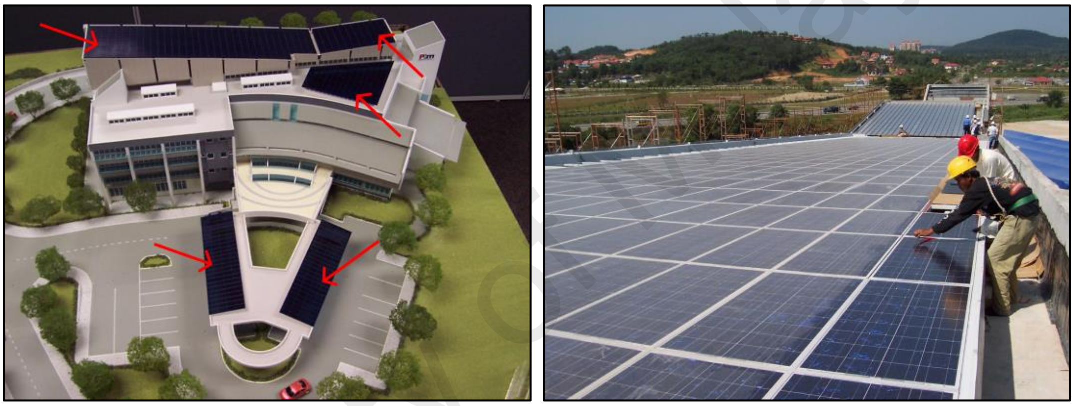


Figure 4.32: Photovoltaic panels installed in GEO building
(Source: Pusat Tenaga Malaysia, 2007)

Energy efficient office equipment ia also utilised in the building such as laptops, desktops with LCD screens, shared network printers, wireless computer network system, and energy efficient server system. The building performance is monitored by the Building Energy Management System (BEMS). The BEMS also helps in optimising the building operation efficiently.

4.3.3.3 Design Elements in Open-plan Offices in GEO Building

Due to the elongated shape of GEO building and the separation of two building wings with the middle atrium, the open-plan offices in the building tends to be rectangular in shapes. Due to its location, GOP1, which is the smaller open-plan office, has an almost square shape, while GOP2 has an elongated rectangular shape. Internal design elements in both open-plan offices are similar to each other as both are located on the second floor of the building. Figure 4.33 shows the locations, layout plans, and

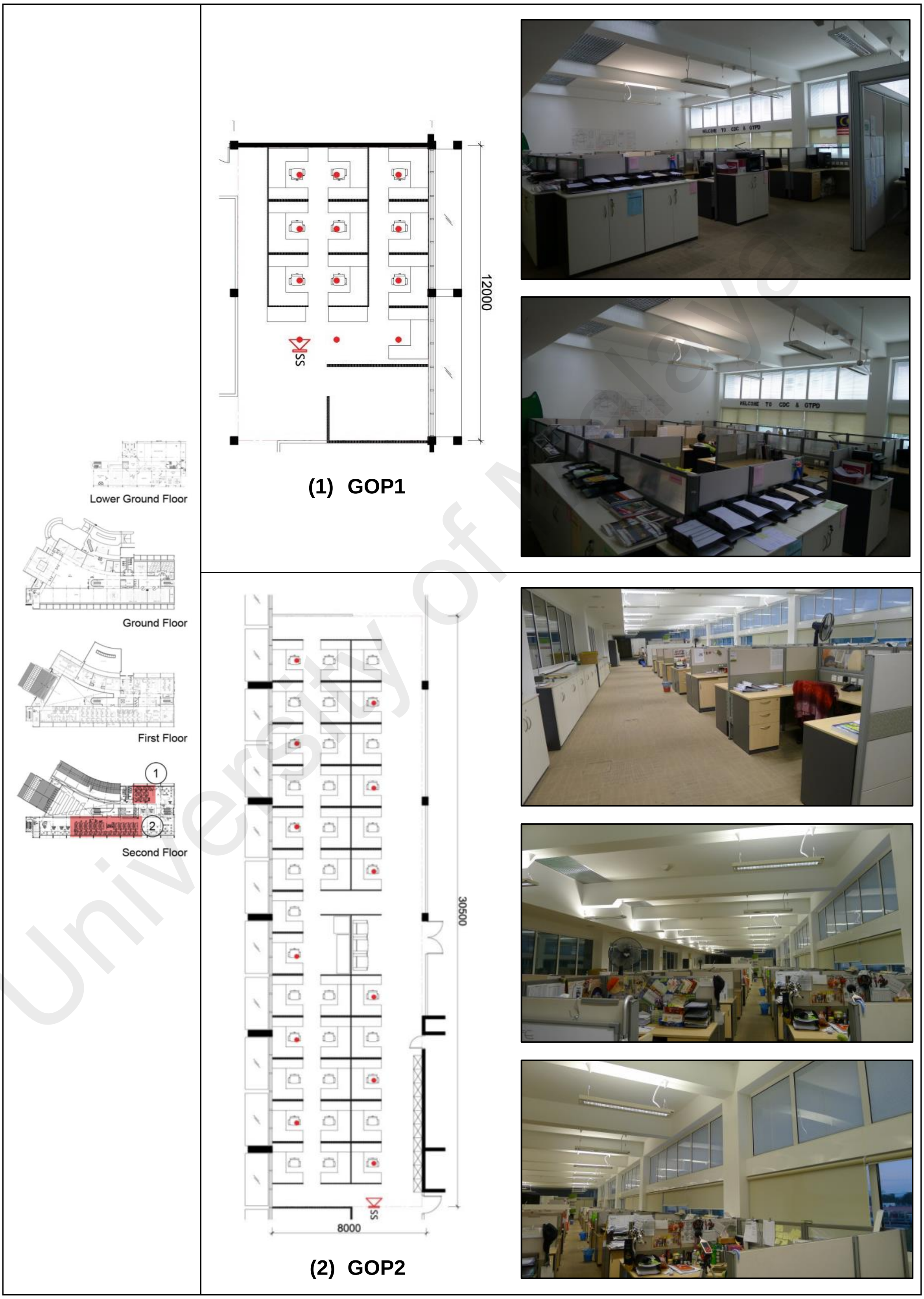


Figure 4.33: Locations and interior views of GOP1 and GOP2

the interior views of GOP1 and GOP2. Meanwhile, Table 4.3 summarises the physical design elements in both GOP1 and GOP2.

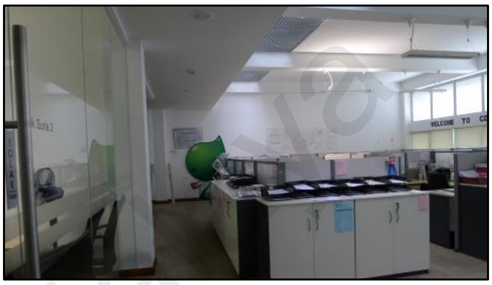
Table 4.3: Summary of physical design elements in OPO of GEO building

No	Design Element
1.	Exterior walls ▪ The external walls (north and south facing walls) of GEO building are made of lightweight wall system using cement compress fibreboard with a layer of Roxul insulation. ▪ The windows are made of double-glazing windows and daylight window to reflect daylight into the building.    
2.	Interior walls ▪ Internal walls dividing the open-plan offices and the corridors, meeting rooms and other individual rooms are made of lightweight wall system (cement compress fibre) and glass doors, full height glass panels, and glass windows.  
3.	Floor ▪ The floor is reinforced concrete floor with thin carpeting. 

Table 4.3, Continued

<table>
<tr><th>No</th><th>Design Element</th></tr>
<tr><td>4.</td><td>Ceiling

The main part of the ceiling is bare concrete ceiling which works as a part of the radiant cooling system.
The bare ceilings are also painted with white paint to double as reflective surfaces for the daylight harvesting system.
Certain parts of the ceiling are boxed up with plasterboards and worked as channels to carry the mechanical and electrical wirings.
The ceiling surfaces of GOP1 and GOP2 also include the glass light diffuser that works as a part of the roof’s light-trough.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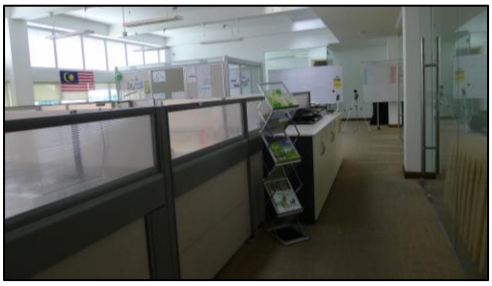
<tr><td>5.</td><td>Furniture

Similar to Diamond and LEO building, the workstations in GEO building are also standardised. However, the workstations in GOP1 are more modular in term of design, sizes, and arrangements.
The U-shaped desks at each workstation are made of laminated fibreboard material. All workstations in both GOP1 and GOP2 have a uniform size of 2100 mm x 1600 mm.
The partitions dividing the workstations had a consistent height of 1.2 m and standardised into two designs:
i) Standard full height (1.2 m) fabric panel with aluminium frame,
ii) Standard fabric panel with 1’ top corrugated polycarbonate vision screen.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4.4 Summary

Though the data obtained from the case studies done on all three green office buildings, the relevant design elements, or more specifically 'green' design elements are identified.

Green building design elements and features are not necessarily different than the design features in non-green buildings. What sets them apart is the way those design features are employ or manipulate to achieve the essential purpose of green buildings, which is sustainability. Hence, the identification of these green design elements is crucial in understanding the acoustical phenomenon happening in the green buildings. This is because the same design features while being employed in a slightly different manner could influence the environmental quality in the office spaces. In the case of this study, attention is directed towards the acoustics part of the environmental element.

Literature reviews of previous work reveals how some green building design features affected the acoustic quality in open-plan offices. Through the case study, these specific design elements with an observation of its effects in mind; along with other design elements are identified and observed. When analysed with data collected during Field Measurement, data from the case study would be crucial to answer the research question and objectives formulated earlier in the thesis.

CHAPTER 5: MEASUREMENT FINDINGS AND ANALYSIS

The first part of this section intends to analyse the data collected (for selected acoustical parameters as discussed in Chapter Three) from the field measurements by verifying the findings with relevant acoustics standards such as ANSI/ASA 12.2 (2008), ISO 11690-1 (1996), and related recommendations found in the literature.

The second part of the chapter will discuss the findings together with the architectural design elements available in the measured open-plan offices and further verify the literature findings of how these elements influence the acoustical conditions in the open-plan offices in the three green office buildings.

5.1 Field Measurement Data Findings

5.1.1 Background Noise (BN) Level and Noise Criteria (NC)

As discussed in the literature review, there are many recommendations for acceptable BN level and noise criteria (NC) found in different standards and literature (ANSI/ASA S12.2, 2008; ISO 11690-1, 1996; Cavanaugh, 1999; Maekawa et al., 2011; Hodgson, 2008; Green Building Index, 2009). For the purpose of this study, the acceptability limits for both BN level and NC applied is summarises in Table 5.1.

Table 5.1: Acceptable BN and NC levels for OPO applied in the study

Measurement parameter	
Background noise (BN) level	Noise criteria (NC)
35 to 45 dB(A)	NC-35 to NC-40

BN data of measured open-plan offices in Diamond building are as depicted in Figure 5.1. The *x*-axis represents the time at which the measurements are taken, which is two minutes. Interval time of which the data is recorded during the measurement is one second. The *y*-axis represents the averaged BN level in A-weighted level dB(A). On the other hand, Figure 5.2 illustrates the NC data of measured open-plan offices in Diamond building. While *y*-axis represents the same value as Figure 5.1, the *x*-axis of Figure 5.2 represents the frequency of which the measurements are taken, which is at 1/1 octave band setting. These settings are applicable to Figure 5.3, 5.4, 5.5, and 5.6 as well.

Using the acceptability criteria outlined in Table 5.1, Table 5.2 summarises the minimum, averaged, and maximum BN level in A-weighting and NC for all the measured open-plan offices in Diamond, LEO, and GEO building. The BN level and NC values depicted are the averaged values of all data collected at each open-plan office's respected measurement points. The data findings of averaged BN level and noise criteria (NC) are highlighted according to the acceptability criteria as per described in the legend provided. Green highlights denote that the data is within the acceptable criteria range. Meanwhile, blue and red highlights respectively mean that the data is lower than the minimum acceptable range or higher than the maximum acceptable range.

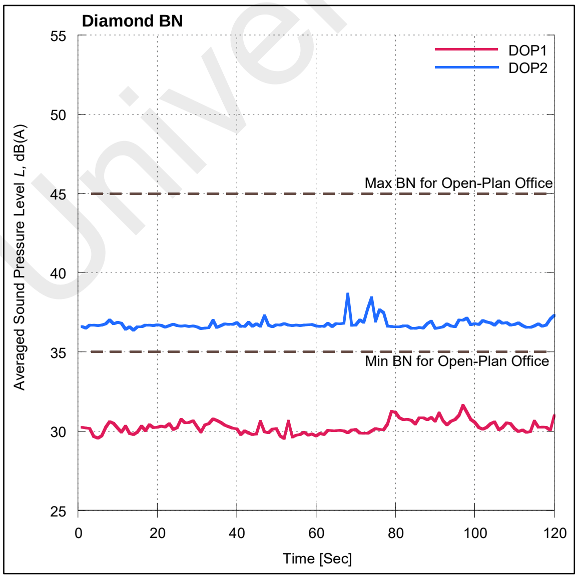


Figure 5.1: BN level of measured open-plan offices in Diamond building

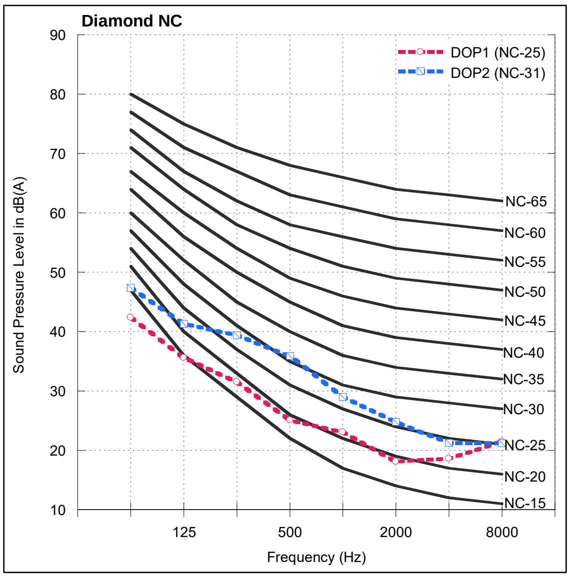


Figure 5.2: NC level of measured open-plan offices in Diamond building

The BN values for both open-plan offices in Diamond building (DOP1 and DOP2) are found to be acceptable as they recorded well below the maximum acceptable criteria applies in the study. However, DOP1 recorded a low BN level of 30.28 dB(A) which is below the minimum acceptable range which is set at 35 dB(A). The NC ratings of measured BN level indicate that both DOP1 and DOP2 record low NC values of NC-25 and NC-31 respectively, which is below the minimum acceptable NC value for open-plan offices as suggested in Table 5.1.

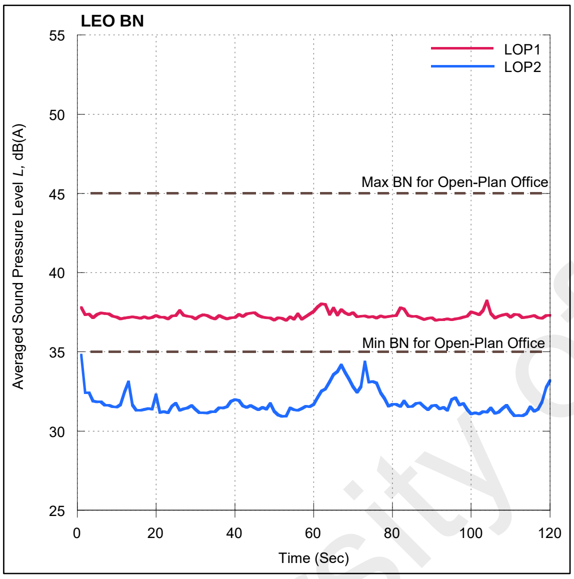


Figure 5.3: BN level of measured open-plan offices in LEO building

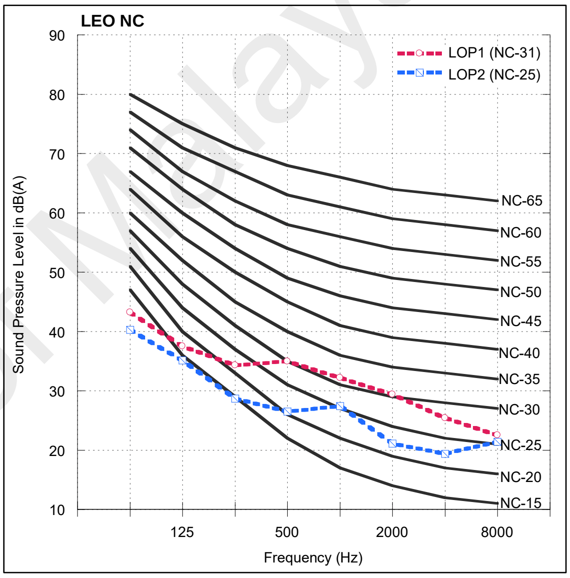


Figure 5.4: NC level of measured open-plan offices in LEO building

Meanwhile, in LEO building, BN level for both LOP1 and LOP2 are found to be satisfactory, as both indicate readings below the maximum criteria. Figure 5.3 illustrates that LOP1 logs a BN level of 37.29 dB(A) which falls within the optimum level of BN level. However, LOP2 logs a BN level of 31.79 dB(A) which is lower than the minimum recommended BN. Figure 5.4 illustrates the NC value recorded for both LOP1 and LOP2. As indicated in Table 5.2, it can be seen that the NC for both open-plan offices in LEO building are below the minimum recommended NC value, with each records an NC value of NC-31 and NC-25 respectively.

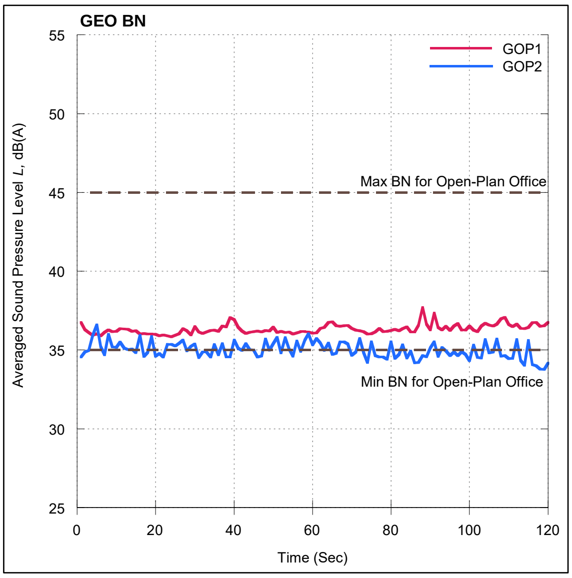


Figure 5.5: BN level of measured open-plan offices in GEO building

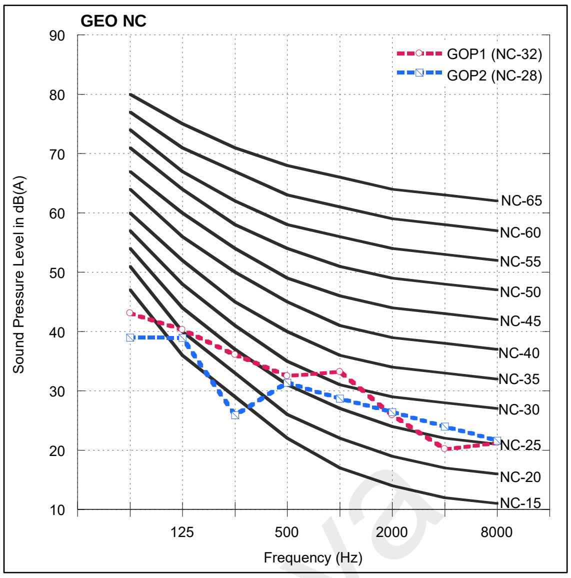


Figure 5.6: NC level of measured open-plan offices in GEO building

GEO building's BN and NC data are as depicted in Figure 5.5 and 5.6. BN level for both GOP1 and GOP2 are found to be at an optimum level of within 35 to 45 dB(A) with GOP1 records a BN level of 36.33 dB(A) and GOP2 with a 35 dB(A). NC rating for GOP1 is logged at NC-32 while GOP2 records an NC value of NC-28. Both of these NC values fall well below the minimum recommended NC levels apply in this study.

Table 5.2: Summary of overall BN level and NC value for all measured OPO

Blue	Lower than minimum recommended level
Green	Optimum level
Red	Higher than maximum recommended level

No	Space	Code	Overall BN, dB(A)			Noise Criteria (NC)
			Min	Ave	Max	
Diamond Building						
1.	Open-plan Office 1 (Level 4)	DOP1	29.54	30.28	31.63	NC-25
2.	Open-plan Office 2 (Level 6)	DOP2	36.37	36.77	38.66	NC-31
LEO Building						
3.	Open-plan Office 1 (Level 2)	LOP1	36.98	37.29	38.22	NC-31
4.	Open-plan Office 2 (Level 3)	LOP2	30.93	31.79	34.79	NC-25
GEO Building						
5.	Open-plan Office 1 (Level 2)	GOP1	35.84	36.33	37.71	NC-32
6.	Open-plan Office 2 (Level 2)	GOP2	33.77	35.00	36.61	NC-28

5.1.2 Reverberation Time (RT)

Depending on its volume, the RT level recorded for each room are analyse using the recommended RT level in ISO 11690-1 (1996) as discussed in the literature review (See Table 2.4). Table 5.3 shows the averaged RT in 500 Hz for all measured open-plan offices. The RT data are rendered according to the acceptability criteria depending on their volumes. As per stated in the legend, blue and red highlights suggest that the RT data is lower and higher than recommended optimum RT respectively, and the green highlight denote that the RT is within the optimum range.

All the measured open-plan offices possess volume of between 200 m³ to 1000 m³ and log varied RT levels. While GOP1 and GOP2 recorded optimum RT of between 0.8 to 1.3 seconds, LOP1 and DOP1 recorded RT levels of 1.41 seconds and 1.5 seconds respectively, which surpasses the maximum limit of 1.3 seconds. The larger open-plan offices, which are LOP2 and DOP2 with the volume of 931.8 m³ and 987.7 m³ respectively, record the lowest RT of below the recommended RT level applies in this study. It was highly likely that the high RT levels are caused by the absence of acoustical ceilings and absorptive materials in the open-plan offices, and the use of sound diffusion was not sufficient to prevent focused reflections.

Table 5.3: Reverberation time (RT) for all measured OPO

(blue)	Lower than minimum recommended level
(green)	Optimum level
(red)	Higher than maximum recommended level

No	OPO	Volume (m^3)	Averaged RT (500 Hz) in s
1.	GOP1	360.0	1.09
2.	LOP1	503.1	1.41
3.	DOP1	887.9	1.50
4.	GOP2	915.0	1.12
5.	LOP2	931.8	0.71
6.	DOP2	987.7	0.70

5.1.3 Speech Transmission Index (STI) and Distraction Distance (r_D)

Figure 5.7 (a), (b), and (c) show the measured STI for open-plan offices for all three green office buildings, in relation to the distance between the sound source (SS) and receiver points. The *x*-axis of the three figures represents the distance of each receiver from the SS, and the *y*-axis represents the measured STI level. The data are presented in this method to help determine the distraction distance (r_D), which are determine by reading the distance which crosses at STI 0.5 in their respective linear curve fit line. It should be noted that the STI data recorded in the figures are taken from the receiver points which are parallel to the SS (straight measurement path) as per specified in ISO 3382-3 (2012).

To truly understand Figure 5.7, it is necessary to observe the distraction distance (r_D) recorded from each open-plan office. The conceptual idea of r_D in open-plan offices is that the lower the value of r_D (distance in meter), the better acoustic performance of the workspace. This is because a longer r_D means that the speech intelligibility (SI) is better. As discussed in the literature (Table 2.6), *good* SI equals to *bad* speech privacy, and *bad* speech privacy resulted in occupants being exposed to other people's conversation and vice versa. Distraction in the office environment would provide unnecessary disturbance and influence badly on occupants' work performance.

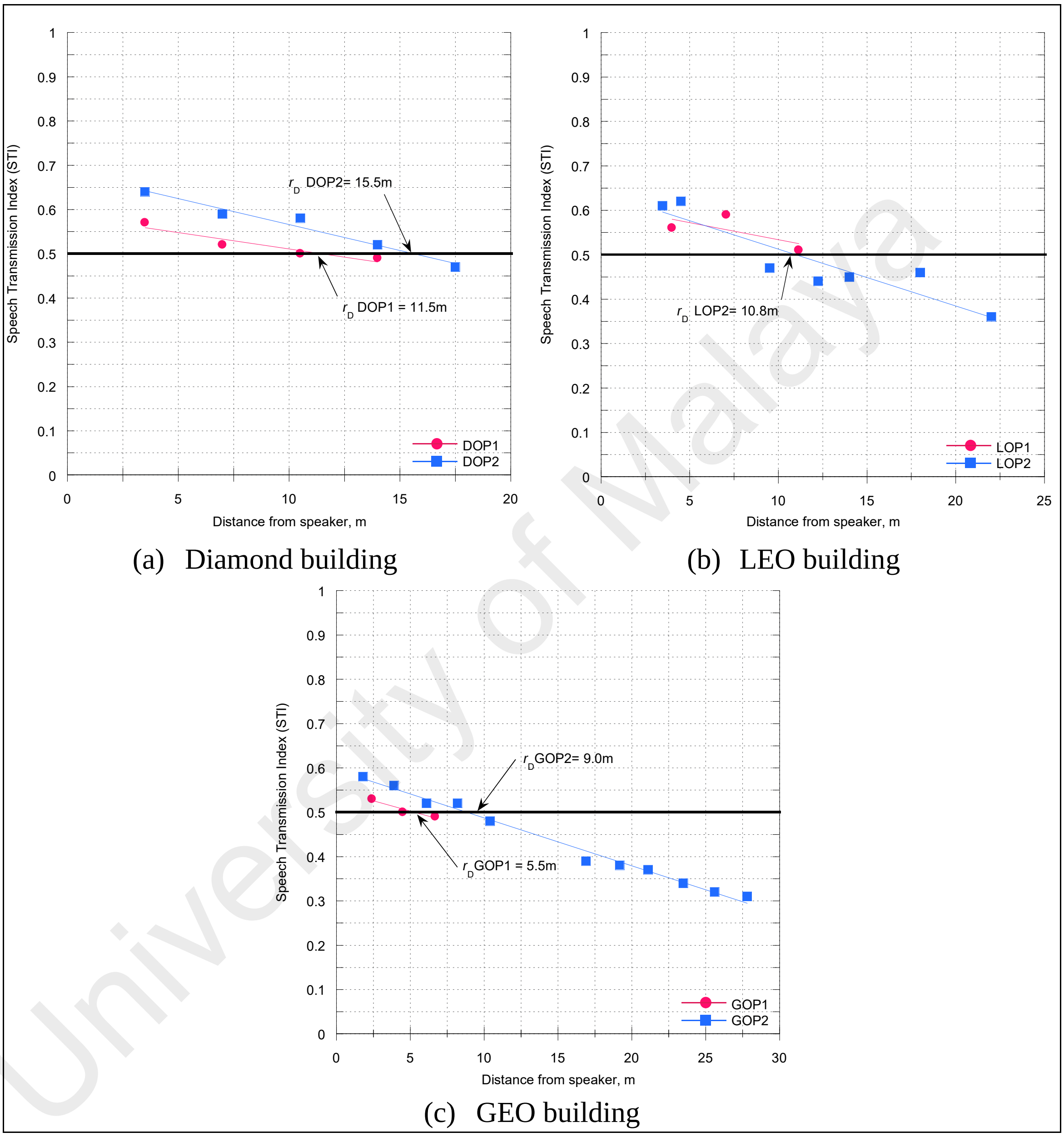


Figure 5.7: Measured STI and r_D of open-plan offices in Diamond, LEO, and GEO building

As illustrates in Figure 5.7 (a), (b), and (c); all r_D from all six OPO ware marked where the linear curve fit line crosses the 0.5 STI mark. However, it can be seen in Figure 5.7 (b), due to the size of the room and the high level of STI reading in LOP1, no r_D could be obtain for the room.

Table 5.4 summarises the r_D recorded for all the open-plan offices in the three green buildings. Each data is classified into the speech privacy range of 'Excellent', 'Good', 'Fair', and 'Poor'. The lowest distraction distance (r_D), which falls under the category of 'Good' speech privacy is found in GOP1 with the r_D of only 5.5 meters. Diamond building recorded 'Poor' speech privacy with r_D of above 11 meters. LOP2 and GOP2 recorded 'Fair' speech privacy with r_D of within 9 to 11 meters.

Table 5.4: Distraction distance (r_D) of measured open-plan offices

Speech Privacy Ratings

< 5 m	Excellent
5 – 8 m	Good
8 – 11 m	Fair
>11 m	Poor

No	Code	Distraction Distance (r_D), m
Diamond Building		
1	DOP1	11.5
2	DOP2	15.5
LEO Building		
3	LOP1	-
4	LOP2	10.8
GEO Building		
5	GOP1	5.5
6	GOP2	9.0

5.2 Data Findings and Architectural Design Elements

Theory dictates certain outcomes when specific design elements are played into the building designs. Earlier in the literature review chapter, some common green building design strategies were identified as being the most influential towards indoor environmental quality (IEQ) of office buildings. The green building design strategies identified are: daylight harvesting, ventilation system, reduced finishes, and open-plan office layout. These design strategies were then identified in the three green office buildings in the case study chapter.

5.2.1 Green Building Design Strategy 1: Ventilation System

Among the green buildings studied, two green buildings namely Diamond and GEO building employ a radiant cooling system in their building. It is crucial to note that in both buildings, the system is only applies to large workspaces such as the open-plan offices. Small spaces such as meeting rooms are still ventilated using conventional A/C system such as fan coil units, etc.

Theoretically, as discussed in Table 2.7 (Chapter 2), spaces ventilated using the radiant cooling system would experience low BN and NC levels due to the low mechanical noises from the system. In this study, it can be verified through findings shows in Figure 5.8. It can be seen that the BN and NC levels for DOP1, DOP2, GOP1, and GOP2 is between 'Low' to 'Optimum' level.

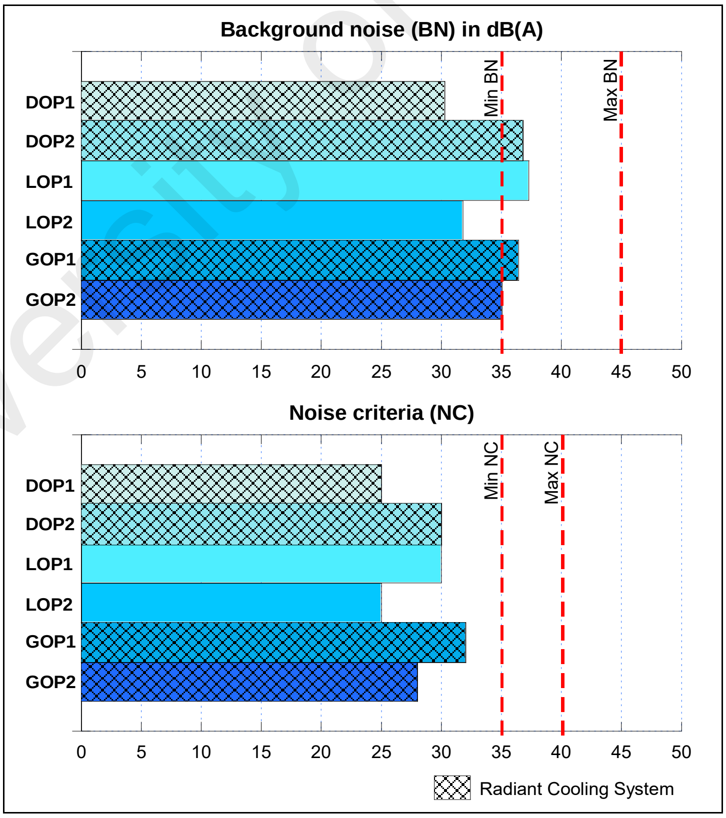


Figure 5.8: Comparison of BN and NC levels between different A/C systems in the three green office buildings

LEO building, on the other hand, uses a conventional air-conditioning system of AHU with fan coil units in its open-plan offices. Despite using the conventional A/C system, which in theory should be able to produce enough mechanical noises to act as a background noise, it, unfortunately, did not. As discussed in Chapter 4, this is because the A/C system in LEO building was designed with a supply fan that adjusted its speed according to the supply demand. It should be noted that as a green building, LEO building has been passively designed to maximize the reduction of heat gain into the building; hence the low A/C demand in the building resulted in low mechanical noises from the ventilation system. It can be seen in Figure 5.8 that the BN and NC levels recorded in both LOP1 and LOP2 are consistently low due to the similar centralised A/C and fan coil type installation methods, which are concealed in the acoustical ceiling spaces.

On a different side, it is worth mentioning that both Diamond and GEO building which uses the radiant cooling system have much lower Building Energy Index (BEI) of 65 $kWh/m^2/year$ compared to LEO's 104 $kWh/m^2/year$. As green buildings aim towards a maximum reduction in energy consumption, the radiant cooling system seems to be contributing quite an impact, notwithstanding the acoustical issue of low BN level and NC value resulted from it.

5.2.2 Green Building Design Strategy 2: Lighting System

In the effort of reducing the BEI, most green buildings adopted daylight harvesting as a mean to illuminate the spaces in the buildings. The utilisation of daylight would not only reduce energy consumption in green office buildings, but it would also help in optimising the visual quality in the office building which in turn ensure visual comfort for the occupants.

Daylighting is a dominant green building design strategy, and it is widely implemented in Diamond, LEO, and GEO building. The design strategy is extensively exploited especially in Diamond and GEO building through the use of large windows, light shelves, and roof light-troughs. The atrium in Diamond building is specifically designed with band reflectors to reflect daylight into the office spaces in the lower floors.

As discussed in the previous section, the air-cooling systems adopted in the three green office buildings would ensure a consistently low BN and NC levels in the open-plan offices. However, three open-plan offices namely DOP2, LOP1, and GOP1 recorded a slightly higher BN that falls into the category of 'Optimum' BN, which is the ideal and more preferred BN level.

During the field measurement, it is observed that the slightly high background noise (BN) level in DOP2 is not triggered by any design elements concerning the usage of daylighting such as the usage of big glass windows or the light shelves. The higher BN level is in fact caused by the server room which is located in the vicinity of the office space. In a way, the noises originated from the server room became a masking sound for the open-plan office DOP2 (See Figure 5.9). Appendix F illustrates the noise spectra in 1/3-octave band for details of tonality in each of the selected measurement points for all open-paln offices.

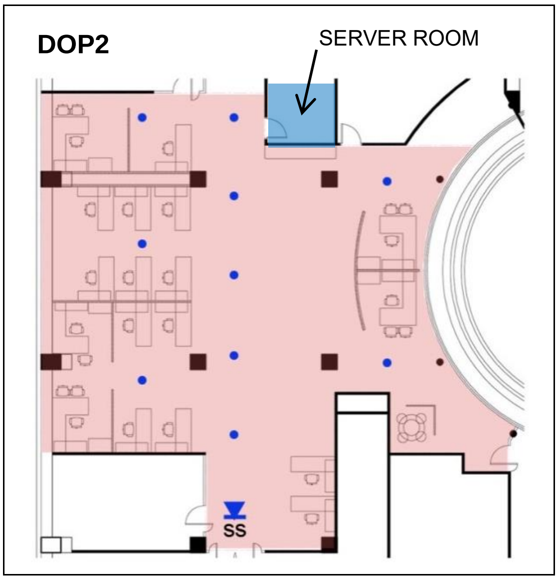


Figure 5.9: Location of the server room adjacent to DOP2

As for LOP1 in LEO building, it is observed that the open-plan office was exposed to an external corridor, which opens towards the naturally ventilated atrium. It is observed that the slightly higher BN level was due to the external traffic noise incoming from the corridor. Regardless of the unpleasantness of the noises, the traffic noise ingress has somehow become a masking noise for the quiet LOP1 space.

5.2.3 Green Building Design Strategy 3: Internal Building Finishes

Most green buildings implement the design strategy of using 'minimal finishes' in the interior spaces as part of the effort to provide better air quality for the occupants. Previously, building finishes used ranges from ceilings that contained some hazardous elements such as asbestos, wall paints with a high content of volatile organic compounds (VOC), and roof insulations which contained harmful glass fibre; all of which are the cause of some significant health threats towards the building occupants. Additionally, carpeting or wall panelling contained textile fibres which over time tend to collect dust and affect the indoor air quality of the office space (Singh, 1996; Salonen et al., 2002; Lockwood, 2006).

While ‘green’ versions of these interior finishes have been created to replace the previously harmful ones, more and more green buildings opted towards removing "finishes" entirely from its material lists. Besides keeping up-to-date with the current ‘industrial look’ trend, the absence of these interior finishes made controlling indoor air quality (IAQ) much less of a hassle. Also, building management is able to save up on the cost of maintaining the finishes which need to be regularly clean and replace. Moreover, green buildings also took out the option of having ceiling finishes so that radiant cooling system (chilled slab system) can be implemented.

In theory, reducing the finishes in open-plan offices would affect the reverberation time (RT). Reduction of finishes would leave the structure bare, and the hard surfaces would create massive reflective surfaces which would result in excessive reverberation. Among the acoustically measured spaces in the three green office buildings, open-plan offices in Diamond and GEO building adapted the no-ceiling design to cater for their chilled slab radiant cooling system.

Nevertheless, according to the RT data collected, most of the measured open-plan offices recorded ‘Low’ to ‘Optimum’ RT. On the other hand, the RT recorded in DOP1 and LOP1 exceeded the maximum recommended RT of 1.3 seconds with each logged an RT of 1.5 seconds and 1.41 seconds respectively.

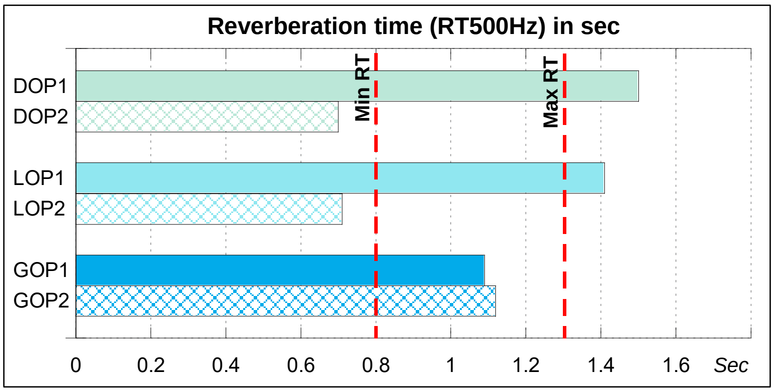


Figure 5.10: Reverberation time (500 Hz) of all open-plan offices

It should be considered that the 'Low' RT in DOP2 and LOP2 and 'Optimum' RT recorded in GOP1 and GOP2 could have been caused by other absorptive materials and finishes such as furniture, window blinds, and other office clutter such as boxes and papers. These materials may have made up for the lack of acoustical ceiling in the spaces in Diamond and GEO building.

It should also be noted that even though the ceilings in open-plan offices in LEO were equipped with an acoustical ceiling finishes, the RT data obtained did not differ significantly from RT data recorded in Diamond and GEO building. Hence, it can be determined that this particular green building design strategy does not have any significant influence on the acoustical performance of the three green office buildings.

Even though reducing the finishes in green office buildings did not result in any significant impact on the RT levels, it is worth mentioning that the level of RT does not, in fact, have any substantial influence in determining the acoustic comfort in open-plan offices. Furthermore, the levels of RT recorded in these OPOs are not critical enogh to be considered as a threat to the acouctic comfort. Additionally, unlike classrooms or music halls, open-plan offices do not need a properly controlled RT to function well.

5.2.4 Green Building Design Strategy 4: Workspace Design

Open-plan office layout has been the most preferred office layout in office buildings, even in conventional office buildings. However, the component which categorised open-plan office layout as 'green' was the fact that it complimented on the execution of other green building design strategies namely daylight harvesting and ventilation system. Open-plan office layout made it possible to extend the benefit of daylight further into the office spaces through its low or sometimes non-existing partitions.

Theoretically, open-plan offices would experience 'Poor' speech privacy as the result of reduced sound isolation caused by the low barrier between the workstations. In the measured open-plan offices in the three green office buildings, the reduced sound isolation was determined by the distraction distance (r_D) which was derived from the STI measurement data. It should be noted that the low BN level also contributed towards 'Poor' speech privacy as low BN level equals to the lack of masking sound to help control the transmission of speech in the room.

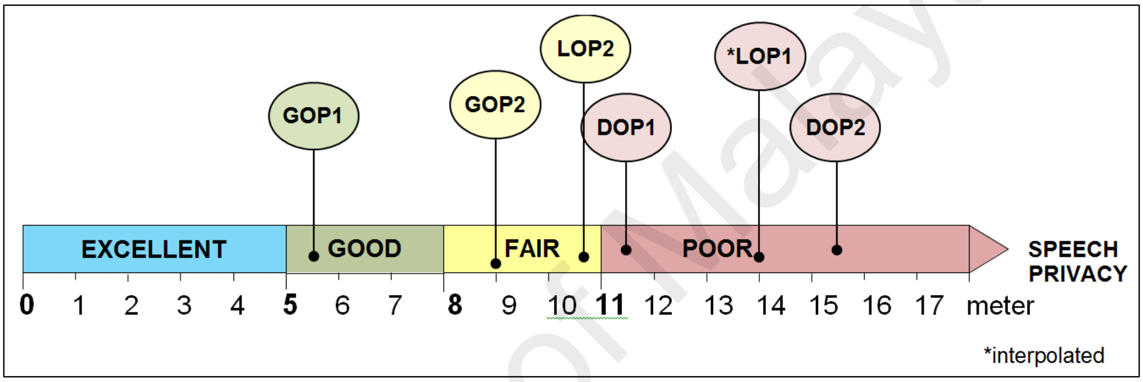


Figure 5.11: Distraction distance (r_D) of all measured open-plan offices

Referring to the major differences in r_D of open-plan offices in Diamond and GEO building, it can be determined that the similar ventilation system and its effect towards BN and NC level in the spaces did not have any significance in determining the level of privacy. This is because although the open-plan offices shared similar ventilation system and recorded similarly low BN levels, the level of privacy did not match; where GOP1 and GOP2 experienced slightly better speech privacy than DOP1 and DOP2 in Diamond building which recorded ‘Poor’ speech privacy as depicted in Figure 5.11.

Although, it should also be noted that the different effect on speech privacy might also be influenced by the difference in the *type of spaces*, *types and material choices of partitions*, and also *the configuration of open-plan office layouts*.

5.3 Summary

The chapter presented the data findings of field measurement work on the selected open-plan offices from the three green office buildings. Acoustic parameters such as background noise (BN) level, noise criteria (NC), reverberation time (RT), speech transmission index (STI), and distraction distance (rD) were measured in each open-plan offices. The quality of these acoustic parameters was verified by comparing them with presently available acoustic standards and recommendations from previous literature. This step in the research work should be able to respond to the first research objective which was to evaluate the acoustic performances in the open-plan offices. It was identified that the acoustic quality in open-plan offices in the three green office buildings was varied. Further discussions would be made in the discussion section in the final chapter.

Through the analysis of field measurement data and the data findings collected during the case study and observations, the effect of green design elements on respective acoustic parameters was deliberated. Theoretical cause and effects of design elements on acoustic parameters were itemised so that analysis can be done and design elements which gave the most impact on the acoustic quality can be identified.

CHAPTER 6: COMPUTER MODELLING AND VERIFICATION

This chapter would explicate the 3D modelling verification work and further summarise on the best model to be used in the acoustic simulation work for spatial configuration for acoustical design in selected open-plan offices.

6.1 Selection of Acoustical Simulation Tool

Selection of acoustical simulation tools was made by identifying the relevant room acoustic parameters to be measured for model verification as well as for the proposal of acoustically comfortable open-plan office design.

For model verification work, it was important that the chosen acoustic simulation software could simulate the same acoustic parameters that were measured during the field measurement. The parameters required to be simulated for model verifications were reverberation time (RT), speech transmission index (STI), and sound pressure level (SPL).

Meanwhile, for the proposal of acoustically comfortable open-plan office layouts, parameters that needed to be simulated were STI which was needed for the derivation of distraction distance (r_D), and SPL to derive the A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\,m}$) and the spatial decay rate of speech ($D_{2,S}$).

As absorption coefficient (α) is an important element in room acoustic, the chosen acoustic simulation tool should provide the prospect to cater for this element. The possibility to set and modify the absorption coefficient (α) was also a crucial characteristic of the selected simulation tool.

6.1.1 ODEON Room Acoustic Software

ODEON is a modelling software tool developed for room acoustical simulation for indoor acoustics. The simulation software was developed at the Department of Acoustic Technology in Technical University of Denmark in 1984 with significant involvement from a group of acoustics consultation companies concerned with having reliable prediction software for room acoustics. The first version of ODEON was developed to resolve acoustical issues specifically in concert and opera halls, and thus ODEON was named after an ancient Greek Odeon, Odeon of Herodes Atticus located in the Acropolis of Athens in 161 AD (ODEON, n.d.; Brüel & Kjær, 2009; Odeon of Herodes Atticus, n.d.).

ODEON's calculation algorithm is a hybrid reflection method which combines the image-source, ray-tracing, and ray-radiosity method together (Christensen & Koutsouris, 2013; Christensen & Rindel, 2005). ODEON is applicable not only for acoustically large spaces such as performance halls, churches, and auditoriums; but also for medium and small spaces like classrooms and open-plan offices. The current version of ODEON was upgraded to respond to the recently available ISO 3382-3 (2012), which is a standard measurement method outlined specifically for the acoustical measurement in open-plan offices (Christensen & Koutsouris, 2013).

3D models of rooms intended for acoustical prediction in ODEON can be modelled using the ODEON parametric modelling language or using ODEON's very own extrusion modeller. Alternatively, ODEON provided the capability of exporting room models from other more familiar 3D modelling tools such as AutoCAD or SketchUp (ODEON, n.d.).

ODEON also provides flexibility in term of sound sources and receivers input, and material choices to suit the need for specific room acoustical simulation. The material library database provides an extensive choice of materials. The materials were defined by the absorption coefficient (α) and the scattering coefficient. The material library is flexible in the sense of existing materials can be modified, and new materials can be added to the library database. Modifications to materials can be done through the adjustment of α by each frequency (Brüel & Kjær, 2009; Christensen & Koutsouris, 2013).

Results of the acoustic simulation may be retrieved visually or as tabulated data, which can be exported into another analysis tools for detailed analysis work. ODEON also provides the option of auralisation for the acoustical simulation results, which is a very convenient tool in presenting acoustic data to a layperson (ODEON, n.d.).

6.2 Computer Modelling and Verification

Before the actual acoustic simulation, it is crucial that the 3D models constructed for the acoustical prediction work to be verified. The verification process is one of the most critical steps in any research work. A verification process is defined as "the process of checking, conforming, making sure, and being certain." (Morse et al., 2002, p.17). Verification work ensures the 3D models constructed were comparable to the real-life conditions of the open-plan offices. In this study, verification process of the 3D models contributes immensely to the reliability and validity of the study henceforth.

In this research, the verification work of the 3D models was carried out by comparing selected acoustical parameters of RT, STI, and SPL; between the measured data taken from the field measurements with that of simulated data.

In finding a 3D model with the most distinct acoustical characteristics that match the real acoustic condition, several models with different level of geometric details were constructed and compared. This step is taken as a precautionary process to tackle the

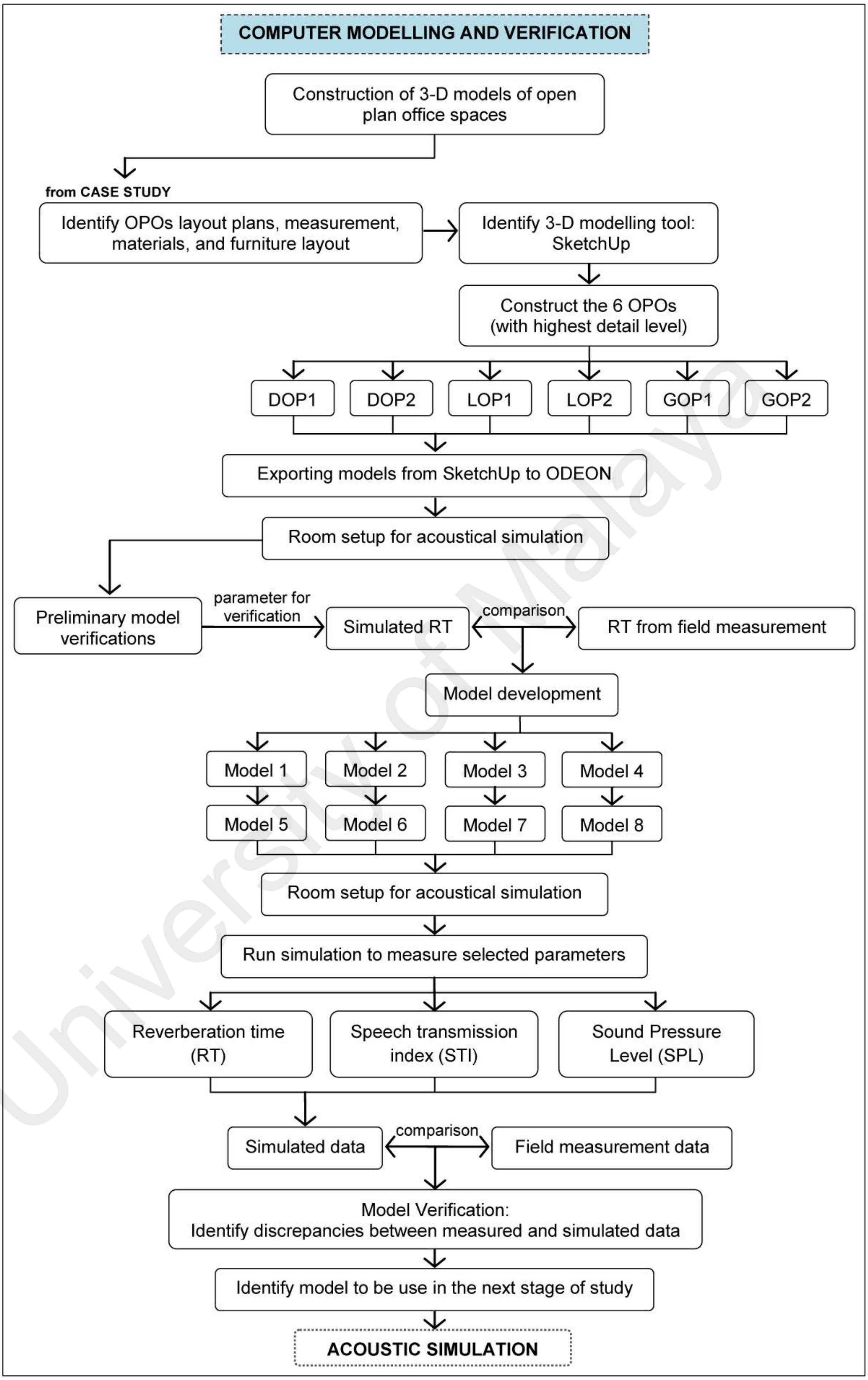


Figure 6.1: Computer modelling and verification workflow

discrepancies that might occur in ODEON. These discrepancies will be discussed in the subsection 'Computer Model Construction' below. The workflow for computer modelling and verification process is as depicted in Figure 6.1.

6.2.1 Computer Model Construction

3D model construction process began by observing the modelling 'guidelines' outlined by ODEON. ODEON recommended that the surfaces of the model should be built in large dimensions. The basic rule laid out was to keep the surface dimension approximately above 0.34 meters, which is larger than one wavelength at the mid-frequency (Christensen & Koutsouris, 2013). Although this might be possible and maybe even more practical for the construction of large spaces such as auditoriums and concert halls, it would be somewhat challenging to keep to the rule when constructing small spaces such as open-plan offices. Depending on the envelope design of the building and the purpose of the space, open-plan offices can be very irregular in geometry. Unlike auditoriums and concert halls, this irregularity may lead to uneven sound diffusion and with different furniture and office equipment settings, sound absorption dispenses unevenly on all surfaces in the room (Rindel & Christensen, 2007). On the other hand, Shiokawa and Rindel (2007) stated that a too simplified 3D model might not bear the correct acoustic behaviour of the space.

Due to these discrepancies of model detail level, the construction process of the models attempted at finding the most optimum model detail level. It is essential to have a sound model, which could characterise the real condition of the open-plan offices for further acoustic simulation work later on.

In defining a primary model for the comparison of model detail level, two models were constructed for each open-plan office. The first models (Model 1) were built as a detail imitation of the real open-plan offices, but still within the limitation of ODEON's recommended modelling mode; which is to have all surfaces be built in a single plane to represent the internal surfaces only. This is an essential point to be considered as the physical and geometrical depth of walls, and external surfaces of the planes do not bear any significance and purpose in ODEON's acoustical calculation algorithm. Moreover, the extra geometrical planes would only contribute to an unnecessary modelling setup and calculation time. It is also crucial to understand that the internal surfaces of the 3D models in ODEON are to be distinguished by the interchangeable absorption coefficient (α); which helps to virtually represent the depth of walls or any other materials in the room.

Meanwhile, the second models (Model 0) were constructed as the most basic models of each open-plan office. The walls, ceilings, and other surfaces were raised as planes with minimum consideration of the beams and columns intrusions and extrusions. Figure 6.2, 6.3, and 6.4 shows the constructed Model 1 and Model 0 for all six open-plan offices.

It should be noted that the 3D modelling work in this study was carried out using computer-modelling tool SketchUp. The software's simple interface and user-friendly attributes assisted in a quick modelling process. After the modelling work was done, the models were then exported into ODEON using a plugin option provided by ODEON.

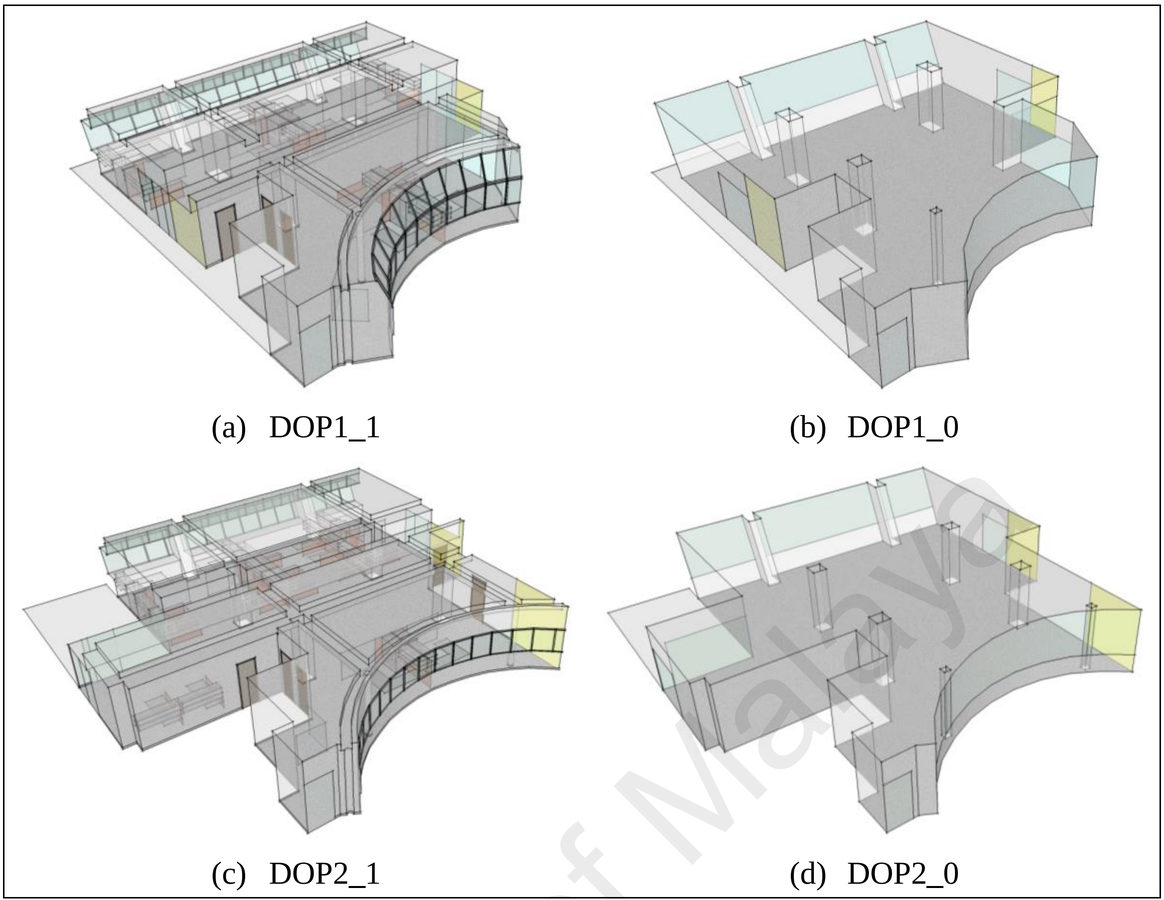


Figure 6.2: Model 1 and Model 0 of OPO in Diamond building

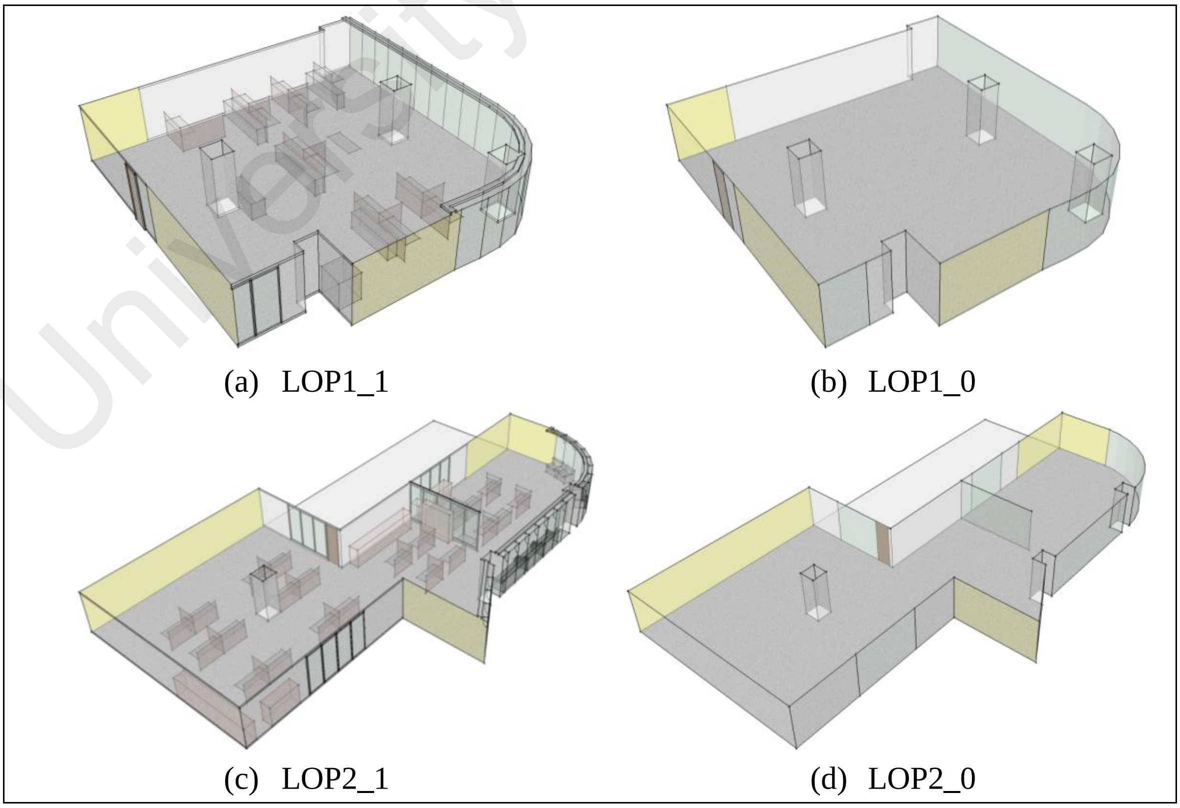


Figure 6.3: Model 1 and Model 0 of OPO in LEO building

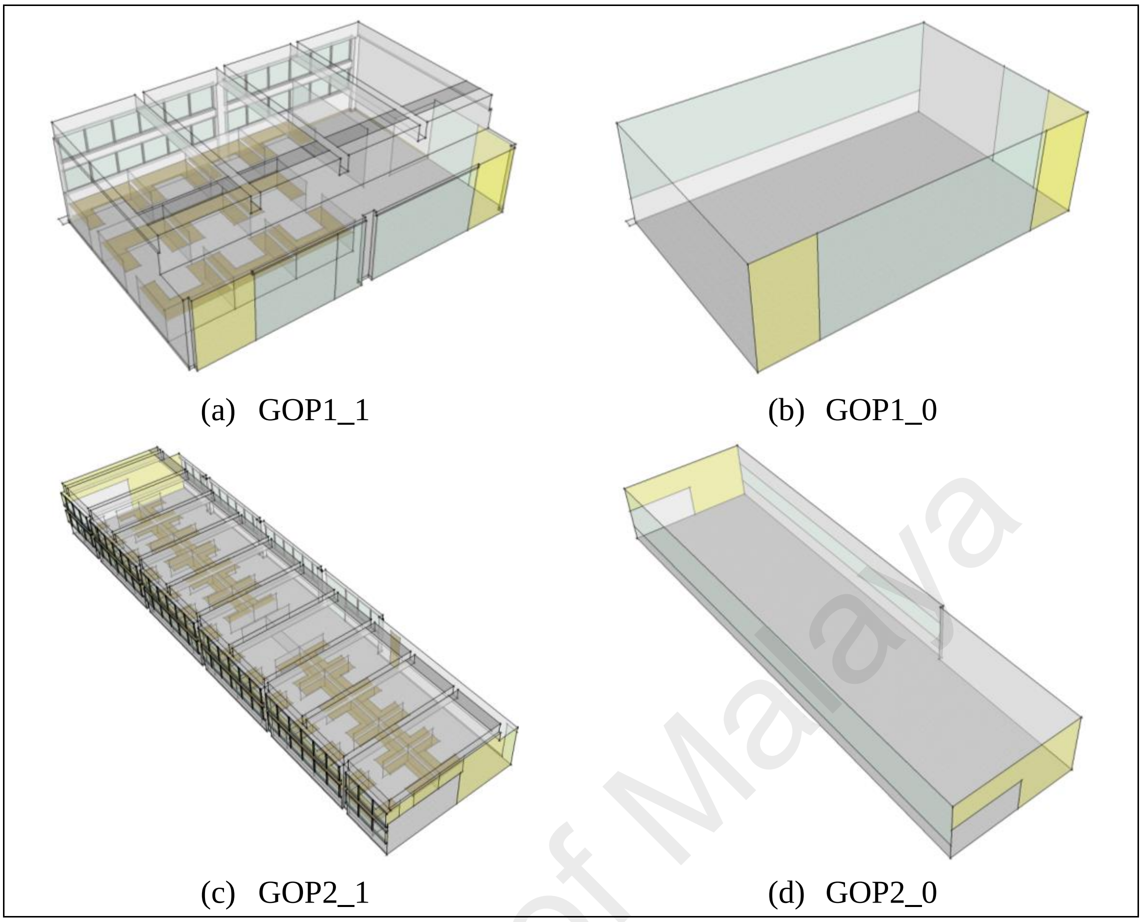


Figure 6.4: Model 1 and Model 0 of OPO in GEO building

6.2.2 Room Setup for Acoustical Simulation

Room setup work essentially began during the model construction stage in SketchUp, before exporting the 3D models to ODEON. Figure 6.5 below summarises the process of room setup in ODEON from the exporting process until the models are ready for the measurement work.

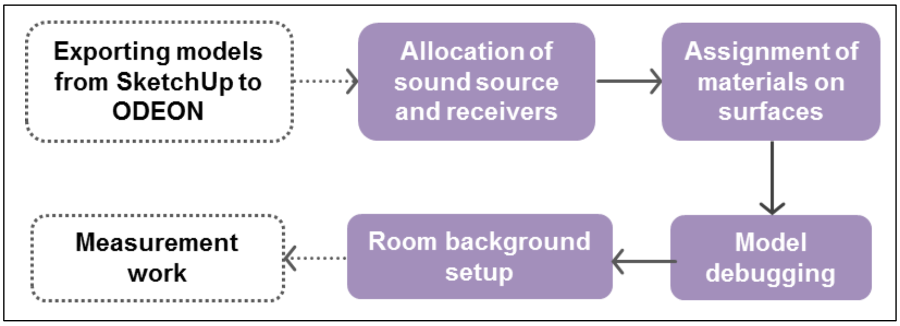


Figure 6.5: Room setup processes

(a) ***Allocation of sound sources (SS) and receivers***

During the model construction stage, two crucial modelling details were considered. The first one was the setting out of the models, and the second one was the surface layering. The setting out of the models was an essential step in facilitating the initial phase in the room setup process, which would be the allocation of the sound sources and receivers. During the 3D model construction phase in SketchUp, all the models were set out at ‘point zero’ at the visible X-Y-Z axes shown in SketchUp. This setting out was done to ensure the allocation of sound sources and receivers in ODEON were similar to that in the field measurement settings.

For model verification, sound sources and receivers were allocated similarly to the positions established during the field measurement according to respective open-plan offices. The positioning of the sound sources and receiver points were measured from the setting out point, and the height of each point was set out at 1.2 meters to match the height established during the field measurement. Figure 6.6 illustrates the positions of sound sources and receivers in all six open-plan offices in ODEON model interface.

The sound source type used for the simulation work was also fixed to match the sound source utilised during the field measurement. The sound source used in ODEON was an omnidirectional sound source with the frequency input total power of 75.4 dB(A) to match the sound power during the field measurement.

On the other hand, sound receivers used in ODEON were omnidirectional receivers which matched the characteristics of the SLM’s ½-inch microphone used during field measurement.

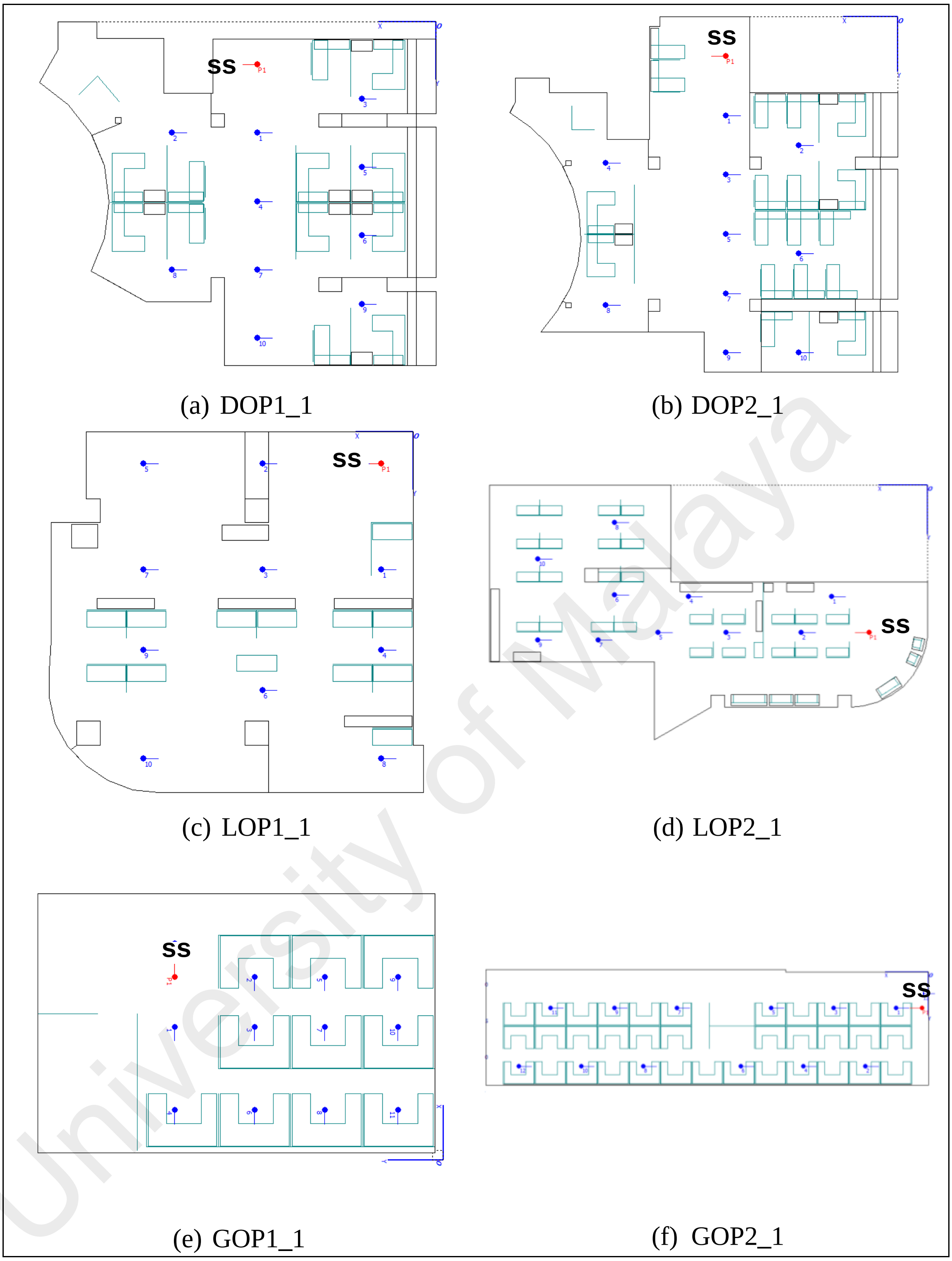


Figure 6.6: Position of SS and receivers in all OPO Model 1 in ODEON

(b) *Assignment of materials on model surfaces*

After the allocation of sound sources and receivers were done, the next step was the assignment of materials on the surfaces of the models. For this stage, it was crucial that the surface layering was done during the 3D model construction work in SketchUp.

Surface layering basically means to group surfaces with similar attributes such as materials, finishes, and absorption coefficient (α); into the same “Layer”.

During the 3D model construction work, all surfaces in the open-plan office models were identified and “layered” into their respectively Layers. The surfaces layering processes were done in two-step characteristics identification. The first step is to identify which component group the surface belongs to. For instance, all vertical perimeter surfaces would generally be classified as the component ‘Wall’. The second step is to identify the finishing materials of the surfaces in the component group ‘Wall’. The surfaces with ‘plaster and paint’ finishes would be grouped in a layer coded as ‘Wall_PP’ and surfaces made of ‘glass’ will be group into another layer called ‘Wall_G’. Furthermore, when surfaces have the same component characteristics and finishes but dissimilar in details which affect the absorption coefficient (α), the surfaces would be layered separately.

Besides easing up on the material assignment procedure in ODEON, surface layering work during 3D model construction stage was an important step to ensure all surfaces would be assigned with a material and a correct one at that. It was an essential step in the Room Setup process as the acoustical simulation algorithm in ODEON would be ineffective even if merely one surface was not assigned with any material.

Since it was impossible to obtain the absorption coefficient (α) for every single material in the six open-plan offices, the material assignment work was done using the list of materials available in ODEON material library. The type of materials of surfaces in the open-plan offices was identified during the case study stage and similar or equivalent material from the material library was assigned to each of the surfaces. Few uncommon surfaces were experimented through several trials of material assignment to ensure the material assigned is closest to the materials’ absorption properties on site.

Materials that were not readily available in ODEON material library were imported from other reliable sources such as Maekawa et al. (2011). As for surfaces built to represent the void area which connects the spaces to nearby spaces or corridors, the surfaces were assigned with a '100% absorption' material which was available in the material library. The complete list of materials assigned and its absorption coefficient (α) for all the open-plan offices are as listed in Appendix G.

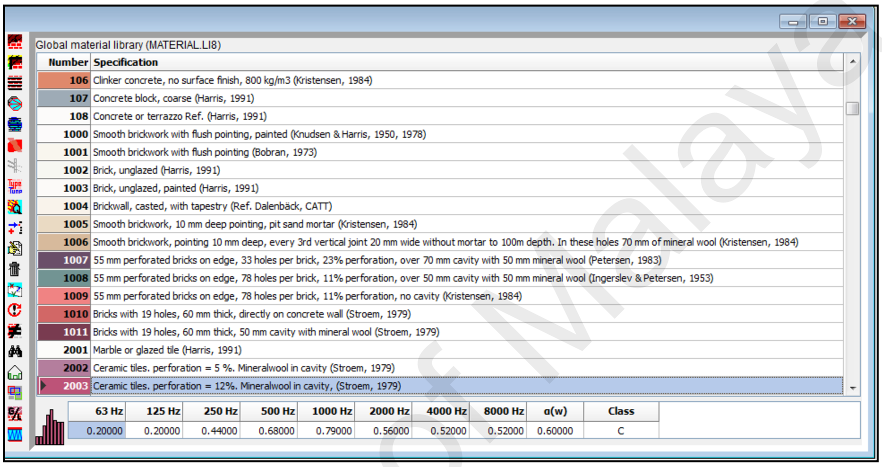


Figure 6.7: Interface of material list in ODEON material library

In addition, each surface of materials was assigned with a scattering coefficient of 0.05 at 707 Hz, which is a default scattering setting in ODEON material library. Furthermore, the Lambert scattering method is applied in this simulation and this scattering coefficient accounts for the roughness of the material at the mid-frequencies around 700 Hz. It was expanded during calculations in order to take into account the reflection based scattering method by frequency dependent behaviour of scattering occurred due to the geometrical properties such as the surface sizes, path lengths, and angle of incidence (Christensen & Koutsouris, 2013). It should be noted that the application of scattering coefficient might influence the outcome of acoustical simulation, especially of models with lower level of geometric detail (Wang, Rathsam, & Ryherd, 2004). The same case can also be said for auralization results (Pelzer & Vorländer, 2010), however, due to insufficient databases on specific in-situ materials, the scattering coefficient of each material surface was assigned with ODEON's default settings for simplification purpose.

(c) ***Model debugging***

After the assignment of materials was done, it was essential to debug the 3D models for any errors such as missing or misplaced surfaces, as well as to check for any leaks in the 3D models. This process is to avoid any missing rays during the acoustical simulation. This process was usually referred to as the 'water tightness test'. Model debugging was carried out using the 3D Investigation Rays or 3D Billard tool available in ODEON. These tools primarily visualise the ray tracing process of the acoustic simulation and demonstrate the effects of scattering flutter echoes or coupling effects that happen during the simulation work (Christensen & Koutsouris, 2013).

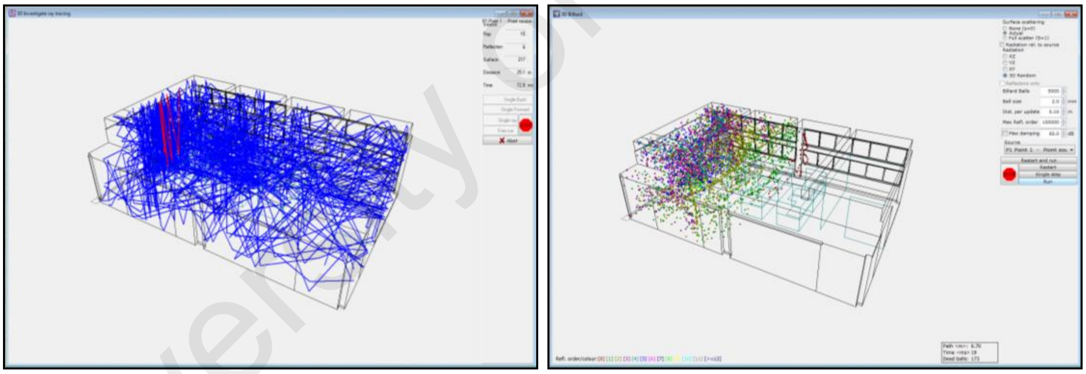


Figure 6.8: Model debugging process using 3D Investigation Ray and 3D Billard tools in ODEON

(d) ***Room background setup***

ODEON required that the impulse response length not to be lower than 2/3 of the longest estimated reverberation time (RT). To determine the most optimum impulse response length, quick estimates were done for all the open-plan office models to obtain the estimated RT. Through the results of estimated RT retrieved from the Quick

Estimate tool found in the material library, it was determined that the most optimum impulse response length to be utilised for all models was 2000 ms.

Table 6.1: Background noise (BN) octave band frequency input in room setup

OPO	Frequency, Hz								Total level, dB(A)
	63	125	250	500	1000	2000	4000	8000	
DOP1	43.1	36.4	31.9	25.4	23.3	18.4	18.7	21.5	30.1
DOP2	47.7	41.5	39.5	36.0	29.3	25.3	21.6	21.3	37.1
LOP1	43.8	38.0	34.5	35.1	32.3	29.4	25.4	22.5	37.4
LOP2	41.1	37.0	30.4	27.2	27.7	21.7	20.0	21.5	31.9
GOP1	43.3	41.0	36.6	32.6	33.3	25.9	20.4	21.3	36.7
GOP2	39.2	39.2	36.0	31.7	29.2	26.7	24.1	21.7	35.2

Background noise (BN) is a crucial parameter in defining the speech transmission index (STI) in any acoustical room measurement or prediction. Thus, to ensure the simulation work can calculate the STI, the BN must be input in the background setup. The BN level keyed in each open-plan offices was imported from the BN data obtained during the field measurement. The averaged octave band frequency from 63 Hz to 8000 Hz recorded from selected points during the field measurement was entered into the room setup. Table 6.1 shows the background noise input in octave band frequency for all six open-plan offices and the total dB(A) level.

6.2.3 Preliminary 3D Model Verification

Preliminary verification of the open-plan office models was done to ensure that the models were acceptable for the usage of acoustical prediction and that it would represent the actual condition of the open-plan offices. Through the preliminary verification results, it can determine the next step that needs to be taken to improve the computer model so that it would portray the acoustical characteristics of the real open-plan offices precisely.

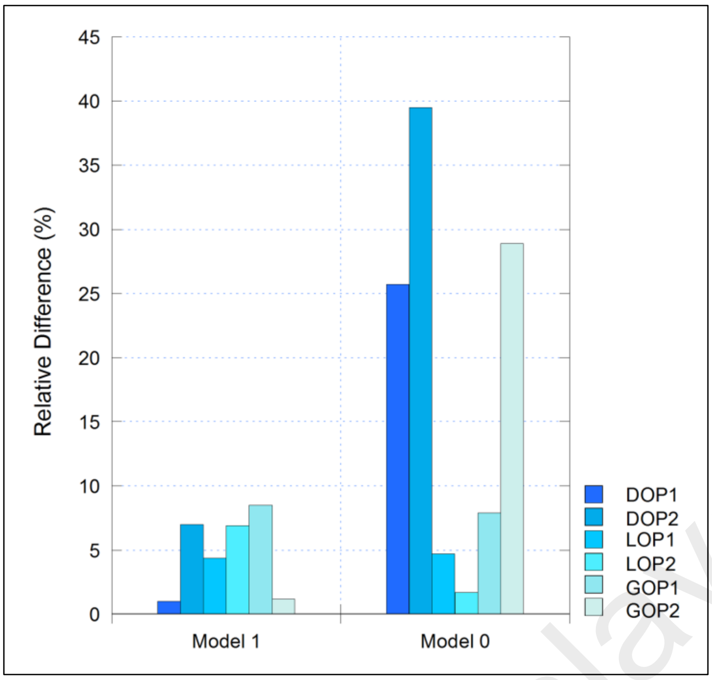


Figure 6.9: Comparison of relative difference between all OPO in Model 0 and 1

Preliminary verification was done using simulated reverberation time (RT) obtained from a quick run-through simulation work on all six open-plan offices. To determine if the open-plan office models were acceptable, the result of simulated RT would be compared to their respective measured RT. ODEON recommended that the subjective limen for RT to be below 5% in relative difference (Christensen & Koutsouris, 2013). However, Hodgson (1996) and Bistafa and Bradley (2000) stated that 10% would be a more practical maximum relative difference for engineering type accuracy for RT. The relative differences were calculated by comparing the mid-frequency RT (mean RT from 500 Hz to 2000 Hz) of measured RT value to that of the simulated ones.

It should be noted that the simulation of RT for all models was done based on the T_{30} calculation done during the field measurement. Figure 6.9 shows the relative difference between all six open-plan offices in their respective Model 0 and Model 1. Based on the results, it can be seen that Model 1 was the more effective model between the two. Even though Model 0 of LOP1, LOP2, and GOP1 recorded small relative differences, and furthermore below the recommended 10% limit, deduction as a group would determine Model 1 as the more reliable model.

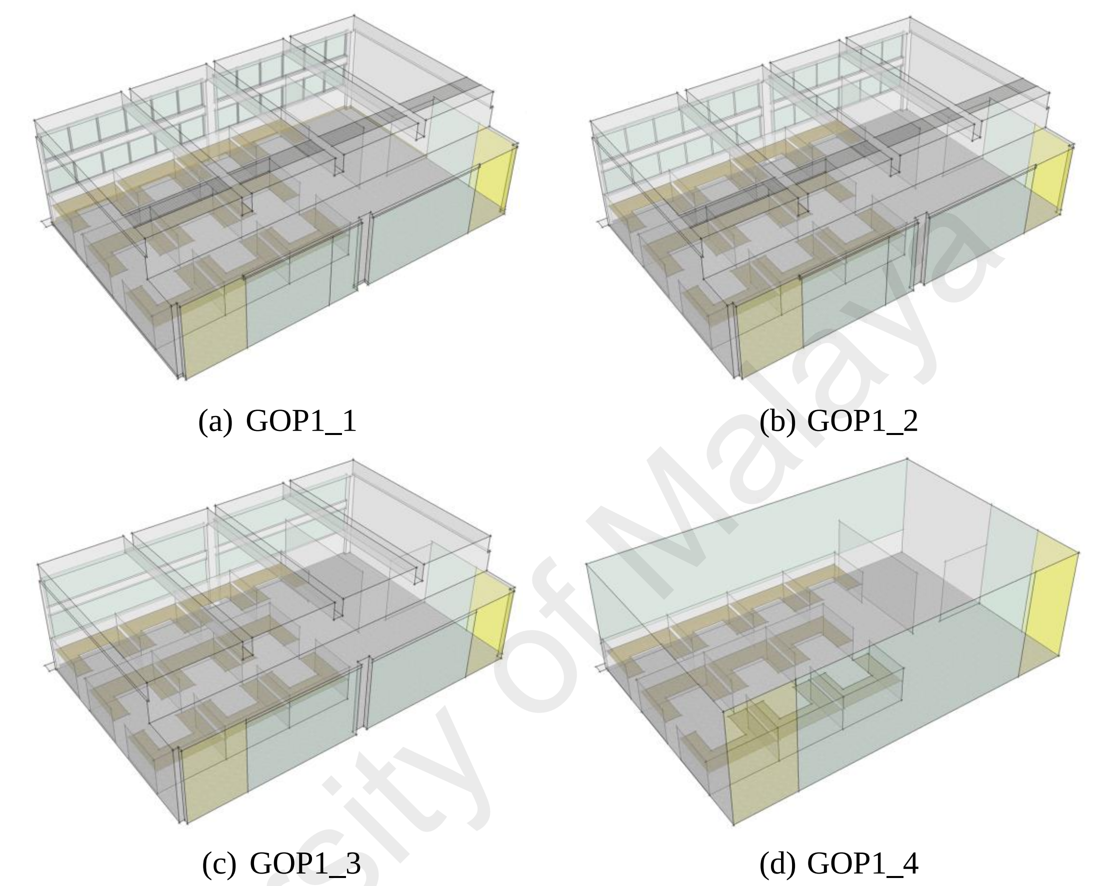
6.2.4 3D Model Development

It was mentioned earlier that ODEON recommended that the surfaces of the model should be built in large dimension, approximately above 0.34 meters (Christensen & Koutsouris, 2013). However, Model 1 of all the open-plan offices evidently contained some small surfaces, and yet the models presented acceptable and more accurate results of being comparable to the real room condition.

Nevertheless, to find the most optimum model detail level that could represent the real room condition, two other models shall be developed. The models would be developed through the deconstruction process of Model 1. Model 1 shall be used as the primary model to define the changes in detail level. The discrepancies of the model detail level would be determined by three acoustical parameters which are RT, STI, and SPL.

Using Model 1 as a basis, two additional models of different detail level were constructed. Since Model 1 was constructed in the most detail imitation of the open-plan offices' geometry, the additional models were fabricated by gradually reducing the detailing of surfaces in Model 1, particularly the surfaces which represents the structure of the room and the building components, specifically the door and window details. However, respective furniture layouts of each open-plan office would stay identical. This is to ensure that any changes occurred in the acoustic parameters data collected would be a direct result of the changes in the room structure and components and not because of the furniture layouts.

To simplify the explanation of the model development process, only GOP1 models would be illustrated in this section as a reference. Figures of other open-plan offices are listed in Appendix H.



(a) GOP1_1

(b) GOP1_2

(c) GOP1_3

(d) GOP1_4

Figure 6.10: Model 1, 2, 3, and 4 of GOP1

Figure 6.10 shows the two additional GOP1 models which were derived from the geometry simplification of Model 1 as discussed earlier. It should be noted that Model 4 (GOP1_4) as shown in Figure 6.10 is the same model as Model 0 used during the preliminary model verification stage. However, at this juncture, the model was embedded with the standardised furniture layout as other GOP1 models. This was to determine the significance of furniture layout in the simulation process and to see if basic model envelopes could work well with the addition of furniture layout.

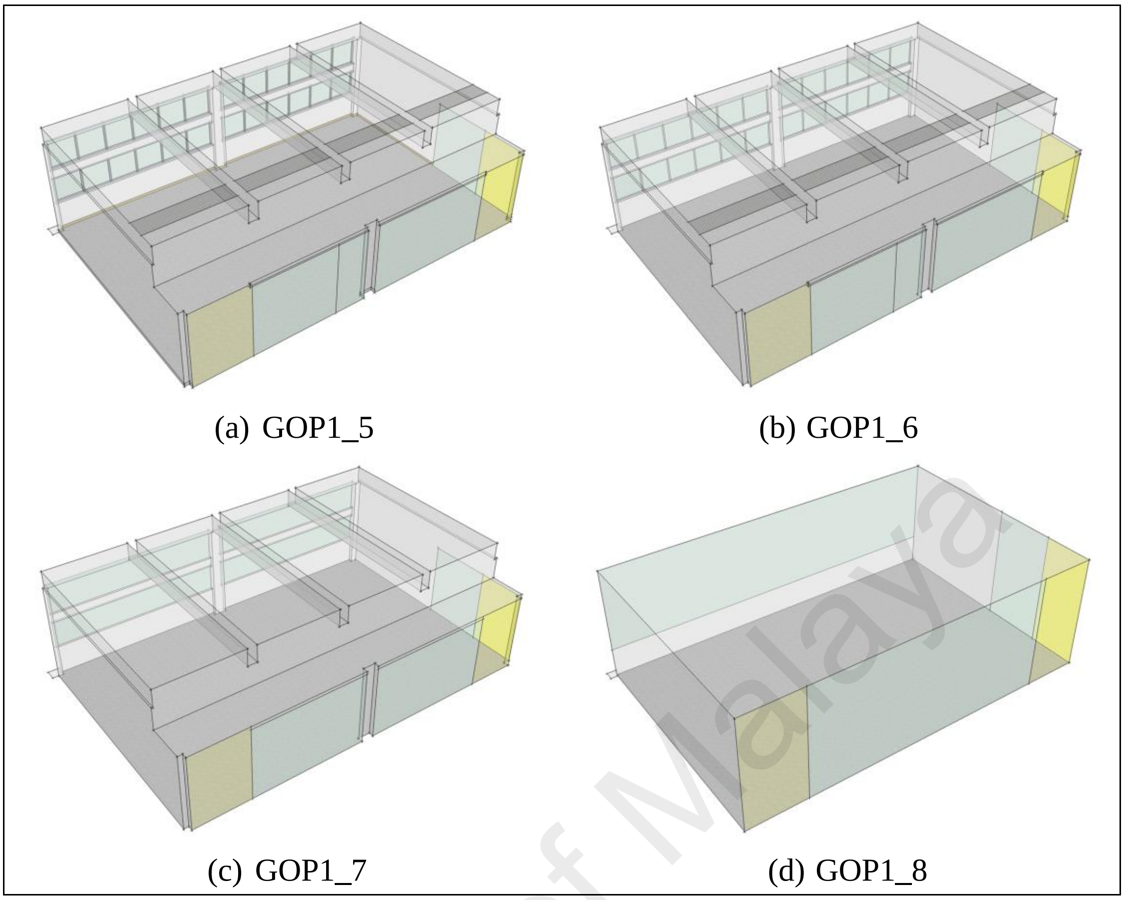


Figure 6.11: Duplicate of Model 1, 2, 3, and 4 of GOP1 without furniture layout

At this point forward, Model 1 would continue to be identified as Model 1, and the other three models would be identified as Model 2, Model 3, and Model 4. For comparison, duplicates of Model 1, 2, 3, and 4 without furniture layout would also be simulated. These duplicates would be identified as Model 5, Model 6, Model 7, and Model 8 respectively as shown in Figure 6.11. It should be noted that Model 8 in this stage of the study was, in fact, the same model as Model 0 in the preliminary model verification stage.

As the number of surfaces for each open-plan office varied according to its building design complexity and features, controlling the surface reduction precisely throughout the six open-plan offices would be impossible. Hence, the surface reduction control was done using percentage range. This is to ensure that the reduction for all models from different open-plan offices to be within the same relative range for fair comparisons.

Table 6.2: The percentage range of the number of surfaces in Model 1, 2, 3, and 4 in all OPO

OPO	Model	1	2	3	4
	Percentage Range	**100%**	**40 – 60%**	**20 – 39.9 %**	**0 – 19.9%**
DOP1	No. of surfaces	637	305	249	65
	% range	100	47.9	39.1	10.2
DOP2	No. of surfaces	623	295	245	81
	% range	100	47.4	39.3	13.0
LOP1	No. of surfaces	137	72	50	28
	% range	100	52.6	36.5	20.4
LOP2	No. of surfaces	216	116	77	40
	% range	100	53.7	35.6	18.5
GOP1	No. of surfaces	210	96	59	12
	% range	100	45.7	28.1	5.7
GOP2	No. of surfaces	595	238	146	13
	% range	100	40.0	24.5	2.2

Table 6.2 shows the number of surfaces for all open-plan offices and the controlled range of surface reduction. However, it should be noted that the number of surfaces recorded does not include the number of surfaces from the furniture layout as the furniture layouts embedded into all models for each respective open-plan office were constant.

6.3 3D Model Verification

Verifications and comparisons of all the models with different geometrical details were carried out by analysing three acoustical parameters namely reverberation time (RT), speech transmission index (STI), and sound pressure level (SPL). The recorded differences of each parameter were obtained through the comparison of field measurement data and the simulated data, in their respective subjective limen or JND (just noticeable differences). The collective comparison results would assist in defining the best models to be used in the next stage of this study.

6.3.1 Reverberation Time (RT)

As discussed earlier in Chapter Three, the JND for reverberation time (RT) should be measured by its relative difference. Christensen and Koutsouris (2013) in ODEON

Room Acoustic Software User Manual Version 12 stated that the recommended subjective limen for RT should be below 5% of relative differences. However, 10% differences were viewed as a more practical maximum relative difference for engineering type accuracy (Hodgson, 1996; Bistafa & Bradley, 2000). Figure 6.12 shows the relative difference between the measured and simulated RT (mean of 500 Hz to 2000 Hz frequency) for all open-plan offices in Model 1 until Model 8.

In general, it can be observed that Model 5, 6, 7, and 8 of most of the open-plan offices exceeded the maximum relative difference of 10% applied in this study. However, it should be noted that all LOP1 models recorded low relative differences of RT comparison. The same case can be observed for all LOP2 models, except for Model 6 which recorded a slightly higher relative difference of 12.5%.

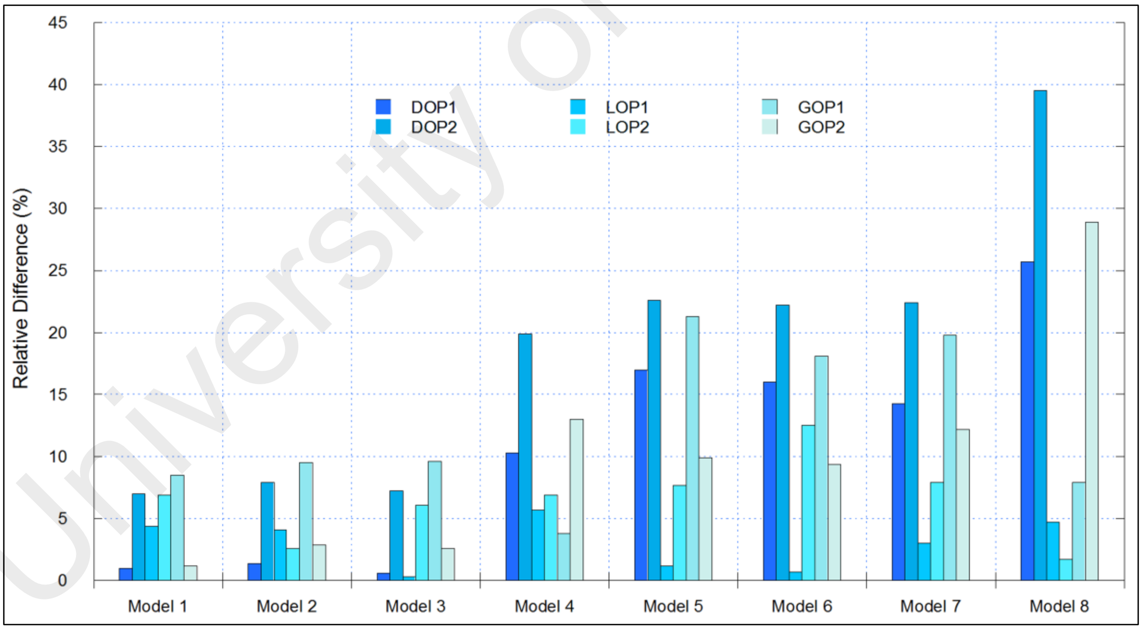


Figure 6.12: Comparisons of relative difference between all OPO in all models

Even though Model 4 contained furniture layout as per Model 1, 2, and 3; the relative difference of RT recorded for Model 4 of DOP2 and GOP2 still exceeded the maximum tolerance with each respectively logged 19.9% and 13% relative differences. On the other hand, Model 1, 2, and 3 for all open-plan offices recorded agreeable RT relative difference of below 10%.

6.3.2 Speech Transmission Index (STI)

Speech transmission index (STI) is one of the key parameters used for the assessment of the acoustical performance in open-plan offices. STI data simulated from selected points were utilised for comparison with the STI data collected during the field measurement. The comparison between the measured and simulated STI for all models from all six open-plan offices are presented in Figure 6.2. The *x*-axis from each graph represents the receiver points for its respective open-plan offices, and the *y*-axis represents the STI value from the minimum value of 0 to the maximum value of 1. The receiver points in the *x*-axis were arranged according to distance, with the first point being the nearest and the last point being the furthest away from the sound source (SS). The simulated STI from selected receiver points were compared directly with the measured STI data of the same receiver point.

From Figure 6.13 it can be seen that the plot-patterns of STI data from all open-plan offices showed a promising comparison. The simulated STI data plotted from respective receiver points seemed to relatively match the measured STI data. Also, it should be noted that the results of simulated STI for Model 1, 2, 3, and 4 (with furniture) were closer to the measured STI compared to the simulated STI results of Model 5, 6, 7, and 8 (without furniture). Even though the plot-patterns showed encouraging results, the discrepancies in STI values should not be dismissed. This is especially crucial when LOP2 results show a significant gap in STI value despite the relatively similar plot-pattern recorded from the simulation data.

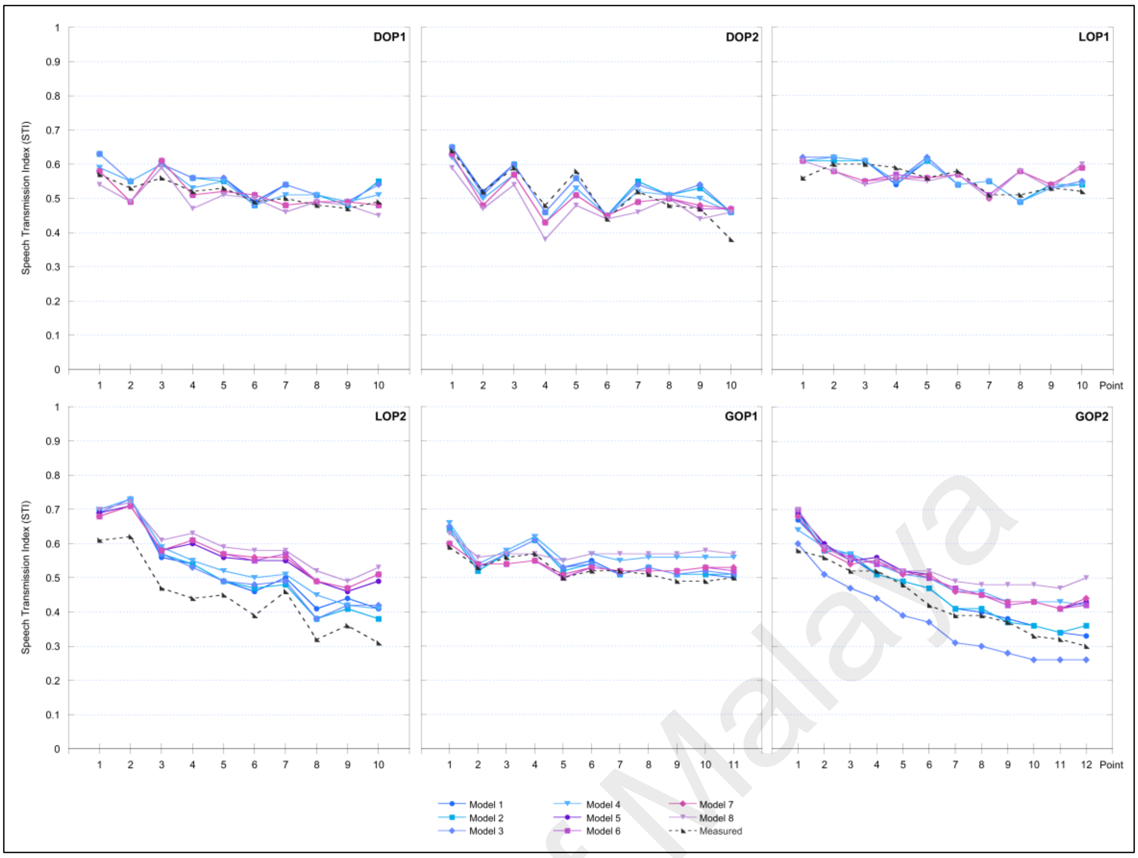


Figure 6.13: Comparison between measured and simulated STI data for all OPO

While the comparison of RT was made using relative difference, the appropriate way to compare STI value is through its own JND. ODEON (Christensen & Koutsouris, 2013) recommended that the JND for STI be equal to a 0.03 absolute difference in STI value. Wang et al. (2014) coined 0.03 absolute differences in STI value, which is the smallest detectable difference; as 1JND. Bradley, Reich, and Norcross (1999) on the other hand said that a 0.03 change in STI would be imperceptible. They also added that any changes in STI value which is smaller than 0.1 would not be too noticeable.

Table 6.3: The comparison of min, max, and average JND value between measured and simulated STI for all OPO

(white)	1JND (0.00 – 0.03)
(lightest blue)	2JND (0.031 – 0.06)
(light blue)	3JND (0.061 – 0.09)
(medium blue)	4JND (0.091 – 0.12)
(dark blue)	> 4JND (> 0.12)

Model	**DOP1**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Max	0.06	0.06	0.06	0.04	0.05	0.05	0.05	0.05
Ave	0.03	0.03	0.03	0.02	0.02	0.02	0.02	0.03
Model	**DOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.00	0.01	0.01	0.00	0.01	0.00	0.01	0.00
Max	0.08	0.08	0.08	0.08	0.09	0.09	0.09	0.10
Ave	0.03	0.03	0.03	0.03	0.04	0.03	0.04	0.05
Model	**LOP1**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
Max	0.05	0.05	0.06	0.05	0.07	0.07	0.07	0.08
Ave	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Model	**LOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.04	0.02	0.03	0.05	0.08	0.07	0.07	0.09
Max	0.11	0.11	0.11	0.13	0.18	0.20	0.20	0.22
Ave	0.08	0.07	0.08	0.10	0.13	0.13	0.13	0.15
Model	**GOP1**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.00	0.01	0.00	0.01	0.00	0.00	0.00	0.00
Max	0.06	0.05	0.06	0.07	0.04	0.04	0.04	0.09
Ave	0.02	0.02	0.02	0.05	0.02	0.02	0.02	0.05
Model	**GOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.01	0.00	0.02	0.02	0.03	0.02	0.02	0.03
Max	0.09	0.11	0.09	0.12	0.13	0.12	0.14	0.20
Ave	0.03	0.03	0.06	0.07	0.07	0.07	0.07	0.10

Table 6.3 shows the minimum, maximum, and the average of absolute differences between the measured and simulated STI from each respective point from all models in all the open-plan offices. The JND of STI value from all models in DOP1, DOP2, LOP1, and GOP1 recorded satisfying results of having not more than 4JND (≤ 0.12).

The highest difference detected within the four open-plan offices was from Model 8 of DOP2 which recorded a 0.10 maximum absolute difference; which still roamed within the acceptable range of JND (Bradley et al., 1999).

Meanwhile, LOP2 and GOP2 recorded maximum JND of more than 4JND in Model 5, 6, 7, and 8. On the other hand, maximum JND value in Model 1, 2, 3, and 4 of LOP2 and GOP2 were recorded around 3JND to 4JND which was between 0.09 to 0.12 absolute differences, except for Model 4 of LOP2 which recorded an absolute difference of 0.13 in STI value.

6.3.3 Sound Pressure Level (SPL)

Similarly to the comparison made for STI, comparison of spatial decay in sound pressure level (SPL) was presented by plotting the measured and simulated SPL together. The comparison of SPL decay is illustrated in Figure 6.3. The *x*-axis represents the receiver points in which the measurement was taken, and the *y*-axis represents the SPL in dB(A) taken at the said point.

As seen in Figure 6.14, the comparisons of SPL through the plot-pattern for DOP1, DOP2, LOP2, and GOP2 showed encouraging results. The decay curve of simulated SPL data showed similar tendencies as the measured SPL. Meanwhile, the plot-patterns for LOP1 and GOP1 showed quite a disagreement as the measured SPL data resulted in random fluctuation at some receiver points.

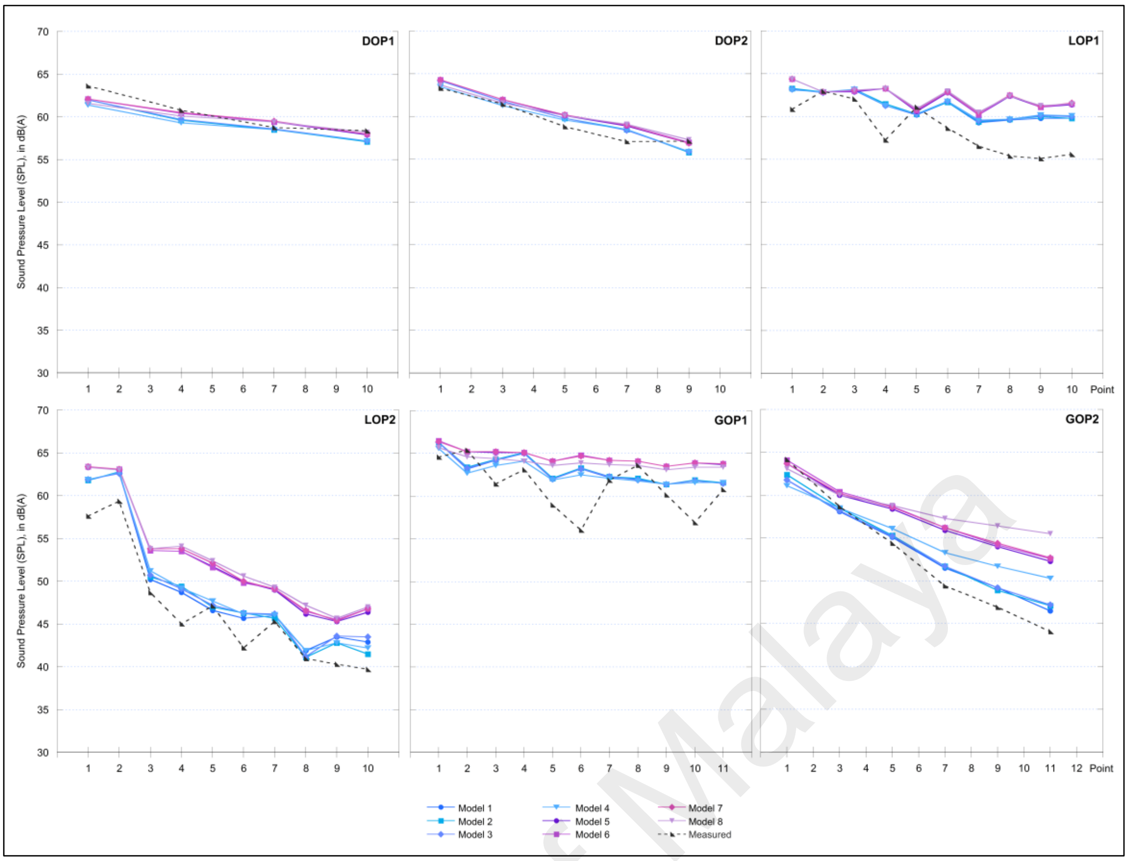


Figure 6.14: Comparison of measured and simulated decay of SPL data for all OPO

Using 3 dB(A) of absolute difference as the JND for SPL comparison (Wang & Vigeant, 2004), Table 6.4 shows the minimum, maximum, average, and the standard deviation of the differences between measured and simulated SPL data for all open-plan offices. DOP1 and DOP2 showed good results as the differences in SPL data do not exceed 3 dB(A) in all models. On the other hand, LOP1, LOP2, GOP2, and GOP2 showed relatively agreeable results. While most of the maximum JND recorded exceed the bound of 3 dB(A), Model 1, 2, 3, and 4 of LOP1 and LOP2 did not go further than 6 dB(A) differences. However, some models in GOP1 and GOP2 recorded quite excessive differences between the measured and simulated SPL data.

Table 6.4: The comparison of min, max, average, and standard deviation difference value between the measured and simulated SPL data for all OPO

0 - 3 dB(A)
3.01 - 6 dB(A)
6.01 - 9 dB(A)
9.01 - 12 dB(A)
> 12 dB(A)

Model	DOP1							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.26	0.26	0.16	0.26	0.38	0.38	0.28	0.18
Max	1.63	1.63	1.63	2.23	1.53	1.53	1.53	2.03
Ave	1.09	1.09	1.01	1.29	0.76	0.73	0.73	0.88
STD	0.58	0.58	0.62	0.82	0.53	0.55	0.57	0.8
Model	**DOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.35	0.35	0.35	0.15	0.23	0.13	0.23	0.15
Max	1.42	1.42	1.32	1.42	1.82	1.92	1.92	2.02
Ave	0.99	0.99	0.95	0.75	0.97	0.99	1.01	0.80
STD	0.43	0.43	0.38	0.59	0.62	0.70	0.67	0.82
Model	**LOP1**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.08	0.08	0.18	0.08	0.08	0.08	0.08	0.08
Max	4.69	4.89	4.99	5.09	6.99	7.09	7.09	6.99
Ave	2.73	2.80	2.83	2.84	3.76	3.79	3.83	3.83
STD	1.61	1.67	1.67	1.72	2.53	2.56	2.58	2.59
Model	**LOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.52	0.12	0.08	0.58	3.68	3.75	3.75	3.65
Max	4.18	4.38	4.28	4.28	8.48	8.48	8.78	9.08
Ave	2.48	2.29	2.60	2.56	5.57	5.66	5.78	6.01
STD	1.39	1.70	1.66	1.41	1.59	1.60	1.65	1.77
Model	**GOP1**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.35	0.45	0.45	0.25	0.18	0.18	0.18	0.02
Max	7.15	7.25	7.15	6.45	8.75	8.75	8.65	7.85
Ave	2.53	2.54	2.51	2.28	3.42	3.44	3.43	2.93
STD	1.97	2.00	1.96	1.86	2.63	2.62	2.61	2.47
Model	**GOP2**							
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Min	0.58	0.18	0.48	0.18	0.49	0.09	0.49	1.09
Max	2.44	3.04	3.14	6.24	8.24	8.54	8.64	11.44
Ave	1.75	1.70	1.90	3.31	4.60	4.79	4.85	5.94
STD	0.86	1.01	1.03	2.17	3.19	3.34	3.33	4.33

6.4 Summary

Throughout the comparison and simulation process, few crucial details were observed. One of the main observations was regarding the crucial role of absorption coefficient (α) in the whole modelling and simulation process. It was found that the application of absorption coefficient (α) on model's surfaces contributed a significant influence towards the result of reverberation time (RT). Small changes of α in any materials, especially in materials with a large surface area could affect the RT results tremendously. This explained the substantial variances in RT relative difference between Model 1 to 4 and Model 5 to 8. With the addition of furniture layout in the models, the RT improved considerably. It is safe to say that the sound energy absorbed by the furniture also contributes towards achieving good RT results in open-plan offices.

Meanwhile, it was observed that the input of background noise (BN) level was essential for the simulation of speech transmission index (STI). Without the input of BN level, reliable STI simulation would be impossible. However, it should be noted that while Model 1 to 4 contained furniture layouts and Model 5 to 8 did not, the plot-patterns of simulated STI and SPL did not fluctuate too significantly between the two groups. However, noticeable change in value can be seen especially in the spatial decay of SPL. It was also observed that the simulated SPL in Model 1 to 4 (with furniture) decay more accurately with the decay patterns of measured SPL.

In term of model detail level, it was observed that Model 1, 2, and 3 bear satisfactory simulated results when compared to their respective measured data. Concerning the findings in this work, it was found that model simplification by up to 80% reduction in the number of surfaces was acceptable. To summarise, it was determined that Model 1, 2, or 3 were acceptable to be used in the next stage of this research. However, it should be noted that Model 1 for all open-plan offices was used as the "backdrop" for the spatial layout design experiment and configuration for acoustic design in the next stage.

CHAPTER 7: SIMULATION FINDINGS AND ANALYSIS

The chapter would present, discuss, and analyse the data findings of experimental simulation work of spatial configuration for acoustical design in the four open-plan offices as discussed in the methodology chapter.

7.1 Acoustic Simulation Data Findings

As stated previously, the effect of experimental open-plan office layouts using the five design variables would be analysed on the four selected acoustic parameters namely STI (in the nearest workstation), distraction distance (r_D), A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\,m}$), and spatial decay rate of speech ($D_{2,S}$).

The study of STI relates closely to the measure of occupants' work performances. Studies done by Hongisto (2005) predicted the effect of STI on work performances and concluded that STI level in an office environment should fall below STI level of 0.5 which is right in the middle of the scale. The conclusion was found based on the findings that work performance would be highly affected when the speech intelligibility in the room is more than STI 0.6. However, any changes in STI below the 0.2 would not give any significant effect on occupants' work performance. Even though STI values could be interpreted into the scale of speech privacy (See Table 2.6), Andersson & Chigot (2004) argued that the usage of STI to describe speech privacy is not adequate.

On the other hand, the determination of distraction distance (r_D) relates directly to the measurement of STI. STI values recorded should function as a measure of distance so that the single number quantity namely distraction distance (r_D) could be acquired. The limit of 0.5 STI as a benchmark for non-distracting speech intelligibility in an office is used to define the r_D.

ISO 3382-3 (2012) identifies r_D as one of the parameters that need to be measured in order to analyse the acoustic condition of open-plan offices. As open-plan offices focused on speech privacy, the target value for r_D is categorised in term of speech privacy. Table 7.1 shows the target value classification for r_D as specified in the standard. ISO 3382-3 (2012) specified that to provide an office with good speech privacy, the value for r_D should be ≤ 5 meters. Conversely, office with r_D value of above 10 meters would be considered as having a poor acoustic condition.

ISO 3382-3 (2012) also provided the target values for another two acoustic parameters namely A-weighted SPL of speech at a distance of 4m ($L_{p,\mathrm{A,S,4\,m}}$) and spatial decay rate of speech ($D_{2,\mathrm{S}}$). Much like the target value for r_D, the standard specified the ideal target values and the values that would be considered poor for both acoustic parameters (See Table 7.1).

Table 7.1: Target value for acoustic parameters as specified in ISO 3382-3: 2012

Acoustic parameters	r_D **(m)**	$L_{p,\mathrm{A,S,4\,m}}$ **(dB)**	$D_{2,\mathrm{S}}$ **(dBA)**
Target Values	≤ 5	≤ 48	≥ 7
Poor acoustic conditions	> 10	> 50	< 5

While STI and r_D are mostly defined by the level of background noise (BN) level of the room, $L_{p,\mathrm{A,S,4\,m}}$ and $D_{2,\mathrm{S}}$ are mainly depended on the room geometry, volume, and absorption, and also the workstation and partitions available in the room (Haapakangas et al., 2017). Thus, to determine and achieve an optimum acoustic condition in open-plan offices, the consideration of all four acoustic parameters simultaneously is a must.

However, for the purpose of thorough analysis in this study; a more refined acoustic classification and target values would be adopted. The classification method is as presented in Virjonen et al. (2009). The classification divided the acoustic parameter values into classes of A, B, C, and D which translated into the class of “Excellent’, ‘Good’, ‘Fair’, and ‘Poor’ for speech privacy. Table 7.2 presents the classification method and target values for r_D, $L_{p,A,S,4\,m}$, and $D_{2,S}$.

ISO 3382-3 (2012) stated that open-plan office with an exceptional acoustic condition is a rare occasion. Thus, by using the classification method illustrated in Table 7.2, the data could be broken down into several segments and can be analysed meticulously without being too rigid.

Table 7.2: Acoustic parameters measured and their respective target values and classifications

Class	r_D (m)	$L_{p,A,S,4\,m}$ (dB)	$D_{2,S}$ (dBA)
A ‘Excellent’	< 5	< 48	> 11
B ‘Good’	5 to 8	48 to 51	9 to 11
C ‘Fair’	8 to 11	51 to 54	7 to 9
D ‘Poor’	> 11	> 54	< 7

(Source: Virjonen et al., 2009)

7.1.1 Speech Transmission Index (STI) in the Nearest Workstation

To achieve an optimum acoustic environment for open-plan office, the ideal STI (in the nearest workstation) should not exceed the halfway point of the STI index, which is STI 0.5. However, as previously illustrated in Table 2.6 in Chapter Two, STI of 0.4 and below is the most desirable as it would mean that the SI would be classified as ‘Poor’, which translated into reasonable speech privacy.

It should be noted that the mentioned of STI in this section would refer to the value of STI in the workstation nearest to the sound source (SS). All the results would be discussed separately according to specific open-plan offices (OPO).

(a) ***LOP1 and LOP2***

Figure 7.1 and Figure 7.2 show the simulated STI (in the nearest workstation) data for models in open-plan offices LOP1 and LOP2 respectively. Each open-plan office's data is divided into nine graphs according to its $W_{DENSITY\_RATIO}$, W_{SIZE}, and P_{HEIGHT}. The *y*-axis of each graph represents the STI value, and the *x*-axis represents the six variations of workspace layout arrangement (W_{LA}) of linear and cluster arrangements.

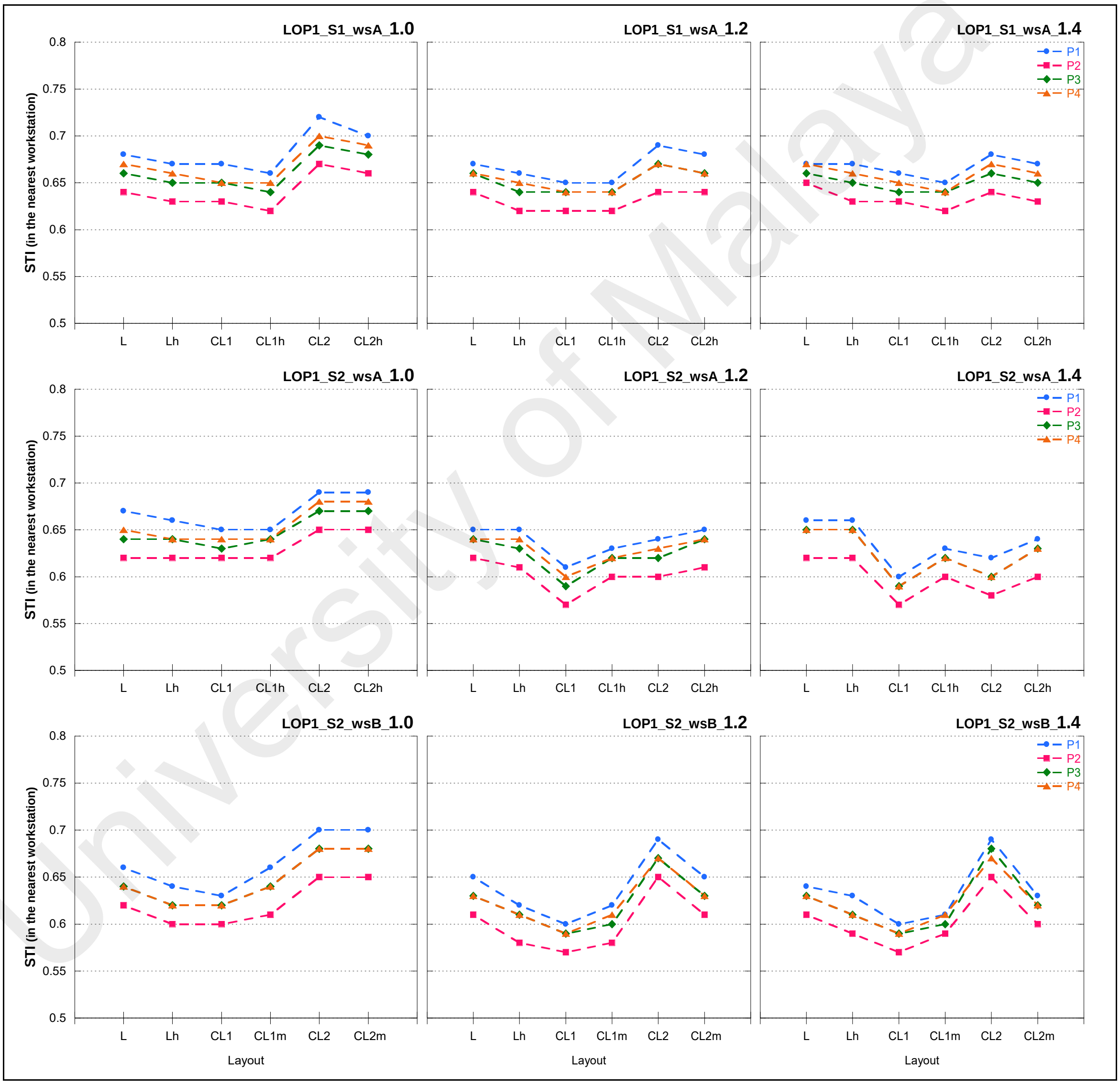


Figure 7.1: Simulated STI (in the nearest workstation) for LOP1 models

The three columns of graphs separate the models into the three variable of P_{HEIGHT} of 1.0 m, 1.2 m, and 1.4 m. Meanwhile, the three rows of graphs divide the models into its respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. The first row shows the STI data for models with

$W_{DENSITY\_RATIO}$ S1 and W_{SIZE} wsA. The second row shows the STI data for models with $W_{DENSITY\_RATIO}$ S2 and W_{SIZE} wsA. On the other hand, the third row shows the models with $W_{DENSITY\_RATIO}$ S2 and W_{SIZE} wsB. Each of the graphs categorise the data into the four different P_{TYPE} according to different colour codes of Blue (P1), (Pink) P2, (Green) P3, and (Orange) P4.

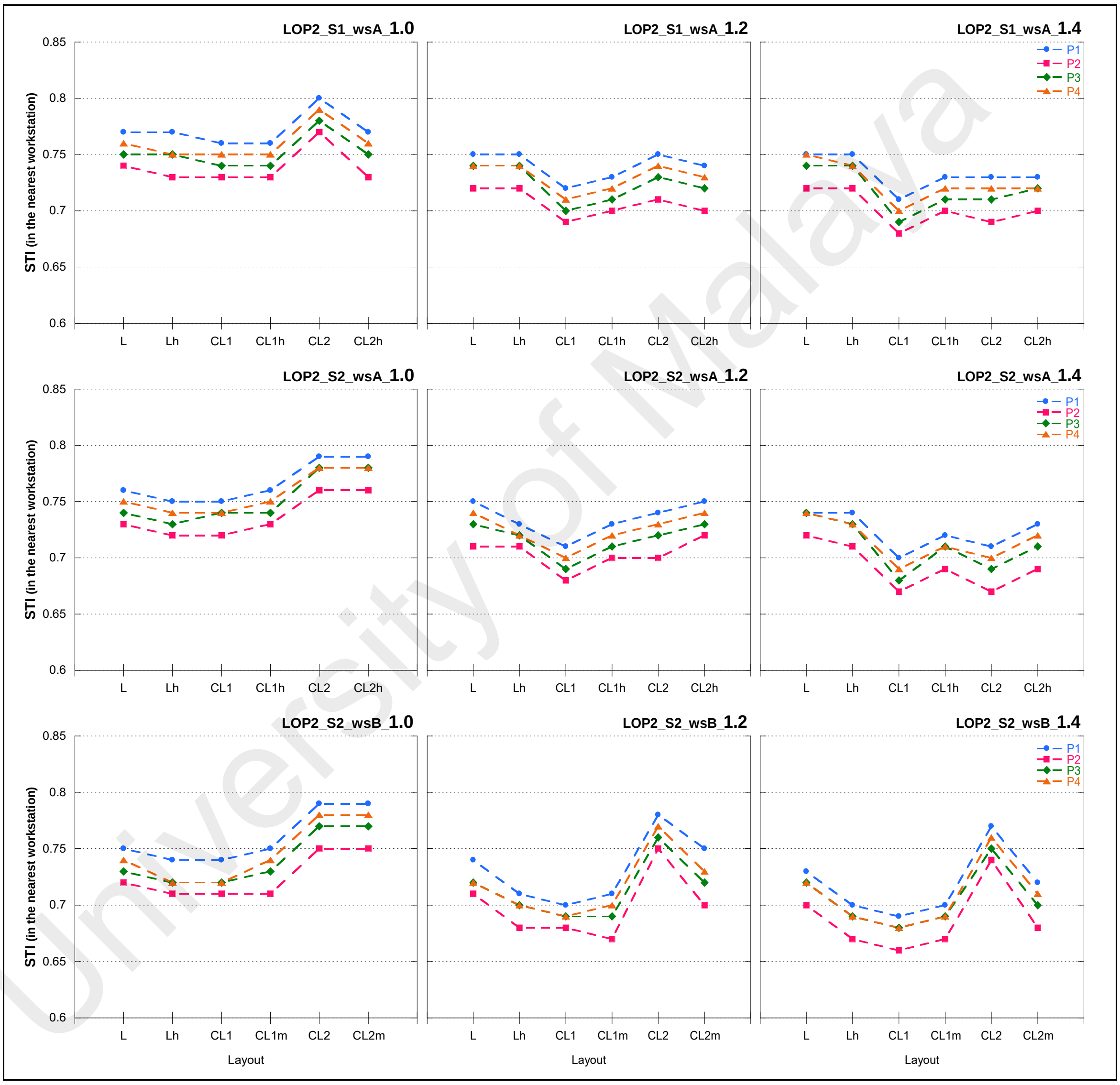


Figure 7.2: Simulated STI (in the nearest workstation) for LOP2 models

As overall it can be observed that none of the models achieve the desired STI value of below 0.5. All the models in LOP1 achieve an STI of between 0.55 and 0.75, which means that the SI of the rooms can be classified as being within the 'Fair' and 'Good' range. LOP2, on the other hand, records a higher STI range from 0.65 to 0.8; which can be translated into SI ratings of ‘Good’ and ‘Excellent’. This means that while the SI recorded to be within the acceptable desired range, the speech privacy in the models of LOP1 and LOP2 can be classify as either ‘Poor’, ‘Very Poor’, or ‘None’ at all.

The most obvious discrepancies in STI value can be identified through design variable P_{TYPE}. For both LOP1 and LOP2, the data shows that P_{TYPE} P2 (Pink) result in the lowest STI values in comparison to other partition types. Meanwhile, P_{TYPE} P1 (Blue) resulted in the highest STI value. Although it should be noted that the differences between the STI value in P_{TYPE} P1 and P2 are very insignificant, lower than 3JND (< 0.1), which is suppose to be imperceptible to the human ears (Bradley et al., 1999).

As the data plot tendencies for all P_{TYPE} are similar in all respective graphs, the differences of STI data between other design variables would be discussed within the data collected in P_{TYPE} P2. Figure 7.3 and Figure 7.4 depict the simulated STI results for all the models of LOP1 and LOP2 respectively, according to the six layout arrangements (W_{LA}) into their own graphs. Much like the previous graphs, the *y*-axis represents the simulated STI data. Meanwhile, the *x*-axis in these bar graphs divides the models into its individual $W_{DENSITY\_RATIO}$ and W_{SIZE}. The vertical bars in each graph present the STI data into the three P_{HEIGHT}.

Roughly, in term of $W_{DENSITY\_RATIO}$ it can be seen that $W_{DENSITY\_RATIO}$ S2 results in a slightly lower STI than S1 for both LOP1 and LOP2. On the other hand, between W_{SIZE} wsA and wsB (within $W_{DENSITY\_RATIO}$ S2), a small decrease of STI can be perceive in wsB. The exception to this observation can be observed in LOP1_CL2 which records a higher STI in wsB (in P_{HEIGHT} 1.2 m and 1.4 m) and LOP2_CL2 where the STI value between the two workstations (in all P_{HEIGHT}) bears identical results.

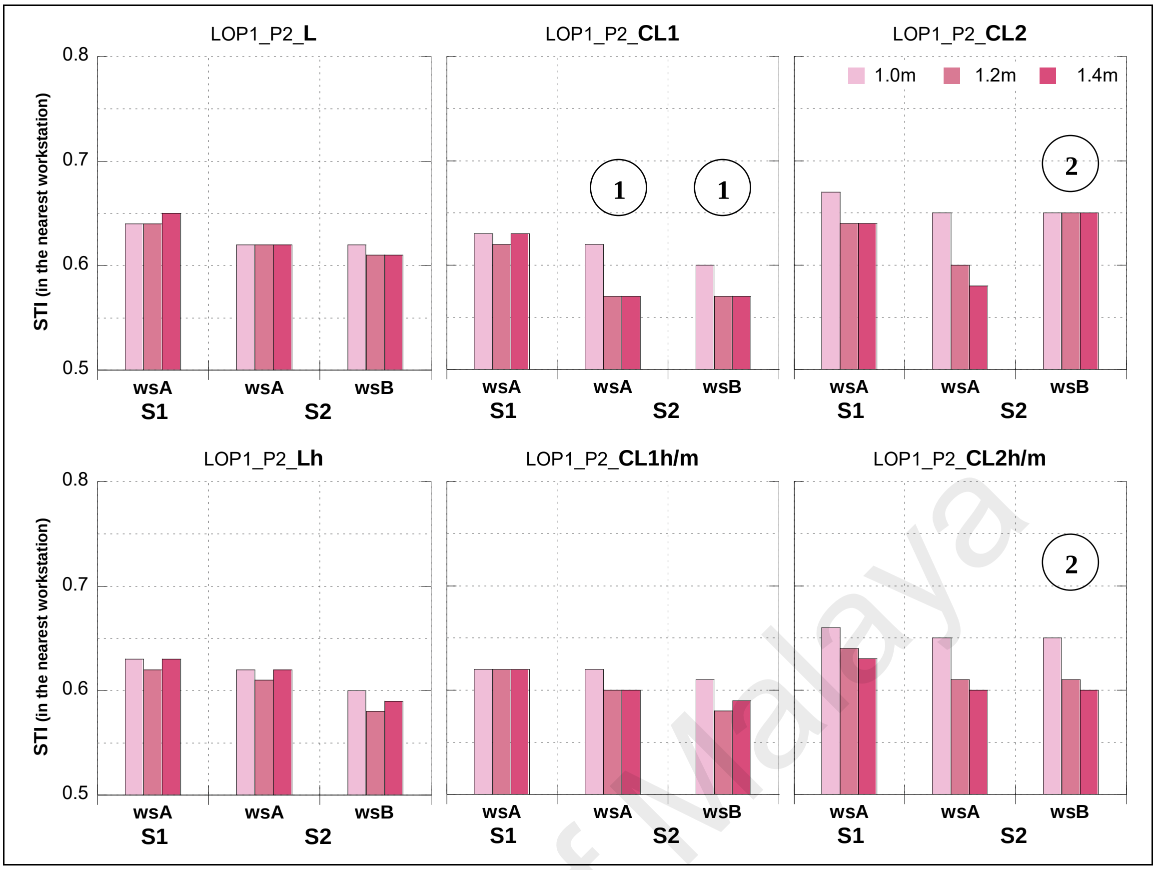


Figure 7.3: Simulated STI for LOP1 models with P_{TYPE} P2

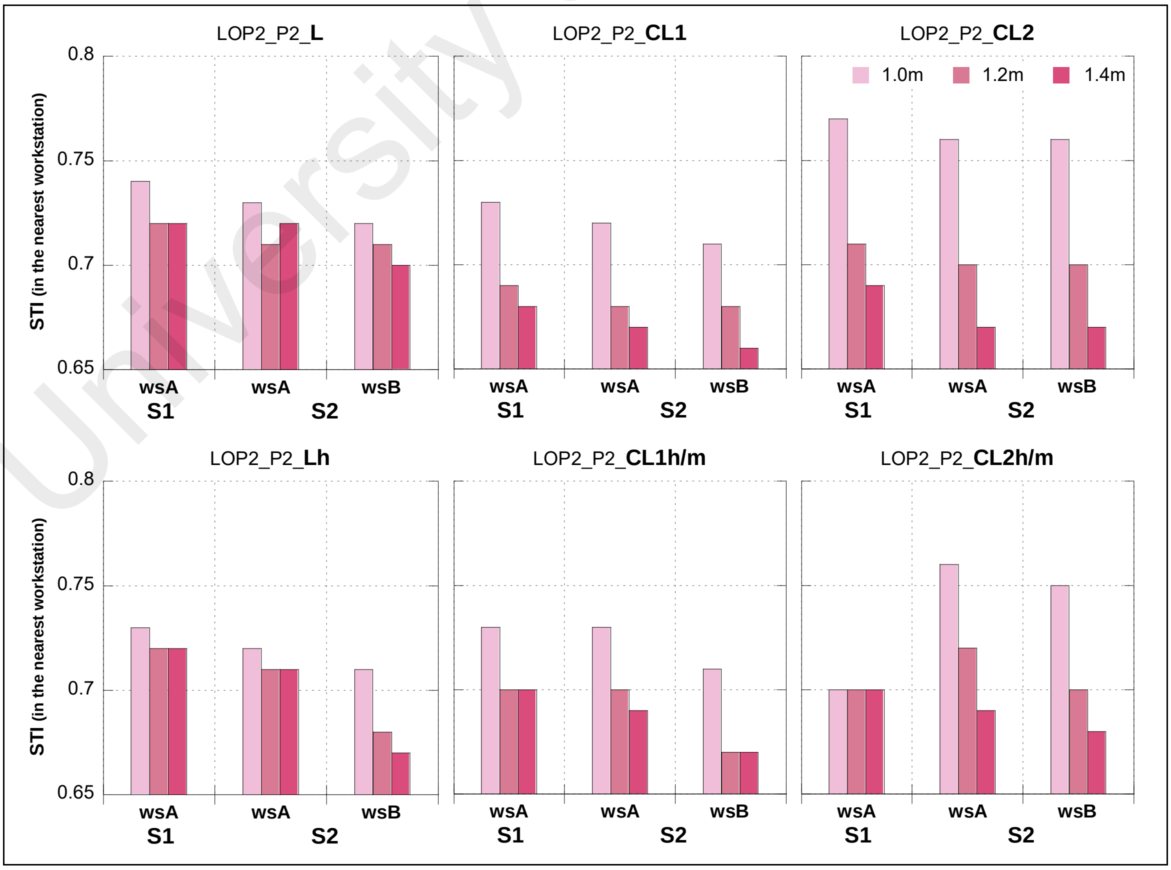


Figure 7.4: Simulated STI for LOP2 models with P_{TYPE} P2

Changes in P_{HEIGHT} variable result in some STI differences. While it is not very significant in LOP1 models, the differences are quite visually noticeable in LOP2 models especially in W_{LA} CL1, CL2, and in some models in W_{LA} CL2h/m within the $W_{DENSITY\_RATIO}$ S2.

In term of the discrepancies of STI (in the nearest workstation) results in $W_{DENSITY\_RATIO}$ S2 in comparison to S1 for both LOP1 and LOP2, it can be observed that, as the density ratio determine the number of workstations, it also influence the distance between the workstations. With lesser workstations to be provided, they are bound to be extra spaces that can be spared for in-between the rows of workstations; hence, explained the slightly lower STI. The same case can be made for the discrepancies of STI results between W_{SIZE} wsA and wsB. Since wsB is somewhat larger than wsA, the distance between the listener points in layouts with wsB is farther than the distance between the listener points in layout with wsA.

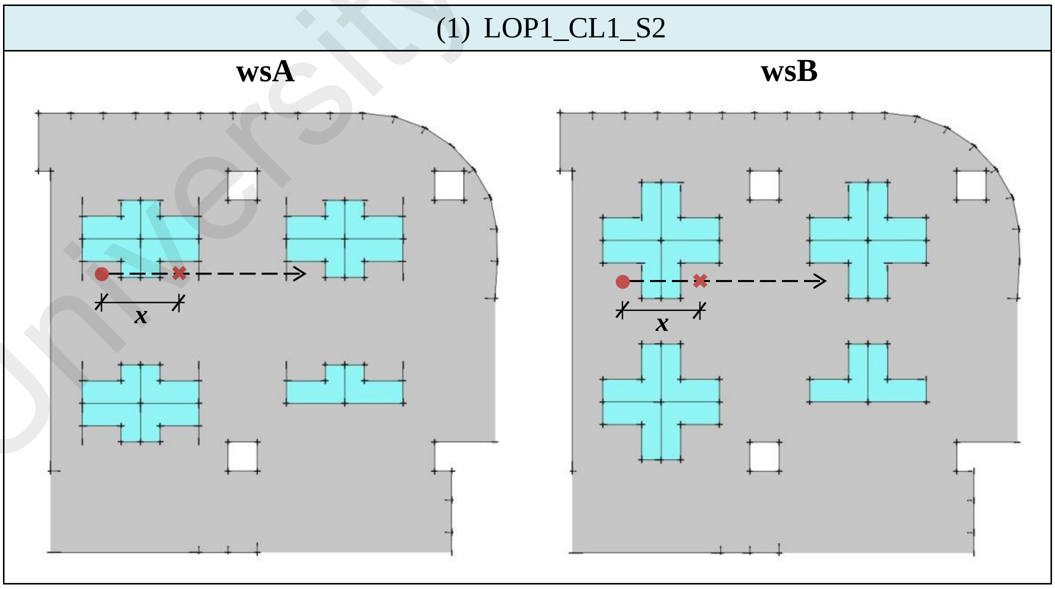


Figure 7.5: Comparison of distance between the workstations in model LOP1_CL1_S2_wsA and wsB

Furthermore, referring to model LOP1_CL1_S2_*wsA* and LOP1_CL1_S2_*wsB*; both models in P_{HEIGHT} 1.0 m and 1.4 m record the lowest STI data for LOP1, which is 0.57 (Refer to No.1 in Figure 7.3). Comparison of both layouts (See Figure 7.5) show that despite the differences in W_{SIZE}, it could be observed that the distance between the workstations in both models with W_{SIZE} wsA and wsB is the same and thus explains the similar STI data between the two models.

In term of W_{LA}, a significant example can be seen from the results of models LOP1_S2_wsB_*CL2* and LOP1_S2_wsB_*CL2m* (Refer to No.2 in Figure 7.3 and Figure 7.6). These two models have identical $W_{DENSITY\_RATIO}$, W_{SIZE}, P_{TYPE}, P_{HEIGHT} range, except for the W_{LA}. Although it can be seen that the layout arrangements of the models are practically the same, the modified workstation is what set the two layouts apart. The discrepancy between the two is that workstations in CL2 did not have the intermediate panels while CL2m did. The tiny differences in the STI results show that the existence of the intermediate partitions made an impact on the STI results especially when the P_{HEIGHT} was 1.2 m and 1.4 m.

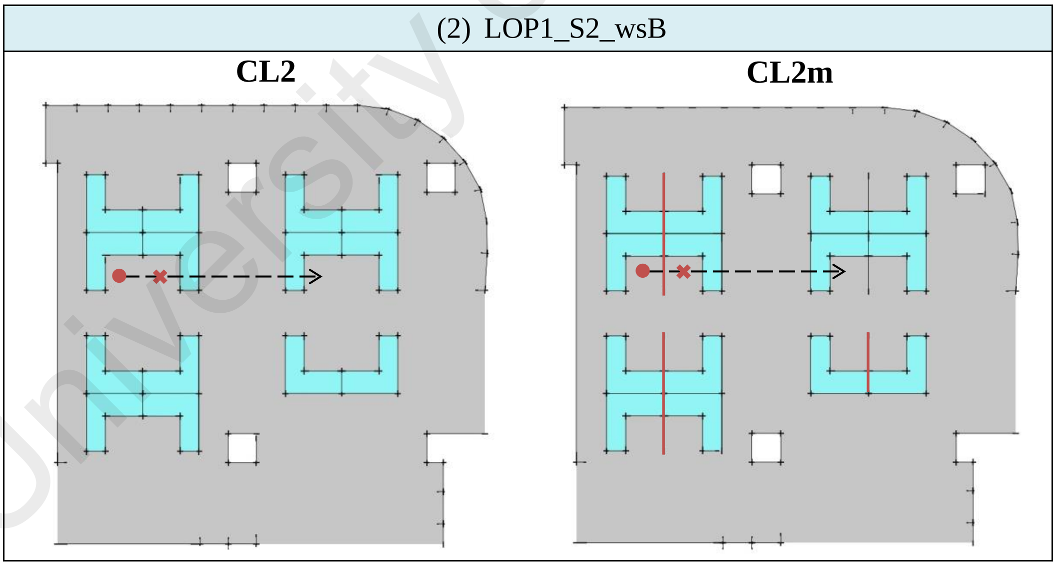


Figure 7.6: Comparison of layouts between model LOP1_S2_wsB_CL2 and CL2m

(b) ***GOP1 and GOP2***

Figure 7.7 and Figure 7.8 depict the simulated STI (in the nearest workstation) data for models in GOP1 and GOP2 respectively. The *y*-axis of each graph represents the STI value, and the *x*-axis represents the six variations of workspace layout arrangement

(W_{LA}) of linear and cluster arrangements. The three columns of graphs for both GOP1 and GOP2 separate the models into the three variable of P_{HEIGHT} of 1.0 m, 1.2 m, and 1.4 m. Each of the graphs categorises the data into the four different P_{TYPE} according to different colour codes of Blue (P1), (Pink) P2, (Green) P3, and (Orange) P4.

Since the design strategy $W_{DENSITY\_RATIO}$ was not applied in GOP1 models, GOP1 data is divided into only six graphs according to its W_{SIZE}, and P_{HEIGHT}. The two rows of GOP1 graphs divide the models into their respective W_{SIZE} of either wsA or wsB. Meanwhile, GOP2 data is divided into 12 graphs according to its $W_{DENSITY\_RATIO}$, W_{SIZE}, and P_{HEIGHT}. The four rows of graphs divide the models into their respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. The first two rows show the STI data for models with $W_{DENSITY\_RATIO}$ S1 and W_{SIZE} wsA and wsB respectively, and the third and fourth rows show the STI data for models with $W_{DENSITY\_RATIO}$ S2 and W_{SIZE} wsA and wsB.

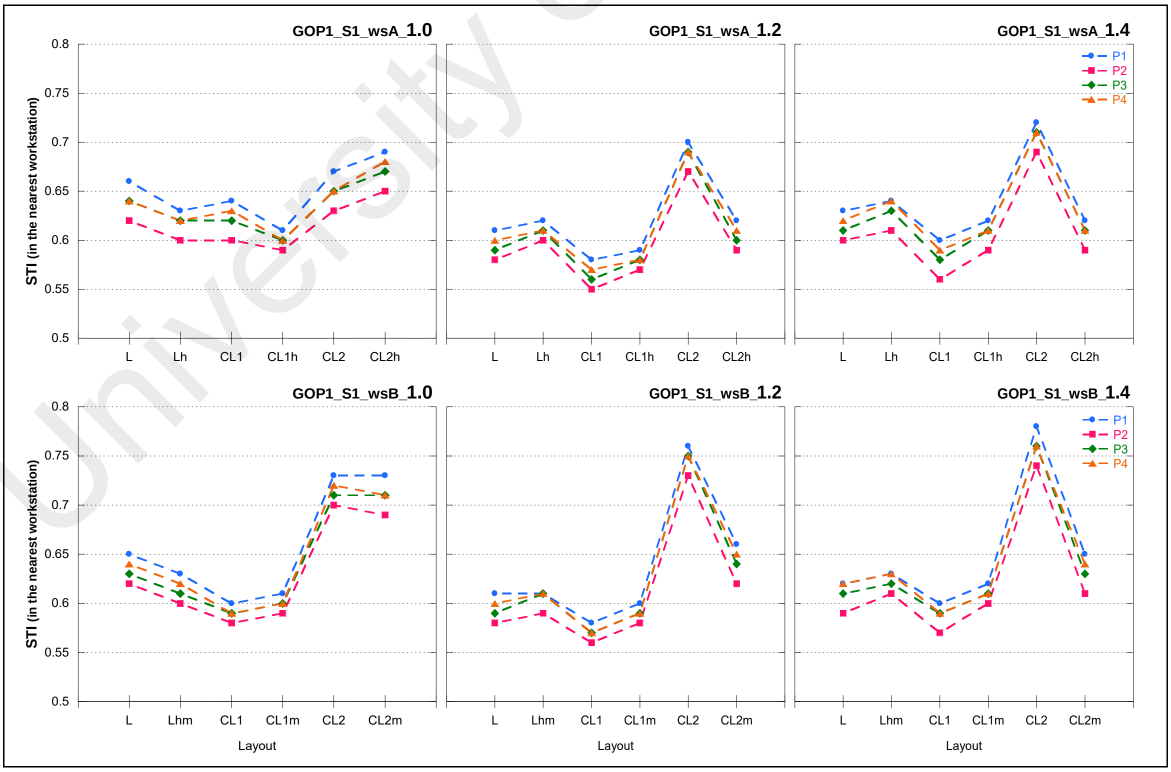


Figure 7.7: Simulated STI (in the nearest workstation) for GOP1 models

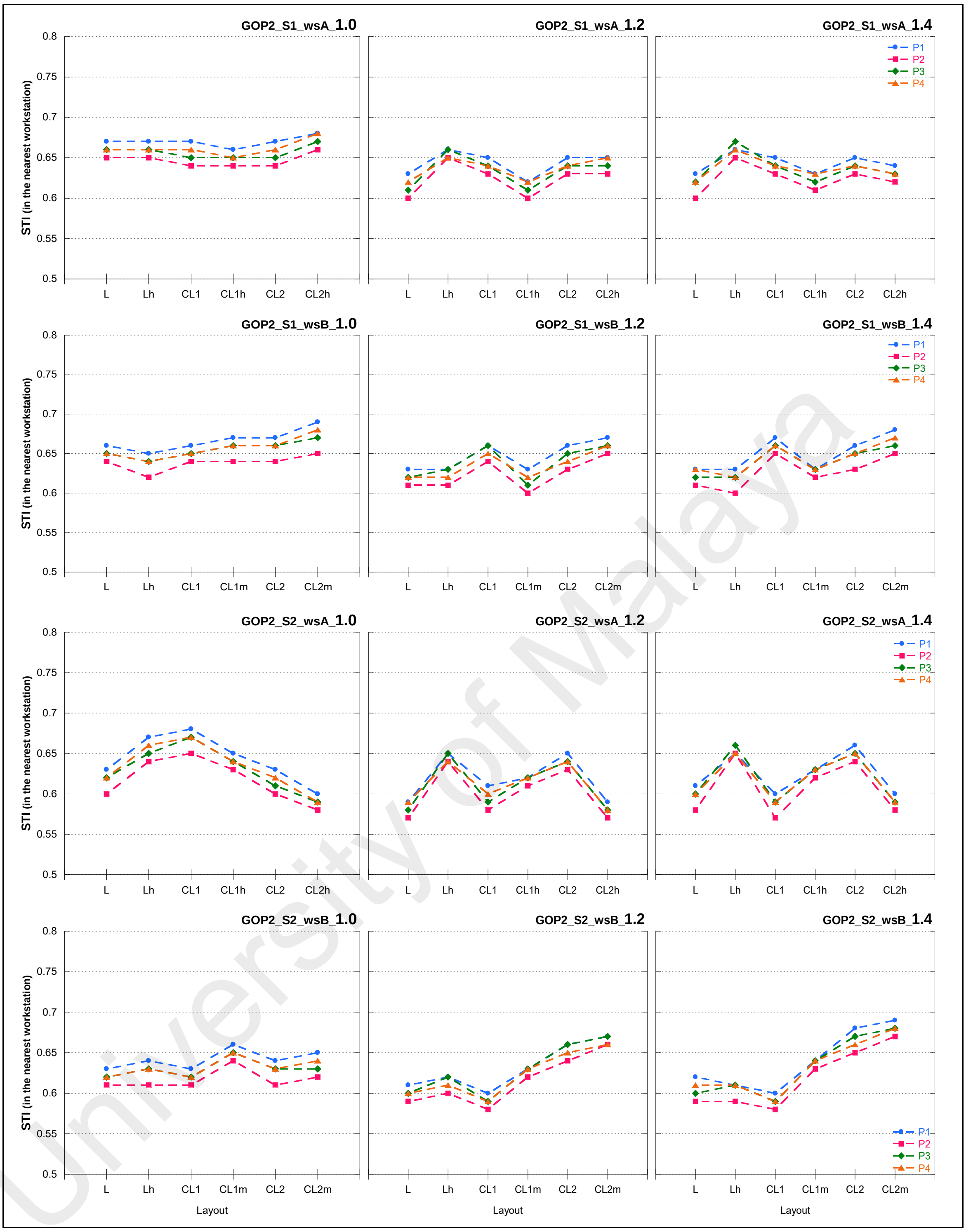


Figure 7.8: Simulated STI (in the nearest workstation) for GOP2 models

Similar to LOP1 and LOP2, all models in GOP1 and GOP2 record an STI value of above 0.5 which translated into 'Fair' to 'Excellent' SI and 'Poor' to 'None' speech privacy. STI data in GOP1 has more considerable STI variations as it record STIs of between 0.55 to 0.8. Meanwhile, models in GOP2 remain rather persistent throughout, as the STI data from each W_{LA} do not fluctuate much from each other (STI of between 0.55 to 0.7).

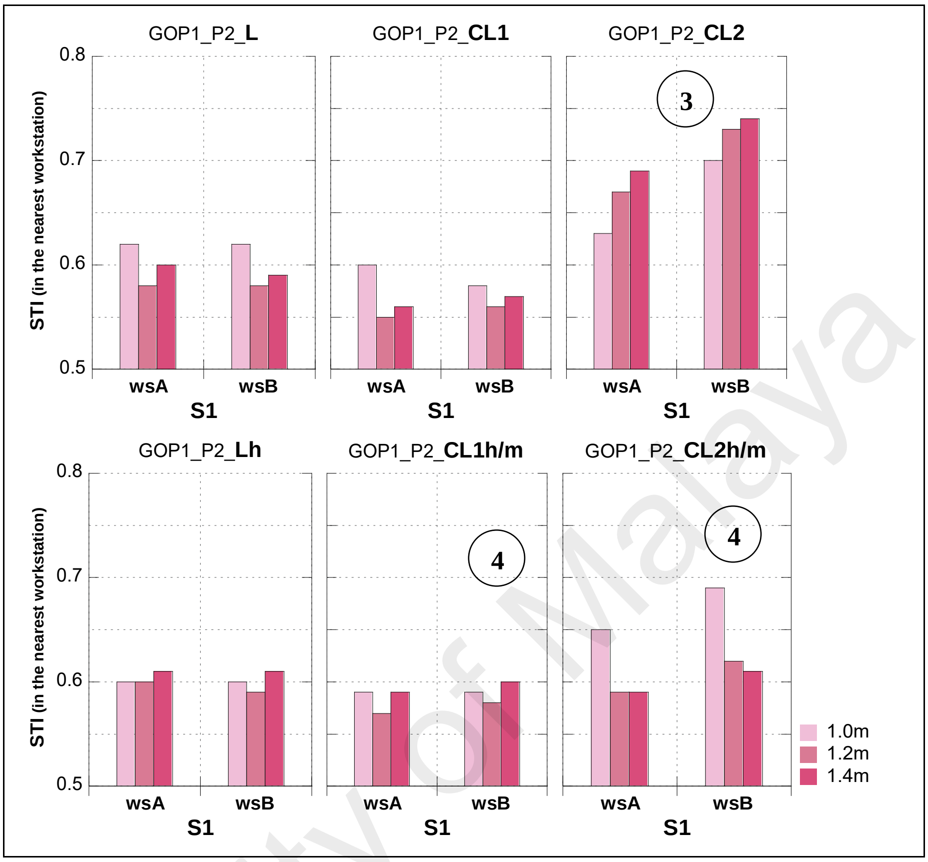


Figure 7.9: Simulated STI for GOP1 models with P_{TYPE} P2

Again, the most obvious and noteworthy differences in STI data can be spot from the variables available in P_{TYPE}. Both GOP1 and GOP2 show that P_{TYPE} P2 (Pink) results in the lowest STI values in comparison to other partition types, and P_{TYPE} P1 (Blue) results in the highest STI value. Similarly to LOP1 and LOP2, it should be noted that the differences between the STI value in P_{TYPE} P1 and P2 are very minor, which is lower than 3JND (< 0.1).

As the data plot tendencies for all P_{TYPE} are similar in all respective graphs, the differences of STI data between other design variables would be discussed within the data collected in P_{TYPE} P2. Figure 7.9 and Figure 7.12 depict the simulated STI results for all the models of GOP1 and GOP2 respectively, according to the six layout arrangements (W_{LA}) into their respective graphs. Correspondingly, the *y*-axis of the graphs represents the simulated STI (in the nearest workstation) data. Meanwhile, the *x*-axis in these bar graphs divides the models into their W_{SIZE} for GOP1, and $W_{DENSITY\_RATIO}$ and W_{SIZE} for GOP2. The vertical bars in each graph presents the STI data into the three P_{HEIGHT}.

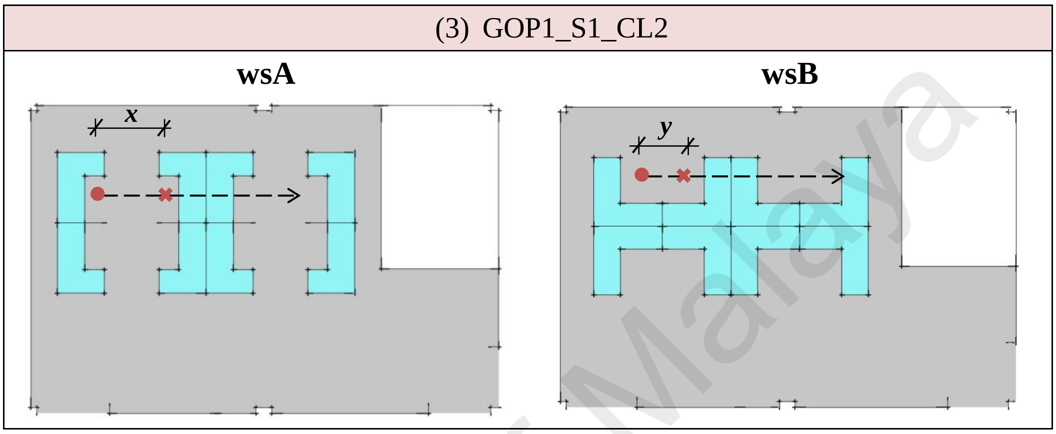


Figure 7.10: Comparison of distance between the workstations in GOP1_S1_CL2_wsA and wsB

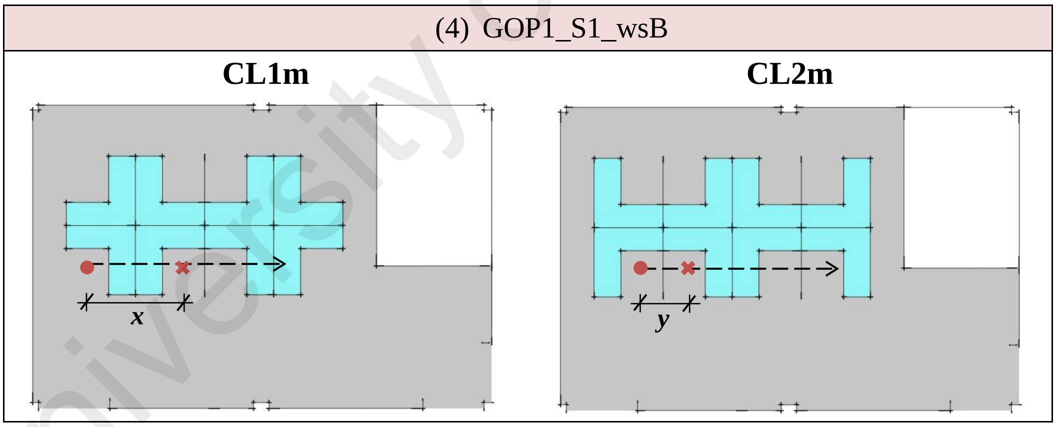


Figure 7.11: Comparison of distance between the workstations in GOP1_S1_wsB_CL1m and CL2m

In GOP1 models where only $W_{DENSITY\_RATIO}$ S1 is applied, tiny differences in STI value can be perceive between W_{SIZE} wsA and wsB. However, some unusual STI results should be highlighted. In all W_{LA} except for CL2 and CL2h/m, it can be seen that the STI data records a continually lower STI in P_{HEIGHT} 1.2 m, in comparison to P_{HEIGHT} 1.0 m. However, the STI starts to fluctuate when the layouts are replaced with a higher partition (1.4 m in height).

The increased in STI value in W_{LA} CL2 (Refer to No.3 in Figure 7.9) in correspondence to the W_{SIZE} and P_{HEIGHT} can be explain by referring to the layouts of both models (See Figure 7.10). The increment of STI happens due to the lack of intermediate panels between the workstations, and a higher P_{HEIGHT} only causes the sound to be contained and bounced off in the same area. The further increase of STI in models with W_{SIZE} wsB can be observed due to the smaller distance between the SS and the receiver point. The discrepancies of STI value between model GOP1_S1_wsB with different W_{LA} of CL1m and CL2m (Refer to No.4 in Figure 7.9) can be seen in the comparison of distance as shown in Figure 7.11. Models with W_{LA} CL2m result in a higher STI due to the fact that the distance between the SS and receiver point is much nearer than the comparable distance in the model with W_{LA} CL1m.

In GOP2, models with W_{LA} L and CL1 in $W_{DENSITY\_RATIO}$ S2 record a lower STI reading in comparison to S1. Again, due to the reduced number of workstations in models with $W_{DENSITY\_RATIO}$ S2, it allowed for more spacing between the workstations and furthermore between the SS and receiver points which influences the STI results. On the other hand, models with W_{LA} Lh record a different tendency as the models with W_{SIZE} wsB record lower STI results in comparison to W_{SIZE} wsA, despite the $W_{DENSITY\_RATIO}$. Therefore, in the case of models with W_{LA} Lh, instead of the $W_{DENSITY\_RATIO}$ being the influencer (like W_{LA} L and CL1), the W_{SIZE} was acting as the part.

It should be noted that the lowest STI recorded from models in GOP2 is 0.57. Four models record this result (See * in Figure 7.12). The four models have an arrangement that resulted in the SS and the nearest receiver points to be farther apart from each other, which means that distance plays an active role in achieving speech privacy in open-plan offices. Additionally, this phenomenon can also be seen by comparing the STI results recorded by model GOP2_S2_wsA_CL1h and CL2h (Refer to No.5 in Figure 7.12). Figure 6.13 shows that the physical difference between these two layouts is essentially the additional distance between the SS and the nearest receiver points.

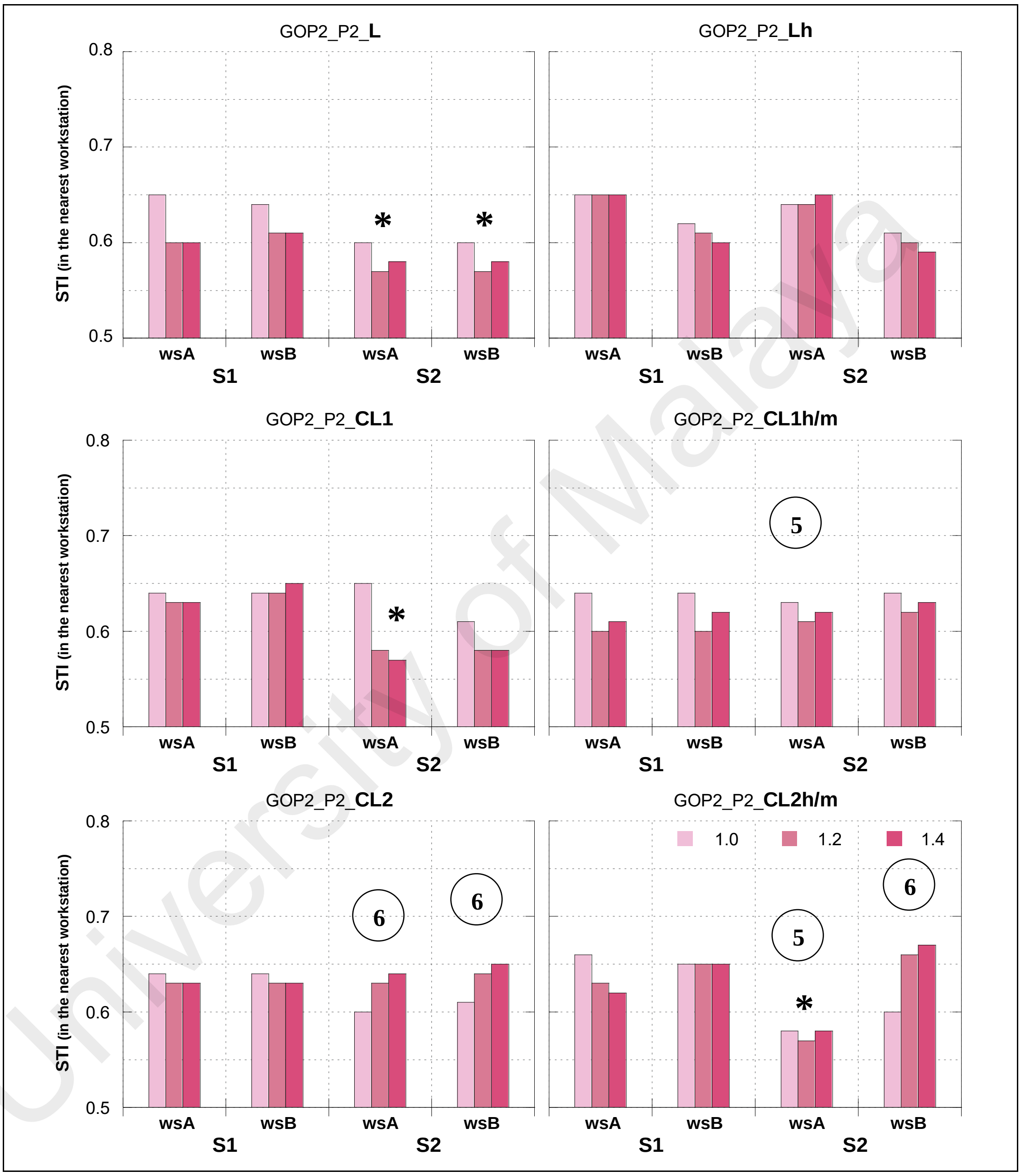


Figure 7.12: Simulated STI for GOP2 models with P_{TYPE} P2

Furthermore, the graphs also show some irregular STI results where the higher the P_{HEIGHT} are, the higher STI values are recorded (Refer to No.6 in Figure 7.12). These results can be explained by referring to the layouts of the models. Figure 7.14 illustrates

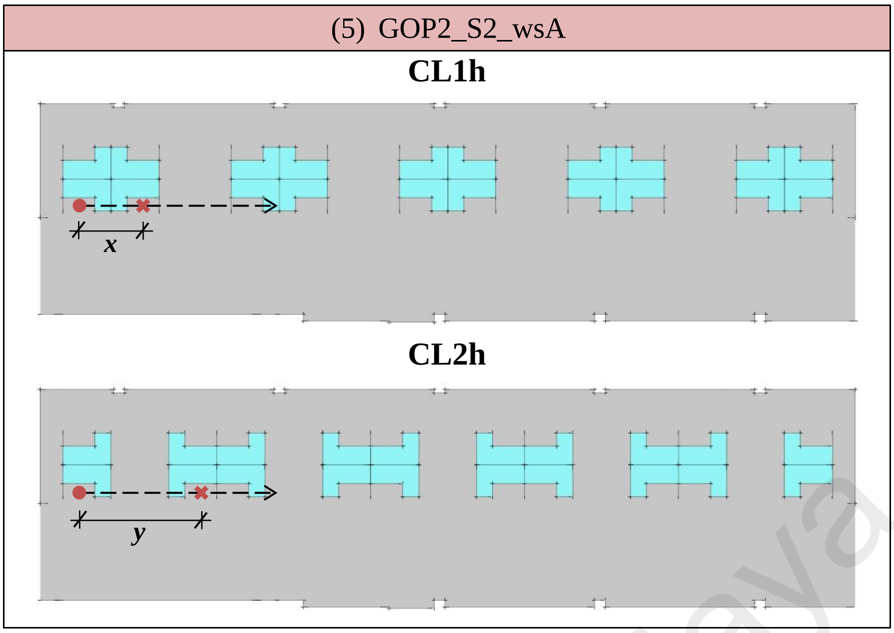


Figure 7.13: Comparison of distance between the workstations in model GOP2_S2_wsA_CL1h and CL2h

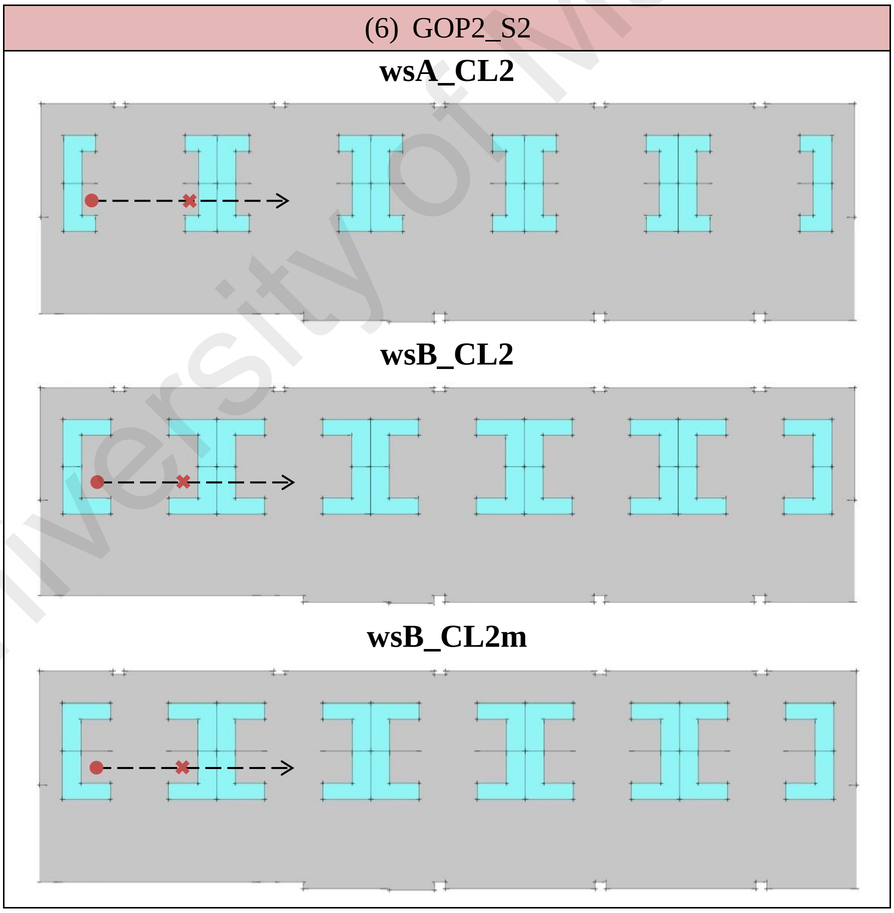


Figure 7.14: Similarities of layouts between models GOP2_S2_wsA_CL2, wsB_CL2, and wsB_CL2m

the layouts for model GOP2_S2_wsA_CL2, GOP2_S2_wsB_CL2, and GOP2_S2_wsB_CL2m where it show that the nearest receiver points in the immediate workstations are not obstructed by any divider or partitions, and thus made it easier for sound to travel to the next workstations.

7.1.2 Distraction Distance (r_D) in Meter

For clearer speech privacy classifications and analysis, all simulated r_D data would be rendered using the micro breakdown segments of colour coding as shown in Table 7.3 below. The simulated r_D data would be classified into four classes of 'Excellent' (Blue), 'Good' (Green), 'Fair' (Yellow) and 'Poor' (Red) speech privacy.

Table 7.3: Speech privacy ratings classification for the simulated r_D data

Speech Privacy Ratings			
Class		**r_D (m)**	
A	'Excellent'	< 5	
B	'Good'	5 - 5.99	
		6 - 6.99	
		7 - 7.99	
C	'Fair'	8 - 8.99	
		9 - 9.99	
		10 - 10.99	
D	'Poor'	11 - 11.99	
		12 - 12.99	
		13 - 13.99	
		≥ 14	

Table 7.4, 7.5, 7.6, and 7.7 denotes the speech privacy ratings for the r_D data collected from the simulated models of LOP1, LOP2, GOP1, and GOP2 respectively. The tables present the data in rows with the combination of $W_{DENSITY\_RATIO}$ of S1 and S2, W_{SIZE} of wsA and wsB, and P_{HEIGHT} of 1.0 m, 1.2 m, and 1.4 m. Meanwhile, the columns separate the data into their respective P_{TYPE} of P1, P2, P3, and P4; and the six W_{LA}. During the data extraction and collection process, the r_D data for each open-plan offices are identified and organised according to their most significant variables, for example,

data for LOP1, LOP2, and GOP2 shown that they are highly dependable on the P_{HEIGHT} and hence are presented in rows according to the three P_{HEIGHT}. Meanwhile, data for GOP1 were highly influenced by the W_{SIZE} and henceforth are presented in rows according to the two W_{SIZE}.

In addition to the tables, the simulated r_D results of LOP1, LOP2, GOP1, and GOP2 would also be presented in groups of linear graphs (see Figure 7.15, 7.18, 7.21, and 7.24) to showcase the tendencies of the data according to their P_{TYPE}. The *y*-axis of each graph represents the simulated r_D value, and the *x*-axis represents the six variations of workspace layout arrangement (W_{LA}) of linear and cluster arrangements. Each figure contains three columns of graphs, which separate the models into the three variable of P_{HEIGHT} namely 1.0 m, 1.2 m, and 1.4 m. Meanwhile, the two (GOP1), three (LOP1 and LOP2), and four (GOP2) rows of linear graphs divide the models into their respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. Each of the linear graphs categorised the data into the four different P_{TYPE} according to different colour codes of Blue (P1), (Pink) P2, (Green) P3, and (Orange) P4.

(a) ***LOP1***

According to the simulated r_D data for LOP1 as presented in Table 7.4, it can be observed that among the three P_{HEIGHT} variables, P_{HEIGHT} 1.0 m records some of the highest r_D readings which mean lower speech privacy in comparison to P_{HEIGHT} 1.2 m and 1.4 m. Concurrently, speech privacy rating of simulated r_D in models with P_{HEIGHT} 1.2 m and 1.4 m are noticeably better than P_{HEIGHT} 1.0 m. However, between models with P_{HEIGHT} 1.2 m and 1.4 m, there are no significant differences in term of speech privacy that can be identified.

Table 7.4: Simulated r_D for LOP1 models and its speech privacy ratings

LOP1		**P1** (0.75)						**P2** (0.25)					
r_D in meter		L	Lh	CL1	CL1h/m	CL2	CL2h/m	L	Lh	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	11.46	10.92	12.16	10.94	10.56	9.28	9.96	9.31	10.24	9.05	9.29	7.83
2	S2_wsA_***1.0***	12.06	11.08	11.36	11.99	9.92	10.86	10.23	9.39	9.56	10.13	8.65	9.23
3	S2_wsB_***1.0***	11.69	11.14	11.97	11.96	10.53	10.86	9.56	9.11	9.77	10.08	8.84	8.52
4	S1_wsA_***1.2***	9.46	9.37	10.30	8.95	9.51	8.05	8.94	8.42	9.08	7.43	8.55	6.98
5	S2_wsA_***1.2***	10.08	9.78	10.28	11.52	9.58	10.49	8.96	8.64	8.57	9.43	8.07	8.70
6	S2_wsB_***1.2***	9.88	9.13	11.25	9.57	9.26	9.42	8.35	7.71	8.63	8.63	7.67	8.38
7	S1_wsA_***1.4***	8.86	9.29	10.26	8.78	9.27	8.15	8.51	8.61	9.43	7.35	8.45	6.88
8	S2_wsA_***1.4***	10.04	9.72	10.20	11.49	9.80	10.73	9.28	8.84	8.38	9.35	8.09	8.61
9	S2_wsB_***1.4***	9.83	9.29	12.04	9.97	9.35	8.99	8.22	7.78	8.69	8.93	7.58	7.94
LOP1		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	11.03	10.40	11.60	10.32	10.18	8.73	11.04	10.44	11.48	10.24	10.13	8.79
2	S2_wsA_***1.0***	11.50	10.59	10.69	11.31	9.49	10.23	11.46	10.52	10.70	11.31	9.45	10.30
3	S2_wsB_***1.0***	10.91	10.43	11.11	11.32	9.97	10.47	10.93	10.33	11.06	11.35	9.85	10.46
4	S1_wsA_***1.2***	9.57	9.28	10.10	8.46	9.41	7.78	9.47	9.15	10.14	8.50	9.32	7.76
5	S2_wsA_***1.2***	9.84	9.59	9.88	10.85	9.24	9.95	9.86	9.52	9.72	10.87	9.02	9.99
6	S2_wsB_***1.2***	9.31	8.77	10.31	9.57	8.86	9.28	9.43	8.63	10.29	9.54	8.76	9.19
7	S1_wsA_***1.4***	9.16	9.41	10.55	8.51	9.33	7.83	8.85	9.19	10.18	8.34	9.08	7.77
8	S2_wsA_***1.4***	10.23	9.79	9.95	10.77	9.59	10.01	9.92	9.56	9.49	10.93	9.11	10.15
9	S2_wsB_***1.4***	9.33	8.93	10.91	10.10	8.84	8.86	9.31	8.78	10.75	9.61	8.77	8.69

In term of P_{TYPE}, from the colour coding applies in Table 7.4, it can be seen that P2, which bears the absorption coefficient of 0.25α records r_D data with visibly better speech privacy than the other P_{TYPE}. The r_D values simulated through models with P_{TYPE} P2 (0.25α) can be classifies within the speech privacy range of 'Good' to 'Fair'. On the other hand, LOP1 models with P_{TYPE} P1 (0.75α) log r_D data with speech privacy ratings of 'Fair' to 'Poor', especially when the models are constructed with P_{HEIGHT} 1.0 m. Meanwhile, P_{TYPE} P3 (0.25|0.75α) and P4 (0.75|0.25α) which are the permutation of P_{TYPE} P1 and P2 log r_D values of within the speech privacy range of 'Fair' to 'Poor', with some exceptions of 'Good' speech privacy in two of the models namely model LOP1_S1_wsA_CL2h_1.2 and 1.4.

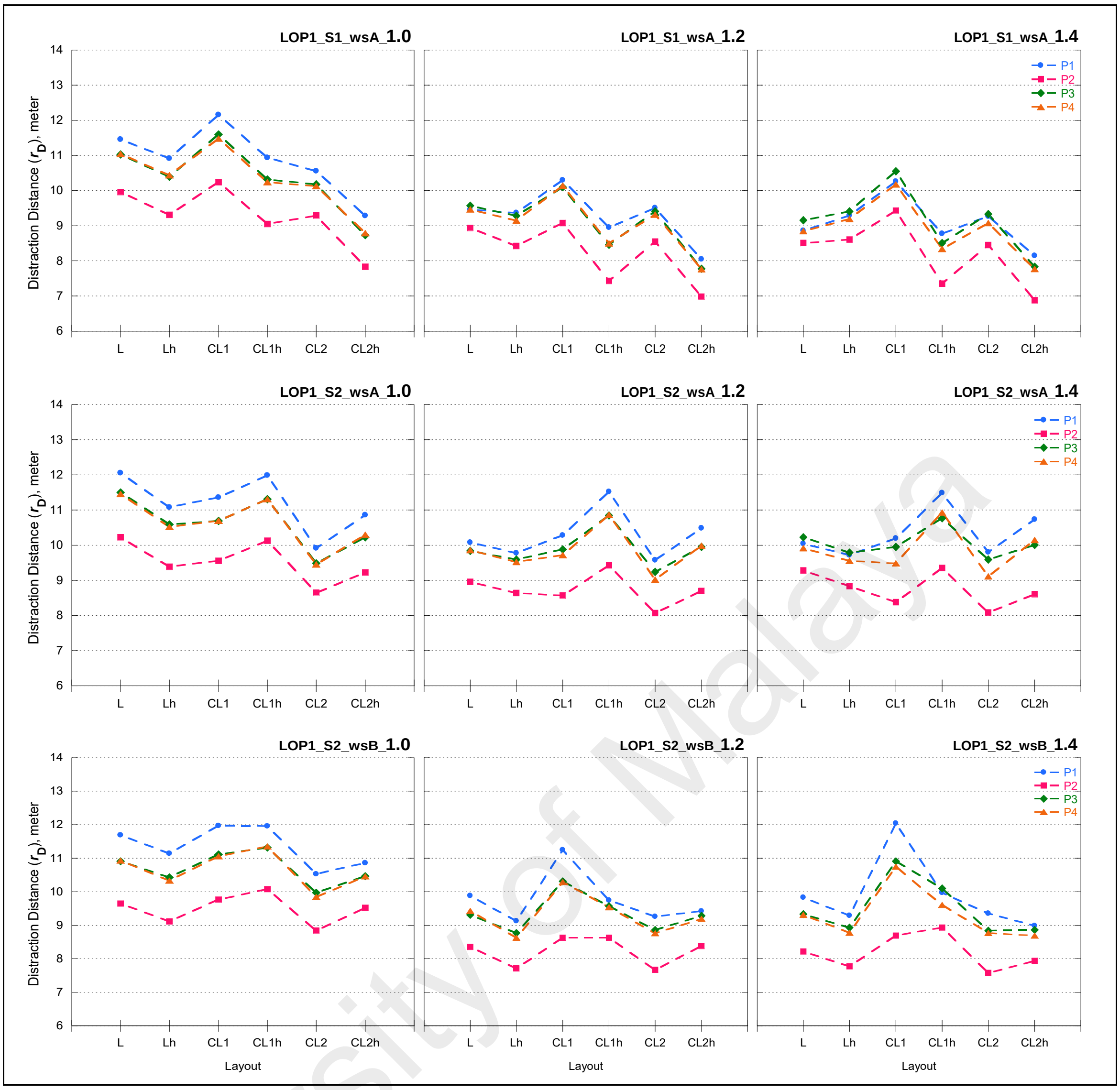


Figure 7.15: Simulated distraction distance (r_D) for LOP1 models

As it was determined that P_{TYPE} P2 contributes the most desired range of speech privacy for models in LOP1, the comparison between the W_{LA} are focus on the simulated r_D results in P_{TYPE} P2 models. Also, due to the consistent pattern of the r_D data simulated for all partition types as illustrates in Figure 7.15, it would be redundant to discuss all the W_{LA} for all P_{TYPE}. Figure 7.16 depicts the simulated r_D results for all the models of LOP1_P2 according to the six W_{LA}. The *y*-axis represents the simulated r_D data, and the *x*-axis in these bar graphs divides the models into its individual $W_{DENSITY\_RATIO}$ and W_{SIZE}. The vertical bars in each graph present the STI data into the three P_{HEIGHT}.

Figure 7.16 shows the r_D simulated for all models constructed using P_{TYPE} P2. While all models simulated acceptable r_D within the range of 'Good' and 'Fair' speech privacy, some W_{LA} show more promising result than others. From Figure 7.16, it can be seen that LOP1_S1_wsA with W_{LA} CL2h results in relatively lower r_D than other W_{LA}, with models in the three P_{HEIGHT} record r_D of below 8 meters ('Good' speech privacy). The lowest simulated r_D is recorded at 6.88 meters by model LOP1_S1_wsA_1.4_CL2h.

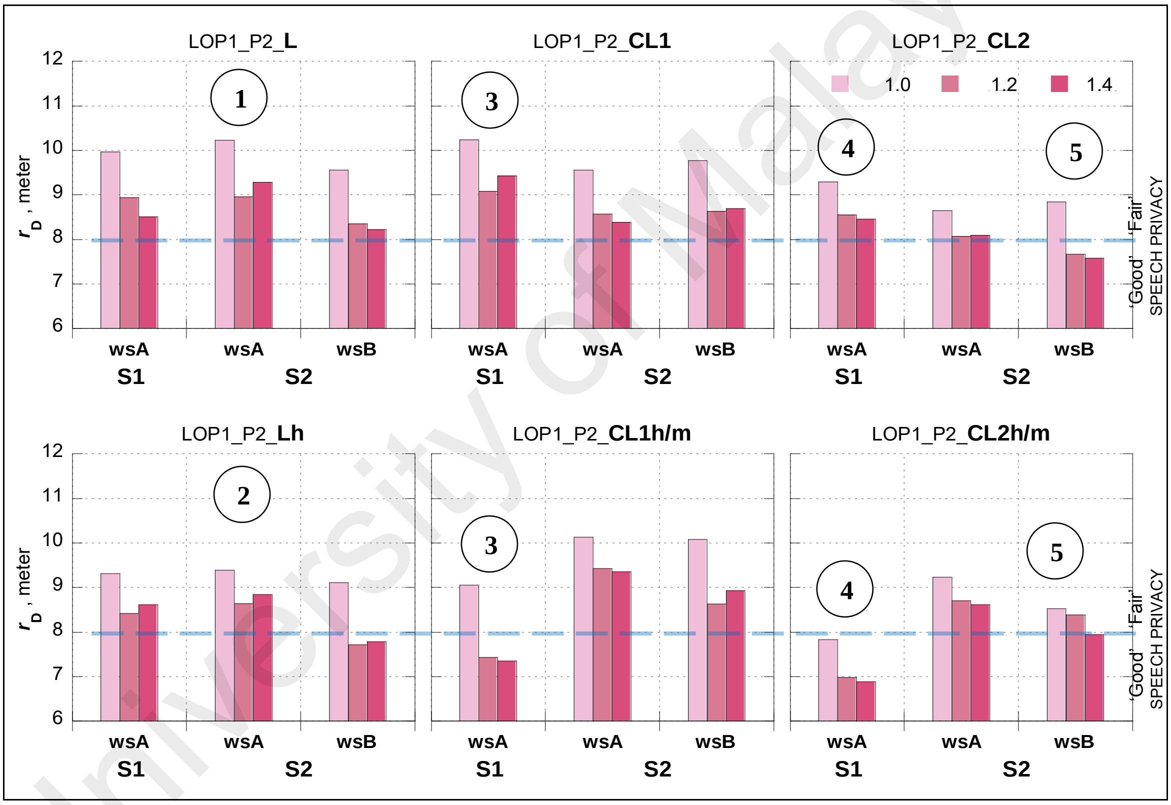


Figure 7.16: Simulated r_D for LOP1 models with P_{TYPE} P2

For a better analysis of the W_{LA}, Figure 7.17 illustrates the layout plans for all LOP1 models. Comparison between the results in models with W_{LA} L and Lh show that for LOP1, when the layout with the same amount of workstations are arrange horizontally across the floor plans, it resulted in lower r_D (Refer to No.1 and 2 in Figure 7.16 and 7.17). This observation can also be applies to model W_{LA} CL1 and CL1h in S1_wsA,

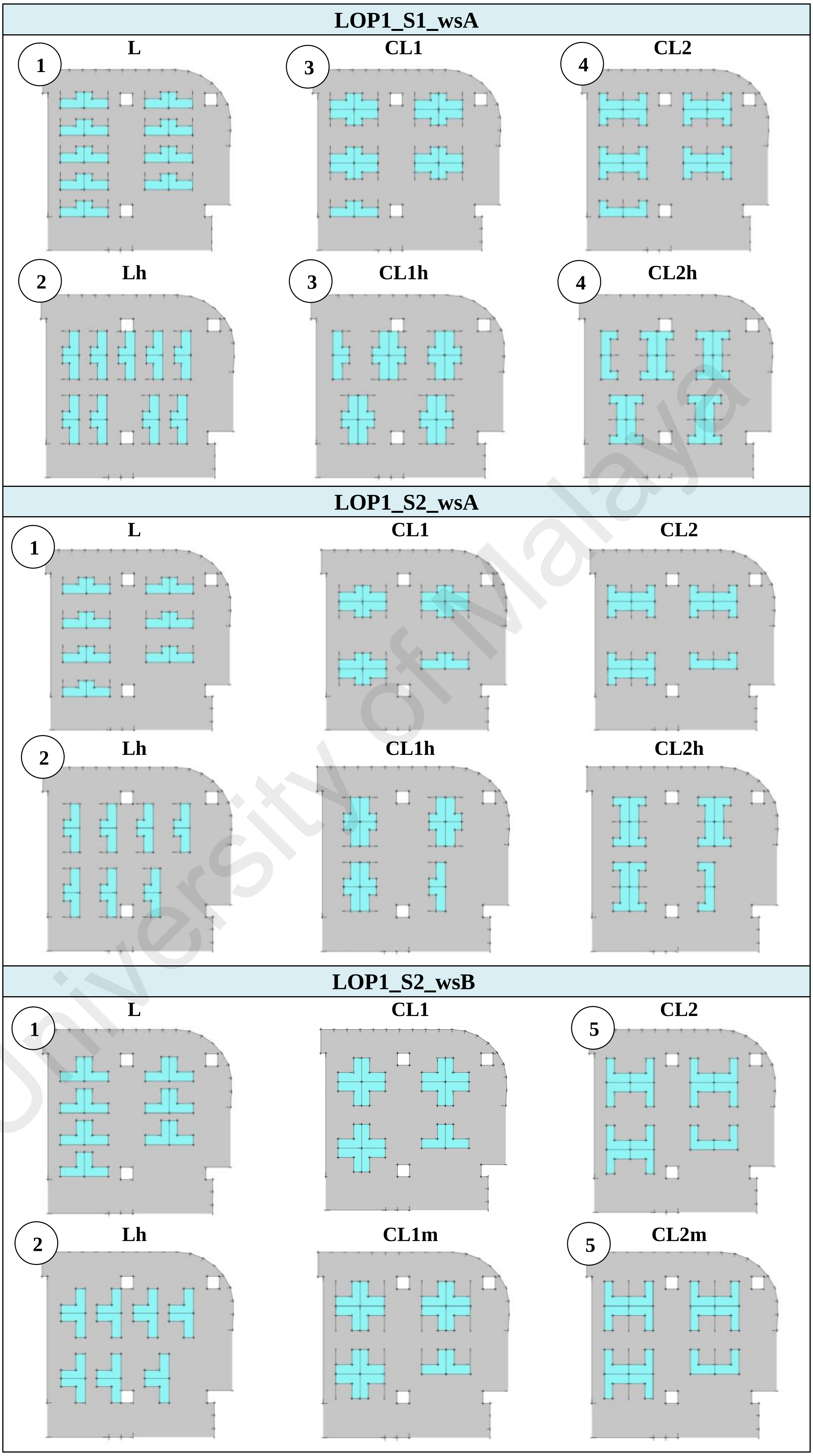


Figure 7.17: W_{LA} for all LOP1 models

and W_{LA} CL2 and CL2h also in S1_wsA (Refer No. 3 and 4 in Figure 7.16 and Figure 7.17 respectively).

Unlike the apparent inclinations of STI results, distances between workstations (SS and receiver points) and the presence of in-between partitions did not give any prediction for the simulation of distraction distance (r_D). This can be seen in the results of model S2_wsB_CL2 and S2_wsB_CL2m (Refer No. 5 in Figure 7.16 and Figure 7.17). The layout plans of the two W_{LA} indicate that the layouts are basically identical except for the modification done on the workstations, which are the additional in-between partitions in W_{LA} CL2m. With the presence of the partitions, the r_D is expected to decrease. However, that is not the case. In fact, the r_D results actually increased.

(b) ***LOP2***

Table 7.5: Simulated r_D for LOP2 models and its speech privacy ratings

LOP2		**P1** (0.75)						**P2** (0.25)					
r_D in meter		L	Lh	CL1	CL1h/m	CL2	CL2h/m	L	Lh	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	19.13	19.74	19.27	21.59	16.29	21.23	17.62	18.19	17.67	19.75	15.03	19.36
2	S2_wsA_***1.0***	22.86	19.61	22.25	21.55	16.66	20.77	20.78	18.27	20.09	20.23	15.35	19.10
3	S2_wsB_***1.0***	22.85	19.44	21.55	20.44	16.42	16.91	21.39	17.79	19.70	18.46	14.91	15.43
4	S1_wsA_***1.2***	14.36	14.66	15.57	16.82	13.65	16.42	13.82	14.60	15.17	16.07	13.08	15.55
5	S2_wsA_***1.2***	16.70	15.25	19.68	18.98	14.77	18.41	15.86	14.87	18.23	18.46	13.83	17.75
6	S2_wsB_***1.2***	17.61	15.57	17.10	14.95	13.25	13.70	16.44	14.60	15.78	14.06	12.08	12.97
7	S1_wsA_***1.4***	12.56	13.20	14.71	14.53	12.18	14.65	13.01	13.74	14.87	14.26	11.99	14.21
8	S2_wsA_***1.4***	15.81	13.62	21.18	22.20	14.17	20.69	15.55	13.92	20.02	21.90	13.18	19.66
9	S2_wsB_***1.4***	17.17	14.39	17.98	14.12	11.97	12.27	15.87	13.39	16.00	14.06	10.88	11.78
LOP2		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	18.72	19.20	18.75	20.84	15.78	20.52	18.70	19.33	18.66	21.02	15.86	20.67
2	S2_wsA_***1.0***	22.20	19.25	21.45	21.19	16.10	20.10	22.13	19.15	21.34	21.03	16.20	20.13
3	S2_wsB_***1.0***	22.38	18.82	20.82	19.68	15.81	16.33	22.43	18.86	20.74	19.79	15.85	16.39
4	S1_wsA_***1.2***	14.36	15.04	15.83	16.78	13.68	16.23	14.30	14.71	15.36	16.64	13.44	16.22
5	S2_wsA_***1.2***	16.57	15.43	19.60	19.27	14.58	18.38	16.56	15.13	19.04	18.73	14.38	18.21
6	S2_wsB_***1.2***	17.05	15.30	16.48	14.84	12.76	13.57	17.43	15.34	16.67	14.65	12.89	13.48
7	S1_wsA_***1.4***	13.44	14.13	15.87	14.85	12.42	14.80	12.64	13.29	14.41	14.44	12.10	14.53
8	S2_wsA_***1.4***	16.37	14.44	24.71	22.80	14.01	20.86	15.66	13.67	19.21	22.30	13.80	20.52
9	S2_wsB_***1.4***	16.42	14.17	17.06	15.40	11.54	12.33	17.13	14.04	17.36	13.70	11.63	12.05

As it was determined in ISO 3382-3 (2012) and Virjonen et al. (2009), the maximum limit for acceptable distraction distance (r_D) should be no more than 11 meters. Both tabulated (Table 7.5) and graphical (Figure 7.18) description show that the r_D recorded in LOP2 models are beyond the 'Poor' speech privacy classification. One minor exception can be seen in model LOP2_S2_wsB_1.4_P2_CL2 where the r_D is recorded at 10.88 meters, which barely made it into the 'Fair' rating of speech privacy. Through initial observation of the r_D data from Table 7.5 and Figure 7.18, it can be seen that models with P_{HEIGHT} 1.2 m and 1.4 m record a marginally lower r_D in comparison to P_{HEIGHT} 1.0 m.

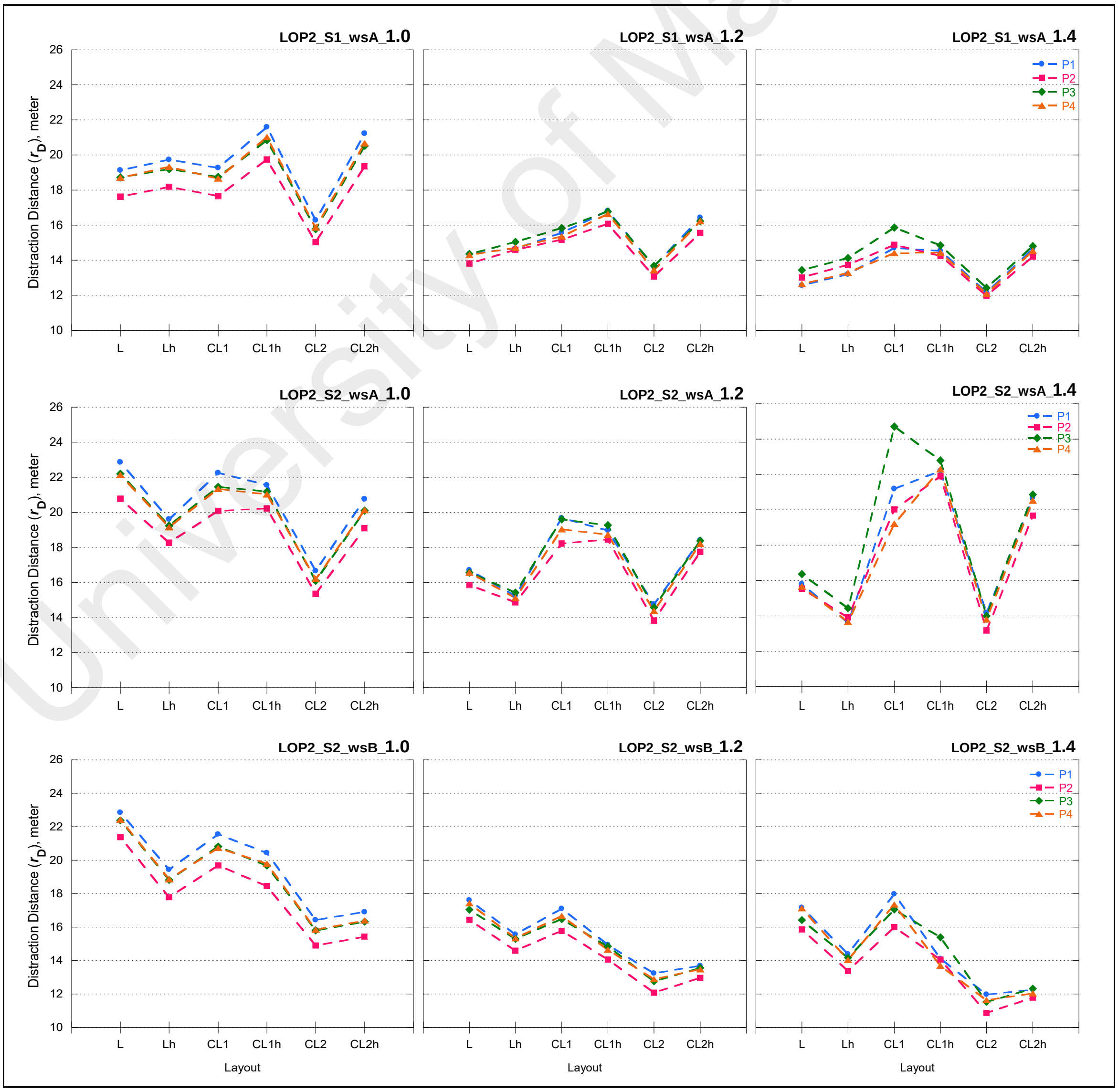


Figure 7.18: Simulated distraction distance (r_D) for LOP2 models

Despite the poor results collected from LOP2 models, it can be seen in Figure 7.18 that P_{TYPE} P2 (Pink) record the lowest r_D results among the other P_{TYPE}. Hence, to identify the W_{LA} that has the most impact on the r_D in LOP2 models, the analysis would focus on the results from models in P_{TYPE} P2. Figure 7.19 depicts the simulated r_D results for all the models of LOP2_P2 according to the six W_{LA}. The *y*-axis represents the simulated r_D data, and the *x*-axis of the bar graphs divides the models into their individual $W_{DENSITY\_RATIO}$ and W_{SIZE}. The vertical bars in each graph present the STI data into the three P_{HEIGHT}. The analysis of the results in Figure 7.19 would be done through the observation of the layout plans as depicted in Figure 7.20.

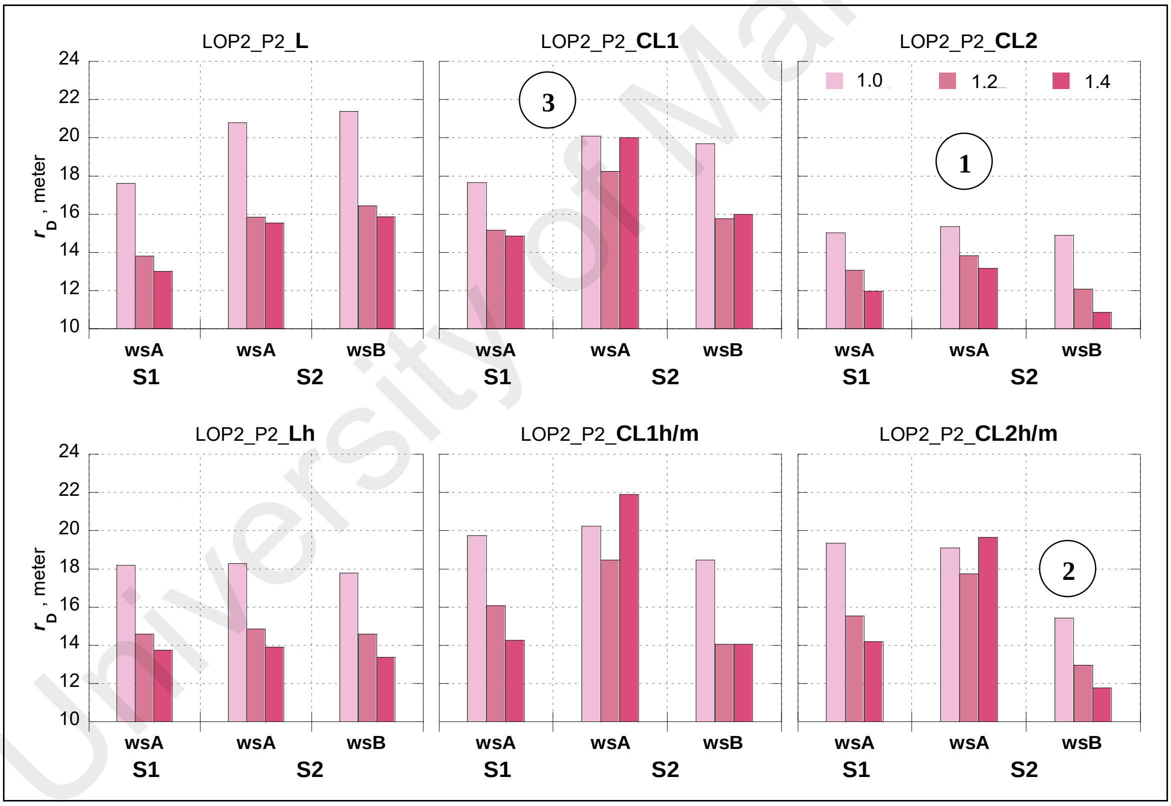


Figure 7.19: Simulated r_D for LOP2 models with P_{TYPE} P2

Through Figure 7.19 it can be seen that W_{LA} CL2 logs a collectively lower r_D results (below 16 meters) compare to other W_{LA}. Observation on the layout suggests a similar pattern of W_{LA} between the three CL2 layouts (Refer to No.1 in Figure 7.19 and Figure

7.20). The same tendency can also be observed in model LOP2_S2_wsB_CL2m which records r_D data of below 16 meters in all P_{HEIGHT}.

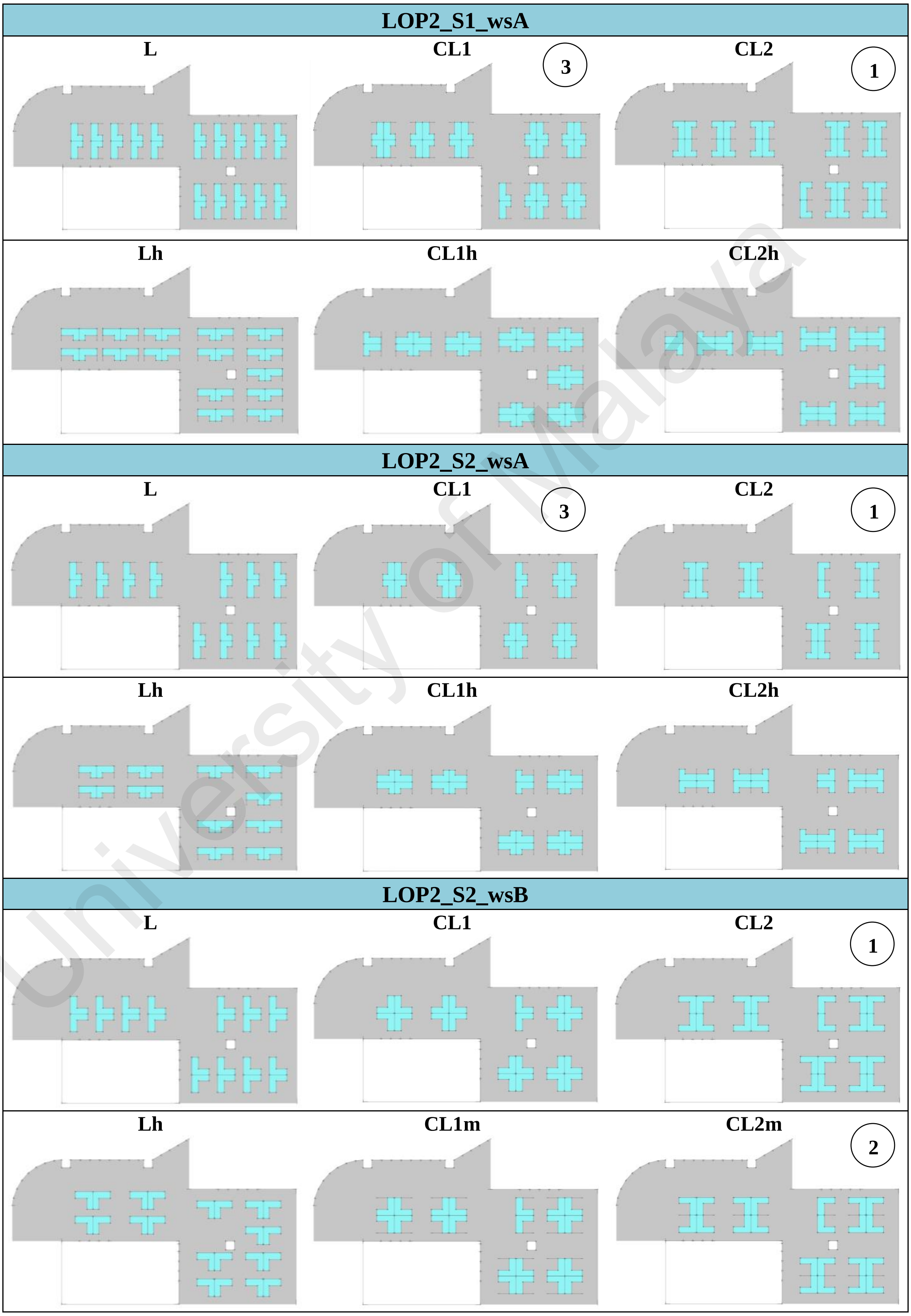


Figure 7.20: W_{LA} for all LOP2 models

This is plausible as model S2_wsB_CL2m is a modification of W_{LA} CL2 (Refer to No.2 in Figure 7.19 and Figure 7.20). It can also be observed that the element of ‘distance’ that was provided through the different variables in $W_{DENSITY\_RATIO}$ and W_{SIZE} do not have any substantial impact on the simulation of r_D. In fact, some models constructed using $W_{DENSITY\_RATIO}$ S2 which resulted in extra distances between the workstations do not affect the r_D results positively (Refer to No.3 in Figure 7.19 and Figure 7.20).

(c) *GOP1*

In general, GOP1 models with W_{SIZE} wsB presents significantly better speech privacy which ranged from ‘Fair’ to ‘Good’ all across the models except for models S1_wsB_1.0_P1 with the W_{LA} of Lhm and CL1. W_{SIZE} wsA, on the other hand, records speech privacy classification of within the range of ‘Good’ to ‘Poor’. Nonetheless, the significant differences of r_D in GOP1 are also highly depended on the W_{LA}. This can be observed in both Table 7.6 and Figure 7.21 where W_{LA} CL2 and CL2h/m record ‘Good’ speech privacy in most of the model combinations in both W_{SIZE} wsA and wsB.

Table 7.6: Simulated r_D for GOP1 models and its speech privacy ratings

GOP1		**P1** (0.75)						**P2** (0.25)					
r_D in meter		L	Lh/m	CL1	CL1h/m	CL2	CL2h/m	L	Lh/m	CL1	CL1h/m	CL2	CL2h/m
1	S1_***wsA***_1.0	9.95	12.66	10.70	13.75	9.10	6.30	8.27	10.27	8.93	11.21	7.71	5.66
2	S1_***wsA***_1.2	10.55	10.20	10.88	13.84	7.05	6.97	8.38	8.15	8.17	10.34	6.16	6.25
3	S1_***wsA***_1.4	9.06	10.48	10.05	12.61	7.28	9.05	7.36	8.52	8.40	10.16	6.41	7.56
4	S1_***wsB***_1.0	7.85	11.28	11.78	10.85	6.05	5.85	6.82	8.67	9.39	8.56	5.51	5.32
5	S1_***wsB***_1.2	7.59	8.36	10.01	9.00	5.50	5.82	6.62	6.41	7.49	6.80	5.13	5.45
6	S1_***wsB***_1.4	7.73	8.23	10.08	8.67	5.86	6.82	6.60	6.41	7.59	6.68	5.45	6.39
GOP1		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_***wsA***_1.0	9.19	11.63	9.90	12.69	8.51	5.97	9.41	11.92	10.08	12.82	8.64	6.11
2	S1_***wsA***_1.2	9.83	9.01	9.69	11.68	6.60	6.72	9.96	9.78	10.15	12.86	6.82	6.83
3	S1_***wsA***_1.4	8.31	9.28	9.54	11.17	6.84	8.29	8.66	9.99	9.63	11.96	7.11	8.77
4	S1_***wsB***_1.0	7.37	10.04	10.59	9.56	5.80	5.58	7.52	10.28	10.79	9.95	5.87	5.71
5	S1_***wsB***_1.2	7.16	7.26	8.57	7.66	5.32	5.75	7.42	7.72	9.01	8.21	5.41	5.76
6	S1_***wsB***_1.4	7.20	7.15	8.58	7.41	5.64	6.73	7.51	7.70	9.16	8.00	5.81	6.90

In the case of partition types, P_{TYPE} P2 (0.25α) records the most optimum r_D results compared to other P_{TYPE}. Majority of the models with P_{TYPE} P2 produce r_D of within speech privacy range of 'Good' and 'Fair', especially the ones with W_{SIZE} wsB. An exemption can be apply to model S1_wsA_1.0_P2_CL1h where the r_D is recorded at 11.21 meters which falls into a 'Poor' speech privacy class.

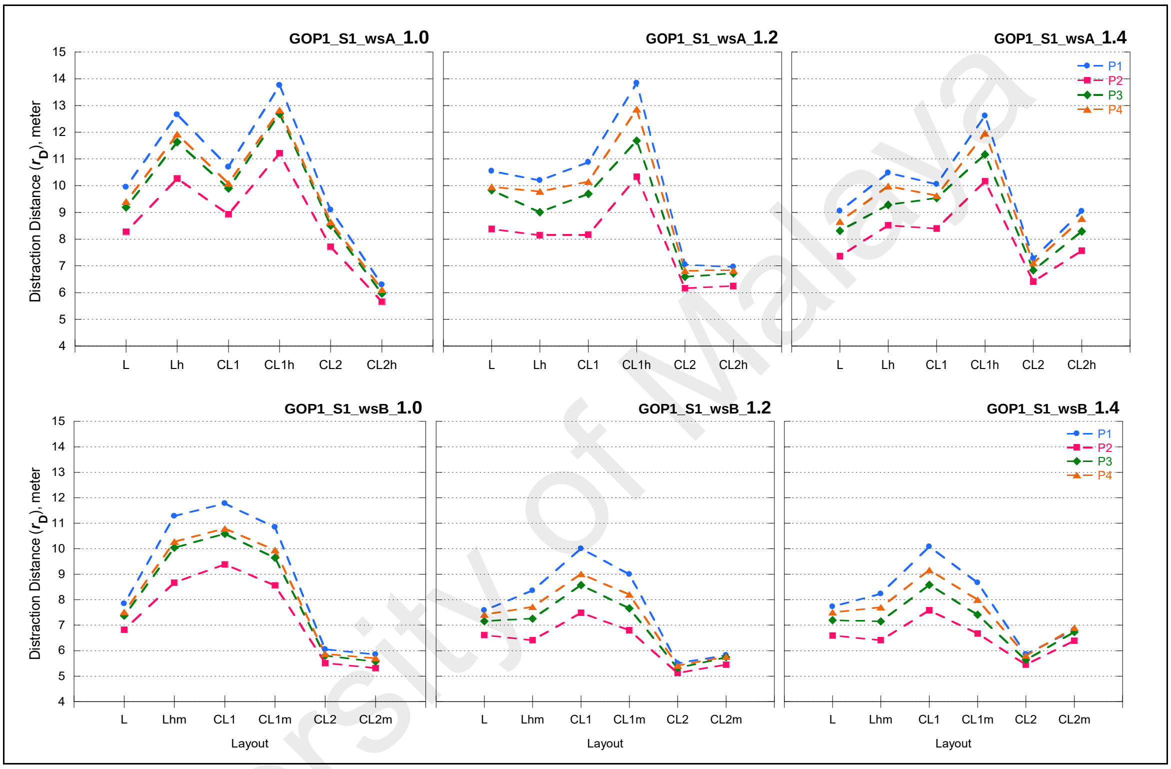


Figure 7.21: Simulated distraction distance (r_D) for GOP1 models

As the r_D data for all models of the same W_{LA} record similar tendencies as shown in Figure 7.21, further analysis of W_{LA} of would be done using the data of models with P_{TYPE} P2 as illustrates in Figure 7.22. Among the models simulated using the P_{TYPE} P2, it is identified that model GOP1 of W_{SIZE} wsB with P_{HEIGHT} 1.2 m in W_{LA} CL2 (GOP1_S1_wsB_1.2_CL2) logs the lowest r_D at 5.13 meters. It should be mention that it is the lowest r_D recorded in all GOP1 models.

Through the data presented in Figure 7.22, it can be seen that models with the W_{LA} CL2 and CL2h/m record low r_D of within the 'Good' speech privacy rating regardless of the differences in W_{SIZE}. However, it should be noted that the r_D data inclinations of both W_{LA} CL2 and CL2h/m are somewhat different according to the P_{HEIGHT} variables. It can be seen that for W_{LA} CL2, the r_D results decreases with P_{HEIGHT}. Meanwhile, r_D for W_{LA} CL2h/m increases gradually (Refer to No.1 and No.2 in Figure 7.22). When these data are analyse together with the layout plans as illustrated in Figure 7.23, it can be observed that the differences in r_D might be caused by the presence/absence of the in-between partitions. For W_{LA} CL2, there is no partition between the SS and the nearest receiver point (Refer to No.1 in Figure 7.23), while for W_{LA} CL2h/m there are (Refer to No.2 in Figure 7.23). However, it should be noted that the presence of additional in-between partitions in model S1_wsB_CL1m in comparison to model S1_wsB_CL1 show a positive impact on the simulated r_D results (Refer to No.3 in Figure 7.22 and Figure 7.23).

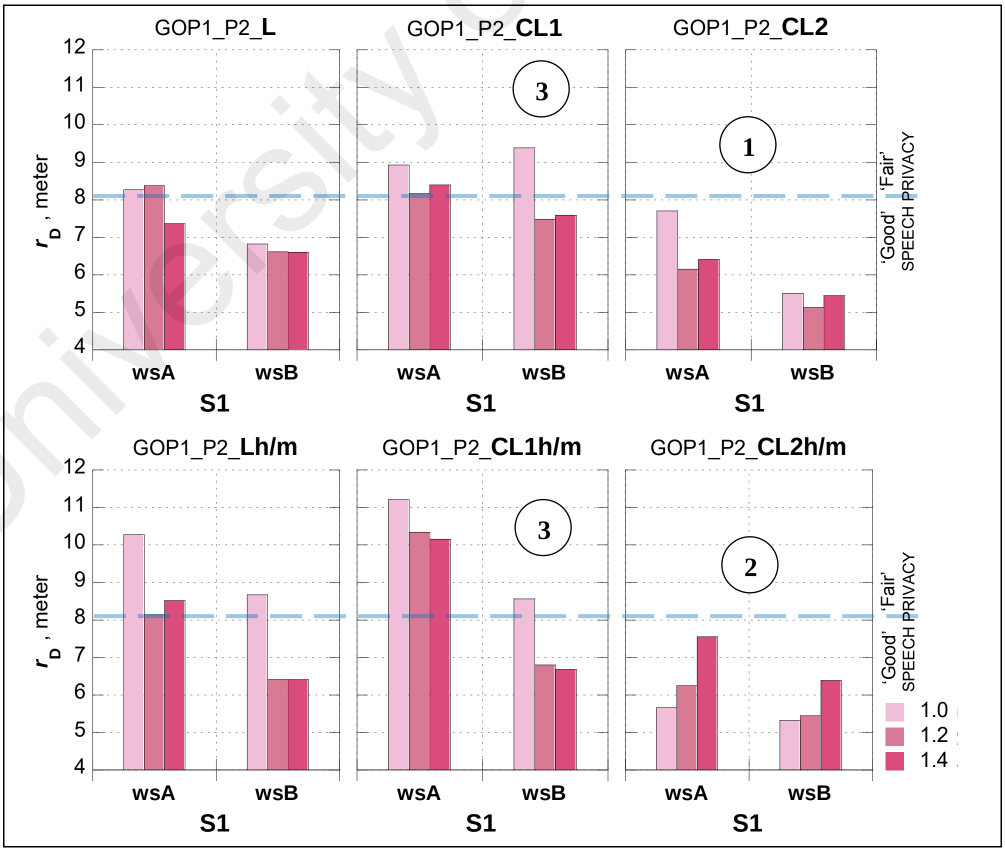
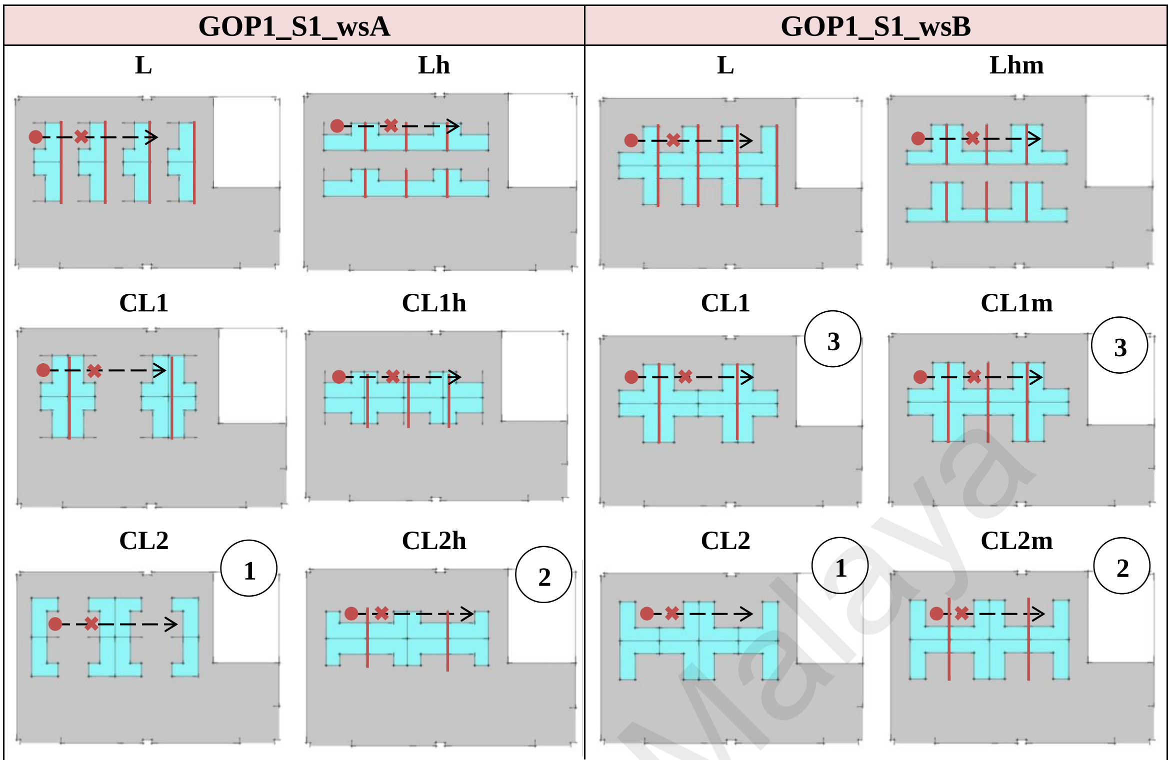


Figure 7.22: Simulated r_D for GOP1 models with P_{TYPE} P2



*See Appendix I1 for ray diagram comparison of No. 1, Appendix I2 for No. 2, and I3 for No. 3.

Figure 7.23: W_{LA} for all GOP1 models

Although, it is interesting to note that the results for models with W_{LA} L, Lh/m, CL1, and CL1h/m show the same tendency as results for models with W_{LA} CL2 where the r_D results decrease with the increase of P_{HEIGHT}. When referring to the layout plans in Figure 7.23, the layouts show that in-between partitions existed between the workstations (SS and the nearest receiver points) for these eight W_{LA} layouts. This is entirely contradicting to the results recorded for models with W_{LA} CL2. However, it can be observed that the difference between layouts W_{LA} CL2 and layouts W_{LA} L, Lh/m, CL1, and CL1h/m is that the distance between the SS and the nearest receiver points. The distance from SS to the nearest receiver point in W_{LA} CL2 is slightly shorter than that in W_{LA} L, Lh/m, CL1, and CL1h/m. As overall it can be conclude that distance between the workstations (SS and receiver points) do not play a major role in influencing the r_D results.

(d) ***GOP2***

As overall, it can be seen in Table 7.7 that models with P_{HEIGHT} 1.0 m record the highest r_D with speech privacy ratings of ‘Poor’ to ‘Fair’, except for models in P_{TYPE} P2 where all the models record ‘Fair’ speech privacy. Models with P_{HEIGHT} 1.2 m and 1.4 m both record almost similar speech privacy ratings of between ‘Good’ and ‘Fair’. However, slight differences in speech privacy ratings can be identify between P_{HEIGHT} 1.2 m and 1.4 m where the majority of models constructed with P_{HEIGHT} 1.4 m render a relatively lower r_D than models with P_{HEIGHT} 1.2 m.

Table 7.7: Simulated r_D for GOP2 models and its speech privacy ratings

GOP2		**P1** (0.75)						**P2** (0.25)					
r_D in meter		L	Lh	CL1	CL1h/m	CL2	CL2h/m	L	Lh	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	11.11	12.55	11.79	11.96	11.85	12.21	10.11	10.58	9.86	10.20	9.91	10.46
2	S1_wsB_***1.0***	11.49	11.56	11.70	12.06	12.06	11.30	9.61	9.58	10.03	10.26	9.91	10.46
3	S2_wsA_***1.0***	11.42	12.39	12.14	11.91	11.83	12.55	9.22	10.38	10.37	10.12	9.97	9.39
4	S2_wsB_***1.0***	11.01	11.35	11.00	11.95	11.78	12.33	9.05	9.47	9.42	10.04	9.76	10.35
5	S1_wsA_***1.2***	9.23	10.29	9.94	9.84	10.01	10.18	7.84	9.37	8.53	8.55	8.55	8.96
6	S1_wsB_***1.2***	9.25	9.76	10.43	9.12	9.71	9.70	7.90	8.40	9.05	8.12	8.19	8.77
7	S2_wsA_***1.2***	8.88	9.91	9.16	9.77	10.91	10.00	7.31	8.95	7.59	8.54	9.52	8.33
8	S2_wsB_***1.2***	9.31	9.55	9.07	9.47	10.87	11.12	7.80	8.14	7.66	8.56	9.47	9.98
9	S1_wsA_***1.4***	8.20	9.17	9.28	9.41	9.41	9.39	7.63	9.15	8.34	8.75	8.52	8.68
10	S1_wsB_***1.4***	8.71	9.26	10.16	8.38	9.19	9.44	7.89	8.26	8.95	8.33	8.12	8.68
11	S2_wsA_***1.4***	8.35	9.04	8.23	9.51	10.65	9.32	7.55	8.82	7.22	8.82	9.56	8.62
12	S2_wsB_***1.4***	8.99	9.15	9.12	8.91	10.68	10.80	7.86	8.01	7.86	8.77	9.49	10.02

GOP2		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	10.71	11.69	10.91	11.13	10.97	11.38	10.97	11.96	11.16	11.41	11.22	11.67
2	S1_wsB_***1.0***	10.64	10.70	10.93	11.24	11.13	11.63	10.86	10.88	11.04	11.54	11.32	11.94
3	S2_wsA_***1.0***	10.44	11.48	11.30	11.09	10.97	10.44	10.68	11.72	11.52	11.28	11.19	10.63
4	S2_wsB_***1.0***	10.14	10.50	10.26	11.10	10.87	11.42	10.27	10.66	10.34	11.32	11.06	11.73
5	S1_wsA_***1.2***	8.80	10.17	9.43	9.36	9.48	9.71	8.88	10.07	9.51	9.44	9.57	9.82
6	S1_wsB_***1.2***	8.70	9.38	9.84	8.80	9.18	9.60	8.89	9.34	9.93	8.89	9.29	9.75
7	S2_wsA_***1.2***	8.35	9.77	8.24	9.36	10.43	9.19	8.42	9.60	8.67	9.33	10.40	9.25
8	S2_wsB_***1.2***	8.70	9.07	8.43	9.30	10.42	10.82	8.81	9.05	8.53	9.19	10.41	10.84
9	S1_wsA_***1.4***	8.30	9.71	9.09	9.38	9.27	9.30	8.08	9.21	9.02	9.21	9.13	9.19
10	S1_wsB_***1.4***	8.50	9.05	9.68	8.75	8.95	9.35	8.52	9.06	9.77	8.38	8.91	9.22
11	S2_wsA_***1.4***	8.32	9.47	7.95	9.53	10.40	9.34	8.14	8.97	7.90	9.24	10.26	9.16
12	S2_wsB_***1.4***	8.62	8.83	8.56	9.31	10.40	10.76	8.66	8.84	8.68	8.85	10.33	10.63

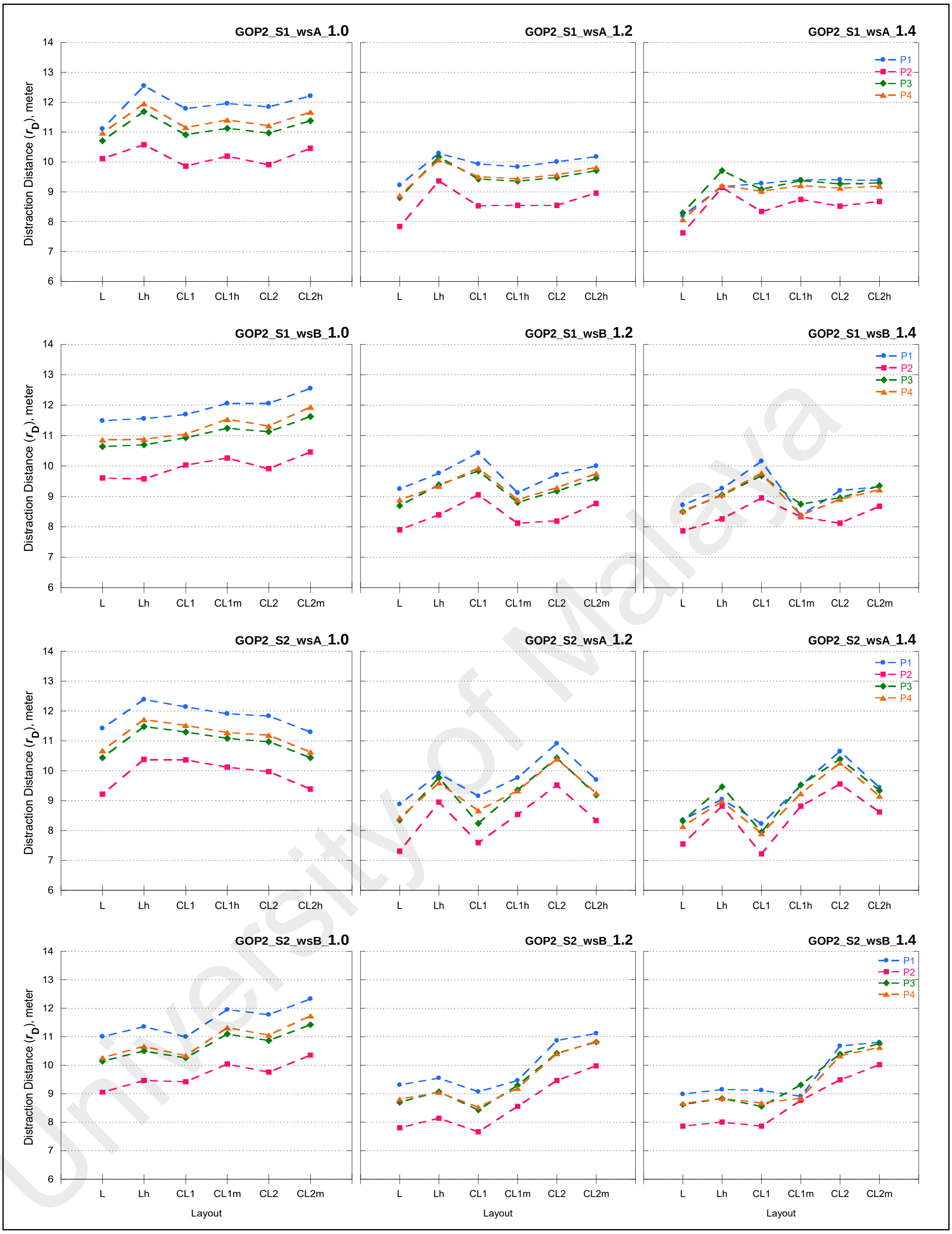


Figure 7.24: Simulated distraction distance (r_D) for GOP2 models

Through the plotted r_D data in Figure 7.24, it can be seen that P_{TYPE} P2 (Pink) logs the lowest r_D data and P_{TYPE} P1 (Blue) records the highest r_D data. It can also be seen that all r_D in P_{TYPE} P2 (0.25α) record speech privacy within the 'Good' and 'Fair' only. Other P_{TYPE}, on the other hand, record a speech privacy of between 'Fair' and 'Poor', with some minor exception on models with P_{TYPE} P3 and P4 which record a borderline 'Good' speech privacy (GOP2_S2_wsA_1.4_CL1).

As it is determined that P_{TYPE} P2 contribute the highest range of speech privacy for models in GOP2, the comparison of the W_{LA} would be focused on the simulated r_D results in P_{TYPE} P2 models. Also, due to the consistent pattern of the r_D data simulated in all P_{TYPE} as illustrates in Figure 7.24, it would be redundant to discuss all the W_{LA} for all P_{TYPE}. Figure 7.25 depicts the simulated r_D results for all the models of GOP2_P2 according to the six W_{LA}. The *y*-axis represents the simulated r_D data in meters and the *x*-axis divides the models into their respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. Individual vertical bars in each graph present the STI data into the three P_{HEIGHT}.

By observing the r_D data presented in Figure 7.25, it can be seen that all models with P_{HEIGHT} 1.0 m constantly record high r_D results of 'Fair' speech privacy. For W_{LA} L, models with the P_{HEIGHT} of 1.2 m and 1.4 m record a relatively lower r_D of around 7 to 8 meters within the 'Good' speech privacy rating. The same results can be seen in models of W_{LA} CL1_S2 with the P_{HEIGHT} of 1.2 m and 1.4 m. Moreover, the lowest r_D is recorded within W_{LA} CL1, where model GOP2_S2_wsA_1.4_CL1 records the lowest r_D of 7.22 meters.

It is interesting to note that even though models S2_wsB_CL1m are a "modified" version of W_{LA} CL1; and the modification consisted of additional partitions between the workstations, it do not affect the simulated r_D results positively (Refer No. 1 and 2 in Figure 7.25 and Figure 7.26). In fact, the r_D actually increases with the additional partitions. The same observation can be made for models S2_wsB_CL2 and CL2m (Refer No. 3 and 4 in Figure 7.25 and Figure 7.26).

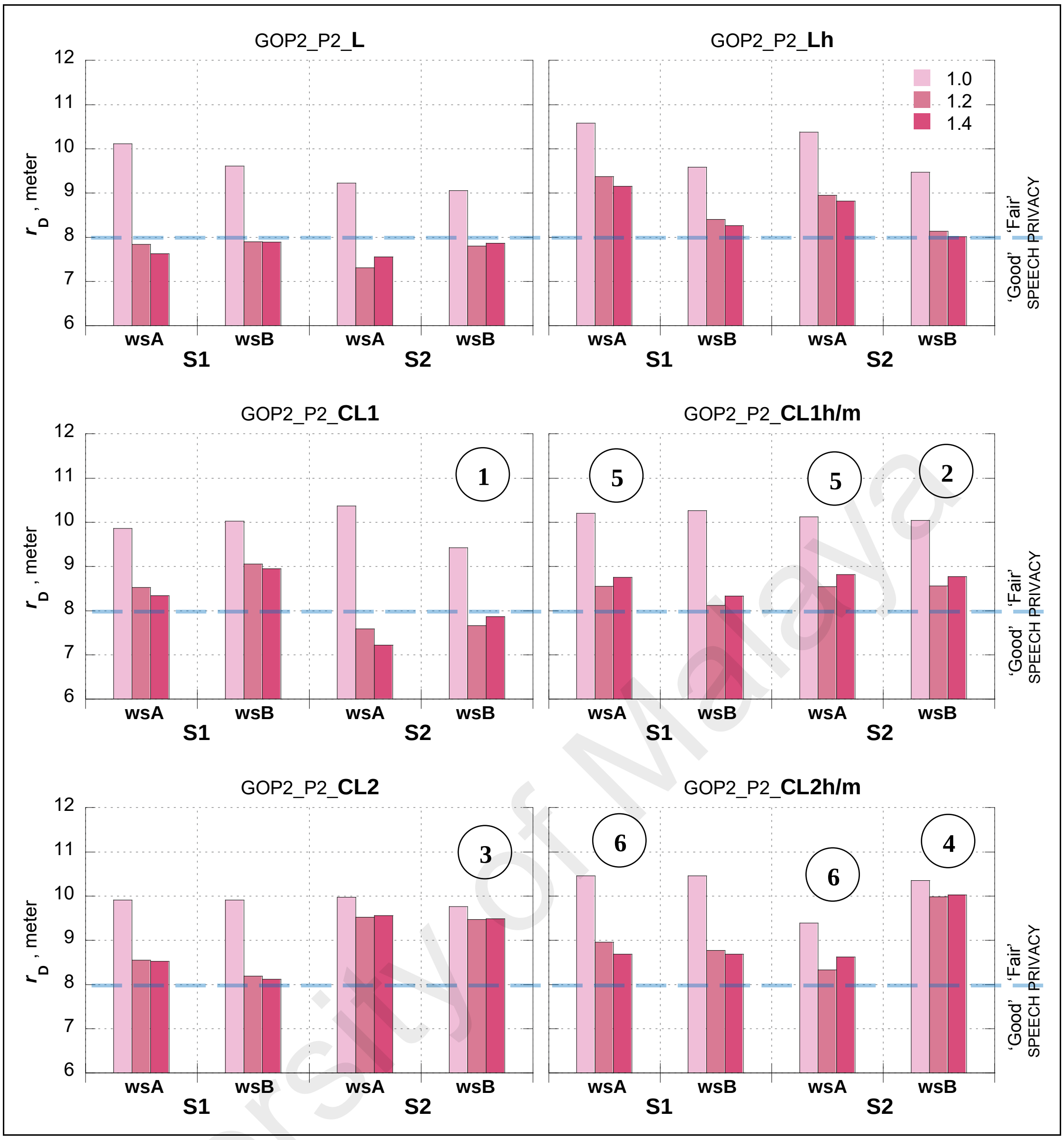


Figure 7.25: Simulated r_D for GOP2 models with P_{TYPE} P2

Comparison of the simulated r_D results for models with W_{LA} Lh between the $W_{DENSITY\_RATIO}$ and W_{SIZE} show that models with $W_{DENSITY\_RATIO}$ S2 and W_{SIZE} wsB resulted in a small decrease in r_D compared to the $W_{DENSITY\_RATIO}$ S1 and W_{SIZE} wsA. For models with W_{LA} CL1h/m, CL2, and CL2h/m it can be seen that models with $W_{DENSITY\_RATIO}$ S2 record a slightly higher r_D results compared to models with $W_{DENSITY\_RATIO}$ S1 despite the increase in distances between the workstations (SS and receiver points). Exceptions can be made for model CL1h/m_wsA_S1/S2 which record an almost similar r_D despite the distance (Refer No. 5 in Figure 7.25 and Figure 7.26) and model CL2h/m_wsA_S1/S2 which record lower r_D (Refer No. 6 in Figure 7.25 and Figure 7.26).

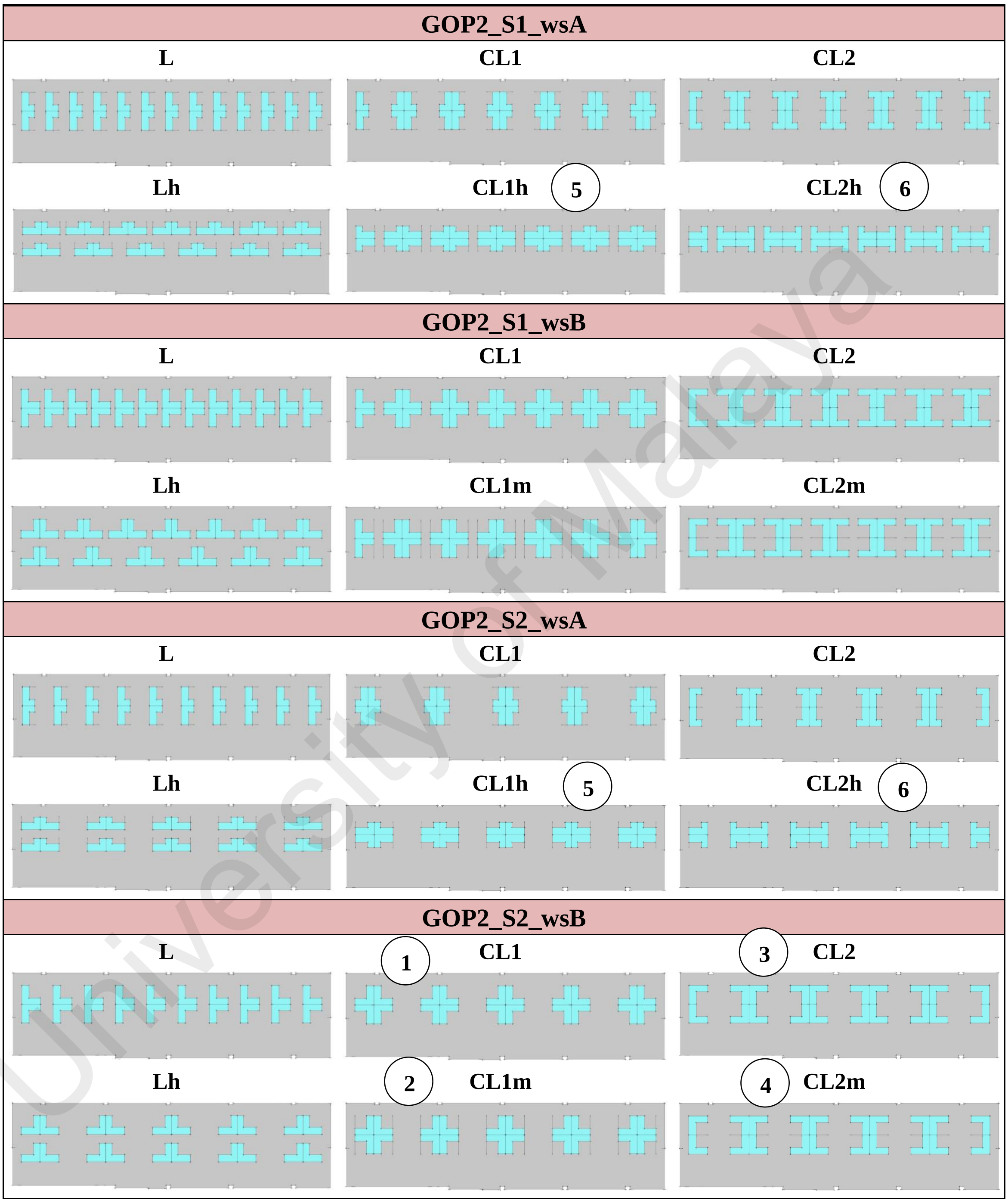


Figure 7.26: W_{LA} for all GOP2 models

Also, unlike the results showed in LOP1 models where the change in the arrangement of the same workstations from Linear (L) to horizontal (Lh) which resulted in a positive r_D results, models with W_{LA} L and Lh in GOP2 do not agree on the same premise. The modification of W_{LA} L into Lh resulted in the increment of r_D results as show in Figure 7.25.

7.1.3 A-weighted SPL of Speech at a Distance of 4m, $L_{p,A,S,4\ m}$ in dB(A)

Similar to the analysis of r_D, and for more precise speech privacy rating classifications and analysis, all simulated $L_{p,A,S,4\ m}$ data, would be render using the micro breakdown segments of colour coding as show in Table 7.8 below. The simulated $L_{p,A,S,4\ m}$ data would be classified into four classes of speech privacy ratings.

Table 7.8: Speech privacy ratings classification for simulated $L_{p,A,S,4\ m}$ data

Speech Privacy Ratings			
Class		**$L_{p,A,S,4\ m}$ in dB(A)**	
A	'Excellent'	< 48	
B	'Good'	48 - 48.99	
		49 - 49.99	
		50 - 50.99	
C	'Fair'	51 - 51.99	
		52 - 52.99	
		53 - 53.99	
D	'Poor'	54 - 54.99	
		55 - 55.99	
		56 - 56.99	
		≥ 57	

The simulated $L_{p,A,S,4\ m}$ results for models in LOP1, LOP2, GOP1, and GOP2 are as depict in Table 7.9, 7.10, 7.11, and 7.12 respectively. Each $L_{p,A,S,4\ m}$ data is highlighted with its speech privacy ratings according to Table 7.8. Each table presents the data in rows of combinations of $W_{DENSITY\_RATIO}$, W_{SIZE}, and P_{HEIGHT} and the columns separate the data into their respective P_{TYPE} and the six W_{LA}.

As overall, it can be seen that models with P_{TYPE} P1 (0.75 α) produce the lowest $L_{p,A,S,4\ m}$ data and P_{TYPE} P2 (0.25 α) produce the highest. Also, it is observe that the tendencies of $L_{p,A,S,4\ m}$ results in all open-plan offices are highly influenced by the partition height. This is illustrates in the way that all the models are primarily divided and arranged (in their tables) into their respective P_{HEIGHT} instead of into groups of $W_{DENSITY\_RATIO}$ or W_{SIZE}.

As P_{TYPE} P1 records the lowest range of $L_{p,\text{A,S,4 m}}$ results for all open-plan offices, observation on the effect of $W_{DENSITY\_RATIO}$, W_{LA}, and W_{SIZE} shall be discussed through the results derive from models with P_{TYPE} P1 as per illustrates in Figure 7.27, 7.32, 7.37, and 7.39. Each figure depicts the simulated $L_{p,\text{A,S,4 m}}$ results for all the models in P_{TYPE} P1 according to the six W_{LA}. The *y*-axis represents the simulated $L_{p,\text{A,S,4 m}}$ data in dB(A) and the *x*-axis divides the models into their respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. Individual vertical bars in each graph present the STI data into the three P_{HEIGHT}.

As $L_{p,\text{A,S,4 m}}$ is technically a measurement of sound pressure level (SPL) and is highly influenced by the amount of absorptive surfaces area in the room, Figure 7.27, 7.32, 7.37, and 7.39 are overlap with linear graphs of the workstation surface area available in the room.

(a) ***LOP1***

Table 7.9 shows that for LOP1, models with P_{TYPE} P1 result in $L_{p,\text{A,S,4 m}}$ with speech privacy range of ‘Fair’, except for few models in with P_{HEIGHT} 1.0 m, which record higher $L_{p,\text{A,S,4 m}}$ with ‘Poor’ speech privacy and few models with P_{HEIGHT} 1.4 m which record $L_{p,\text{A,S,4 m}}$ values with ‘Good’ speech privacy. On the other hand, P_{TYPE} P2 records mostly high $L_{p,\text{A,S,4 m}}$ data with ‘Poor’ speech privacy. P_{TYPE} P3 and P4 which are a derivation of P_{TYPE} P1 and P2 record $L_{p,\text{A,S,4 m}}$ results with similar tendencies to its predecessor.

Table 7.9: Simulated $L_{p,\text{A,S,4 m}}$ for LOP1 models in its speech privacy ratings

LOP1		**P1** (0.75)						**P2** (0.25)					
$L_{p,\text{A,S,4 m}}$ in dB(A)		L	Lh	CL1	CL1h/m	CL2	CL2h/m	L	Lh	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	53.12	53.37	53.99	53.79	52.91	53.83	55.39	55.61	56.02	55.81	55.47	55.86
2	S2_wsA_***1.0***	53.89	53.67	54.66	54.41	54.17	54.48	55.98	55.82	56.37	56.48	56.18	56.52
3	S2_wsB_***1.0***	54.19	54.08	54.69	53.33	52.99	52.75	56.09	55.88	56.15	55.36	55.04	55.12
4	S1_wsA_***1.2***	51.01	51.70	52.42	52.30	52.40	52.44	54.52	54.80	55.28	55.02	55.44	55.16
5	S2_wsA_***1.2***	52.00	52.12	52.87	53.95	52.78	53.89	55.11	55.10	55.31	56.43	55.50	56.41
6	S2_wsB_***1.2***	52.69	52.70	53.33	51.26	51.41	51.21	55.37	55.12	55.31	54.10	54.04	54.25
7	S1_wsA_***1.4***	49.81	50.65	51.42	51.13	52.21	51.46	53.98	54.42	54.95	54.55	55.74	54.79
8	S2_wsA_***1.4***	51.02	51.27	51.88	53.48	52.72	53.71	54.79	54.81	54.96	56.64	55.84	56.82
9	S2_wsB_***1.4***	51.80	51.87	52.60	49.91	50.45	51.40	55.03	54.75	54.96	53.43	53.45	54.74
LOP1		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	54.31	54.62	55.04	54.87	54.32	54.91	53.79	54.02	54.63	54.44	53.73	54.47
2	S2_wsA_***1.0***	54.97	54.81	55.56	55.57	55.31	55.62	54.54	54.34	55.23	55.09	54.80	55.15
3	S2_wsB_***1.0***	55.10	54.95	55.38	54.32	53.99	53.98	54.92	54.80	55.30	54.01	53.76	53.51
4	S1_wsA_***1.2***	53.07	53.60	54.05	53.92	54.19	54.04	51.96	52.53	53.29	53.09	53.30	53.25
5	S2_wsA_***1.2***	53.86	53.91	54.30	55.49	54.53	55.42	52.92	53.00	53.63	54.68	53.56	54.62
6	S2_wsB_***1.2***	54.16	53.97	54.35	52.78	52.68	52.87	53.64	53.62	54.10	52.18	52.45	52.23
7	S1_wsA_***1.4***	52.47	53.09	53.61	53.25	54.48	53.54	50.93	51.64	52.44	52.12	53.17	52.44
8	S2_wsA_***1.4***	53.43	53.52	53.85	55.59	54.81	55.78	52.04	52.24	52.78	54.37	53.58	54.58
9	S2_wsB_***1.4***	53.68	53.43	53.88	51.96	51.98	53.47	52.89	52.94	53.49	50.99	51.55	52.40

Through Figure 7.27, it can be observed that the tendencies of the simulated $L_{p,\text{A,S,4 m}}$ result generally follow the amount of surface area available in each model. It can be seen that as the P_{HEIGHT} gets higher, the amount of surface area in the models increases, and hence the $L_{p,\text{A,S,4 m}}$ decreases.

In term of $W_{\text{DENSITY\_RATIO}}$, a clear comparison between S1 and S2 can only be make with similar W_{SIZE} which in this case, wsA. Again, the decrease in surface areas played a noticeable role in the overall increase of $L_{p,\text{A,S,4 m}}$ in S2 in comparison to S1. On the other hand, between W_{SIZE} wsA and wsB in S2, two different tendencies can be observed between models with W_{LA} L, Lh, and CL1, and models with W_{LA} CL1h/m, CL2, and CL2h/m; where the surface area decreases in the former, and increases in the latter which resulted in the increase and decrease of $L_{p,\text{A,S,4 m}}$ respectively.

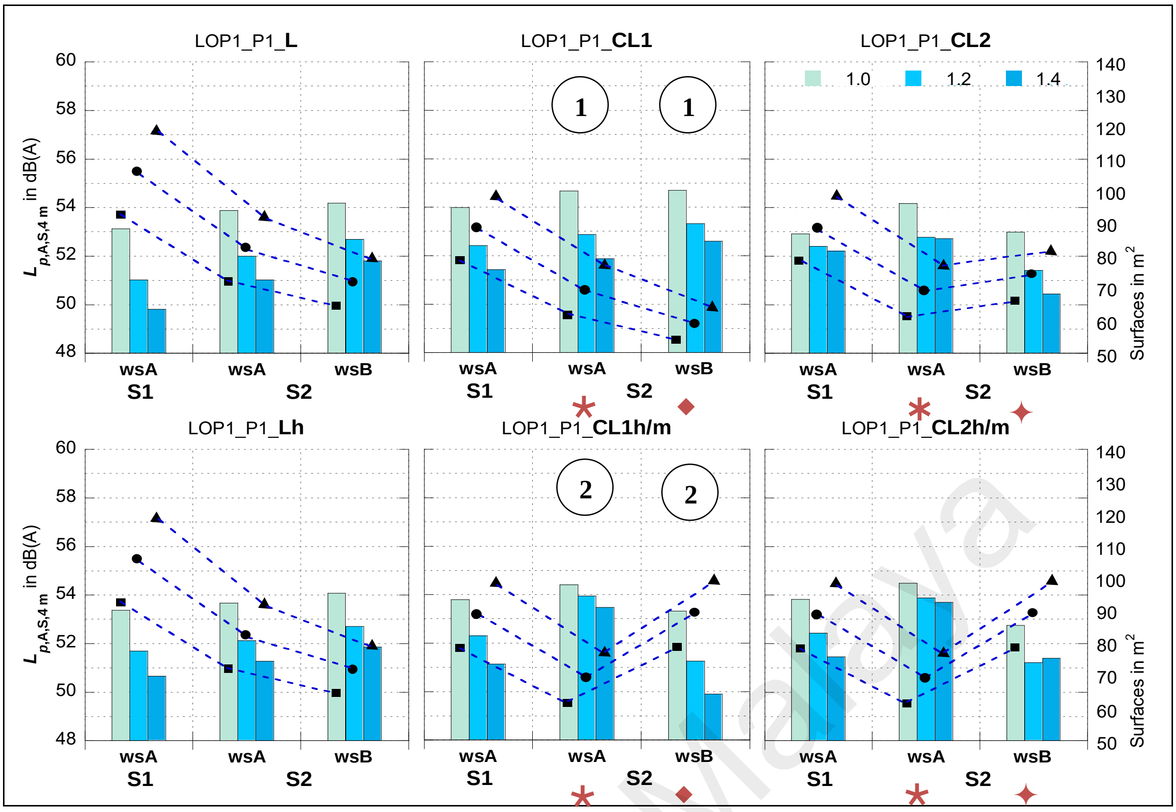


Figure 7.27: Simulated $L_{p,\mathrm{A,S,4\,m}}$ for LOP1 models with $\mathrm{P_{TYPE}}$ P1

Figure 7.27 shows quite a noticeable amount of decrease in surface area between the different $\mathrm{W_{DENSITY\_RATIO}}$ and the $\mathrm{W_{SIZE}}$ in models L, Lh, CL1. However, there is no substantial increase in $L_{p,\mathrm{A,S,4\,m}}$ recorded, which is for all intents and purposes, a good thing. An example can be seen between LOP1_S2_CL1_wsA and wsB, where the $L_{p,\mathrm{A,S,4\,m}}$ record a small increase in wsB despite the decrease in surface area (Refer No. 1 in Figure 7.27). As for Figure 7.28, it can be seen that S2_CL1_wsB could have sustain its $L_{p,\mathrm{A,S,4\,m}}$ reading due to the change in $\mathrm{W_{SIZE}}$ where wsB might have given some sort containment in each of the workstations which put a restraint the sound propagation in the model.

On the other hand, between S2_CL1h/m_wsA and wsB, a generous amount of decrease in $L_{p,\mathrm{A,S,4\,m}}$ (max -3.57 dB(A) in $\mathrm{P_{HEIGHT}}$ 1.4) can be seen due to the increase in surface area (Refer No. 2 in Figure 7.27). Furthermore, a significant decrease of $L_{p,\mathrm{A,S,4}}$

$_{m}$ in CL1m_wsB models with different P_{HEIGHT} can be contributed to the presence of additional partitions which runs across the horizontal measurement paths.

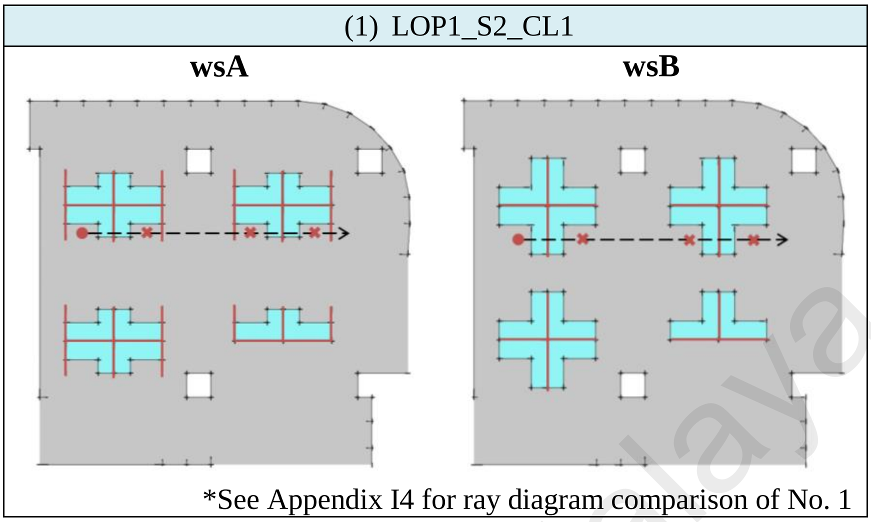


Figure 7.28: Comparison between models' W_{SIZE} in LOP1_S2_CL1

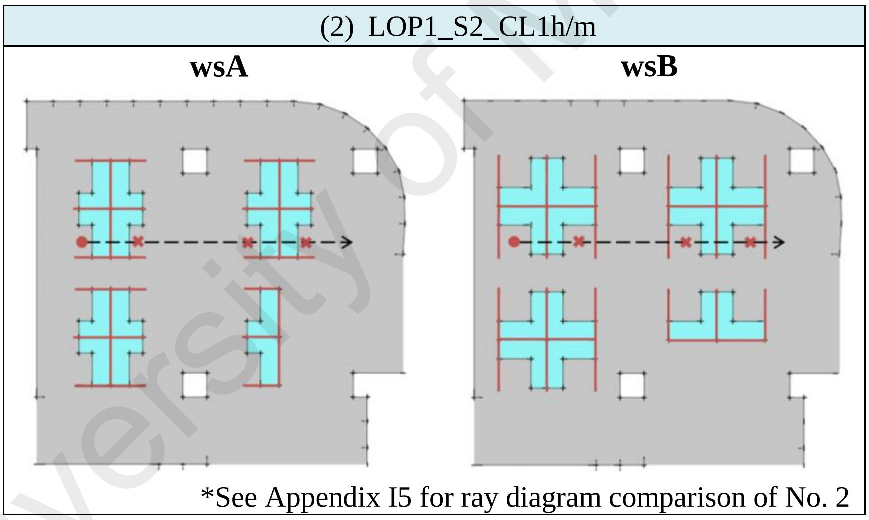


Figure 7.29: Comparison between models' W_{SIZE} in LOP1_S2_CL1h/m

In term of W_{LA}, it can be seen that even though models CL1, CL1h, CL2 and CL2h, in S2_wsA record the same surface area, they did not bear similar $L_{p,\mathrm{A,S,4\,m}}$ results (See ⋆ and ∗ in Figure 7.27). Comparison between LOP1_S2_wsA_CL1 vs. CL1h and LOP1_S2_wsA_CL2 vs. CL2h in Figure 7.30 shows that the only difference in the two models comparisons is the W_{LA} orientation, where layouts in CL1h and CL2h are arranged perpendicular to the arrangement in CL1 and CL2. Hence, the increased $L_{p,\mathrm{A,S,4\,m}}$ in CL1h and CL2h (avg. +1.05 and +1.34 dBA respectively) in comparison to

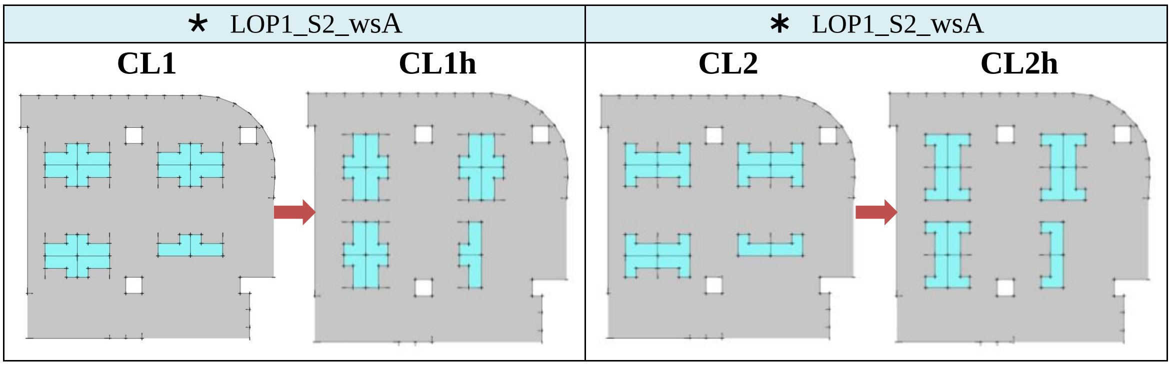


Figure 7.30: Comparison of models' W_{LA} in LOP1_S2_wsA

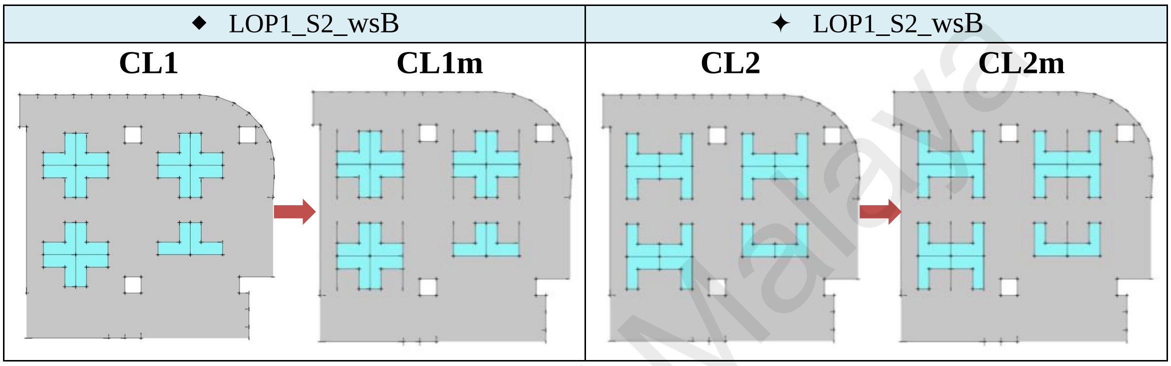


Figure 7.31: Comparison of models' W_{LA} in LOP1_S2_wsB

CL1 and CL2 can be contributed to the arrangement of W_{LA} and geometry of the room itself.

In the case of models CL1, CL1m, CL2, and CL2m in LOP1_S2_wsB, all the models have different surface areas. However, as the W_{SIZE} wsB is square (1.8 m x 1.8 m), the arrangements of all the models are quite similar to each other. Between LOP1_S2_wsB_CL1 and CL1m, besides the increase in the absorptive surface area, the average 2.04 dB(A) decrease in $L_{p,\mathrm{A,S,4\ m}}$ (See ◆ in Figure 7.27) can also be attributes to the additional partitions in each of the workstation clusters (See Figure 7.31), where it provides surplus amount of barrier between the clusters. However, between LOP1_S2_wsB_CL2 and CL2m, even though the surface area clearly increases due to the additional partitions in-between the adjacent workstations in CL2m, the $L_{p,\mathrm{A,S,4\ m}}$ do not show any significant decrease (avg. -0.22 dBA for P_{HEIGHT} 1.0 m and 1.2 m). In fact, the $L_{p,A,S,4\ m}$ in CL2m with P_{HEIGHT} 1.4 m increases at about 0.95 dB(A) in comparison to CL2 (See ✦ in Figure 7.27).

(b) ***LOP2***

As for LOP2, all models in every P_{TYPE} mostly record $L_{p,A,S,4\ m}$ results with speech privacy of between 'Fair' and 'Good'. Few exceptions can be observed in some models with P_{TYPE} P2 and P3 which are models of $W_{DENSITY\_RATIO}$ S2 with W_{SIZE} wsA in P_{HEIGHT} 1.0 m, 1.2 m, and 1.4 m. In P_{TYPE} P1 group, clear differences in $L_{p,A,S,4\ m}$ results can be seen between the P_{HEIGHT} 1.0 m, 1.2 m, and 1.4 m. Models with P_{HEIGHT} 1.0 m record $L_{p,A,S,4\ m}$ results with 'Fair' speech privacy all around while P_{HEIGHT} 1.2 m and 1.4 m record $L_{p,A,S,4\ m}$ results with mostly 'Good' speech privacy, except two models (S1_wsA_1.4_Lh and CL2) which record 'Excellent' results with $L_{p,A,S,4\ m}$ of below 48 dB(A).

Table 7.10: Simulated $L_{p,A,S,4\ m}$ for LOP2 models in its speech privacy ratings

LOP2		**P1** (0.75)						**P2** (0.25)					
$L_{p,A,S,4\ m}$ in dB(A)		**L**	**Lh**	**CL1**	**CL1h/m**	**CL2**	**CL2h/m**	**L**	**Lh**	**CL1**	**CL1h/m**	**CL2**	**CL2h/m**
1	S1_wsA_***1.0***	51.64	51.48	52.43	52.33	52.02	52.46	53.33	53.19	53.83	53.76	53.77	53.94
2	S2_wsA_***1.0***	52.28	51.77	52.87	52.74	52.49	53.10	53.78	53.29	54.13	54.19	54.09	54.63
3	S2_wsB_***1.0***	52.45	51.82	52.55	51.73	51.30	51.24	53.67	53.01	53.42	53.15	52.70	53.11
4	S1_wsA_***1.2***	49.32	49.08	50.27	50.74	50.50	50.85	52.19	51.82	52.52	52.84	52.95	52.97
5	S2_wsA_***1.2***	50.26	49.67	51.13	52.06	50.17	52.68	52.82	52.11	53.10	54.22	52.83	54.65
6	S2_wsB_***1.2***	50.96	49.93	50.95	49.34	48.46	49.48	52.89	51.83	52.29	51.60	50.89	52.11
7	S1_wsA_***1.4***	48.07	47.50	49.17	49.63	50.38	50.19	51.77	51.09	52.13	52.37	53.41	52.73
8	S2_wsA_***1.4***	49.28	48.35	50.60	51.43	50.12	52.67	52.56	51.50	53.15	54.38	53.55	55.34
9	S2_wsB_***1.4***	50.10	48.81	50.07	48.04	47.26	49.45	52.54	51.26	51.79	51.07	50.24	52.69
LOP2		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	52.62	52.46	53.26	53.19	53.13	53.38	52.12	51.98	52.82	52.73	52.46	52.87
2	S2_wsA_***1.0***	53.14	52.63	53.62	53.60	53.53	54.05	52.73	52.25	53.25	53.17	52.90	53.54
3	S2_wsB_***1.0***	53.10	52.42	53.02	52.49	52.06	52.31	52.90	52.28	52.88	52.18	51.81	51.79
4	S1_wsA_***1.2***	51.22	50.87	51.70	52.17	52.13	52.25	50.04	49.80	50.88	51.26	51.13	51.41
5	S2_wsA_***1.2***	51.96	51.27	52.45	53.56	52.02	54.02	50.93	50.34	51.65	52.62	50.86	53.19
6	S2_wsB_***1.2***	52.16	51.05	51.75	50.68	49.86	51.08	51.57	50.57	51.40	50.01	49.34	50.21
7	S1_wsA_***1.4***	50.66	49.99	51.22	51.59	52.62	51.96	48.93	48.38	49.90	50.27	51.04	50.82
8	S2_wsA_***1.4***	51.59	50.52	52.42	53.63	52.66	54.67	50.08	49.15	51.24	52.11	50.95	53.27
9	S2_wsB_***1.4***	51.67	50.33	51.16	50.00	49.10	51.72	50.84	49.60	50.60	48.84	48.25	50.39

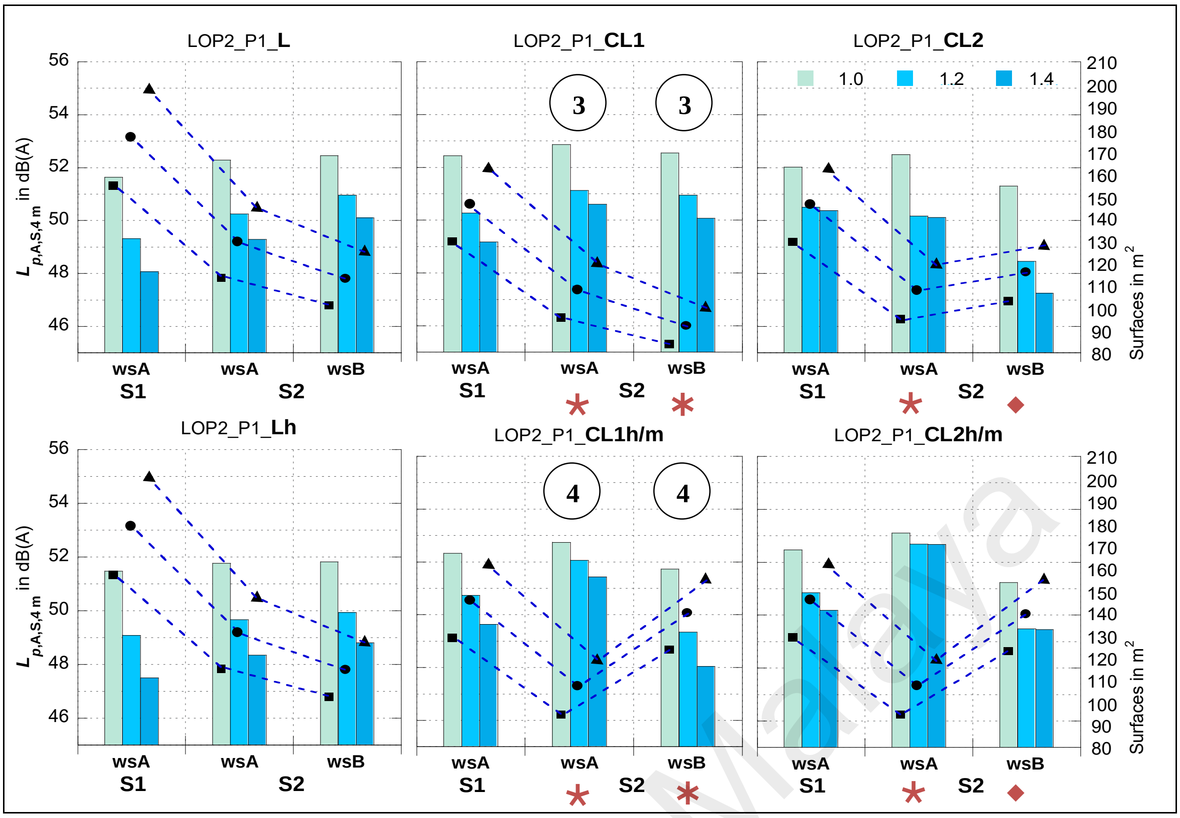


Figure 7.32: Simulated $L_{p,\mathrm{A,S,4\ m}}$ for LOP2 models with P$_{\mathrm{TYPE}}$ P1

From Figure 7.32, it can be observed that the tendencies of the simulated $L_{p,\mathrm{A,S,4\ m}}$ results generally follow the total surface area available in each model. Depending on the P$_{\mathrm{HEIGHT}}$, it can be seen that as the P$_{\mathrm{HEIGHT}}$ gets higher, the surface area in the models increases, and therefore the $L_{p,\mathrm{A,S,4\ m}}$ decreases.

In term of W$_{\mathrm{DENSITY_RATIO}}$, models in LOP2 show similar tendencies as LOP1 where models with S2 (between wsA_S1 and S2) record a slight increase in $L_{p,\mathrm{A,S,4\ m}}$ in accordance to the decrease in absorptive surface area. Conversely, between W$_{\mathrm{SIZE}}$ wsA and wsB in W$_{\mathrm{DENSITY_RATIO}}$ S2, two different tendencies can be observed between models with W$_{\mathrm{LA}}$ L, Lh, and CL1, and models with W$_{\mathrm{LA}}$ CL1h/m, CL2, and CL2h/m; where the surface area decrease in the former and increase in the latter which resulted in the increment and decrement of $L_{p,\mathrm{A,S,4\ m}}$ respectively.

Figure 7.32 show that there is a noticeable decrease in surface area between $W_{DENSITY\_RATIO}$ and W_{SIZE} in models L, Lh, and CL1. Like LOP1, the $L_{p,\mathrm{A,S,4\ m}}$ for these models do not increase extensively as well. In fact, despite the decrease in the total surface area; the $L_{p,\mathrm{A,S,4\ m}}$ in LOP2_S2_CL1_wsB actually decreases at an average of 0.34 dB(A) in comparison to wsA (Refer No. 3 in Figure 7.32). When the layout plans are referred to as per illustrates in Figure 7.33, it can be seen that the $L_{p,\mathrm{A,S,4\ m}}$ readings in LOP2_S2_CL1_wsB could have decrease due to the change in W_{SIZE} where wsB might have restrain the sound propagation between intermediate workstations.

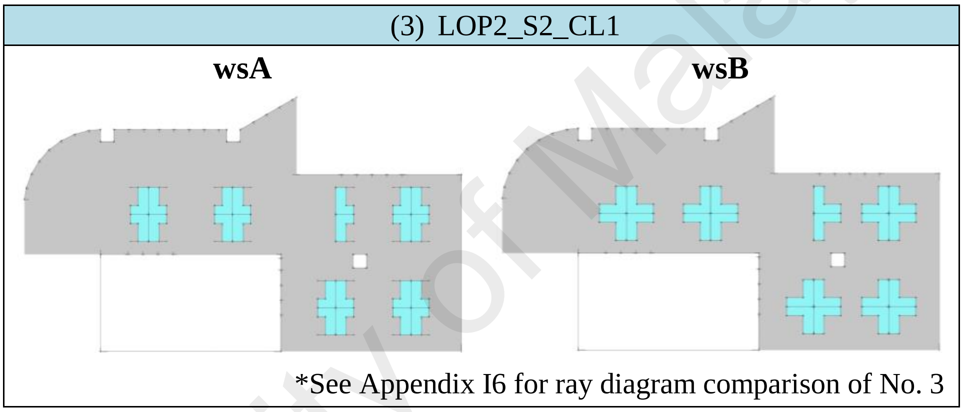


Figure 7.33: Comparison between models' W_{SIZE} in LOP2_S2_CL1

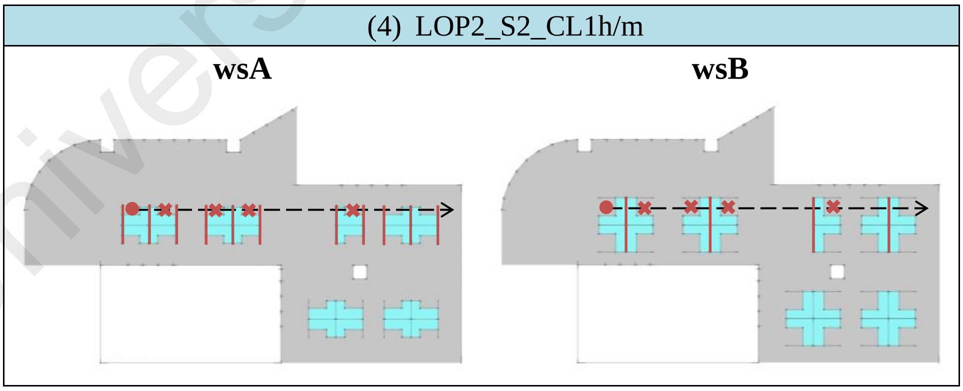


Figure 7.34: Comparison between models' W_{SIZE} in LOP2_S2_CL1h/m

On the other hand, between LOP2_S2_CL1h/m_wsA and wsB, a generous amount of decrease in $L_{p,\mathrm{A,S,4\ m}}$ can be seen due to the increased surface area (Refer No. 4 in Figure 7.32). The large decrease in $L_{p,\mathrm{A,S,4\ m}}$ between models with different P_{HEIGHT} 1.0 (-1.02 dBA), 1.2 (-2.72 dBA), and 1.4 (-3.39 dBA) in CL1m_wsB can be contributed to the presence of additional partitions heights, which adds to the total amount of absorptive materials for each workstation, despite the reduction of partitions between the receiver points (See Figure 7.34).

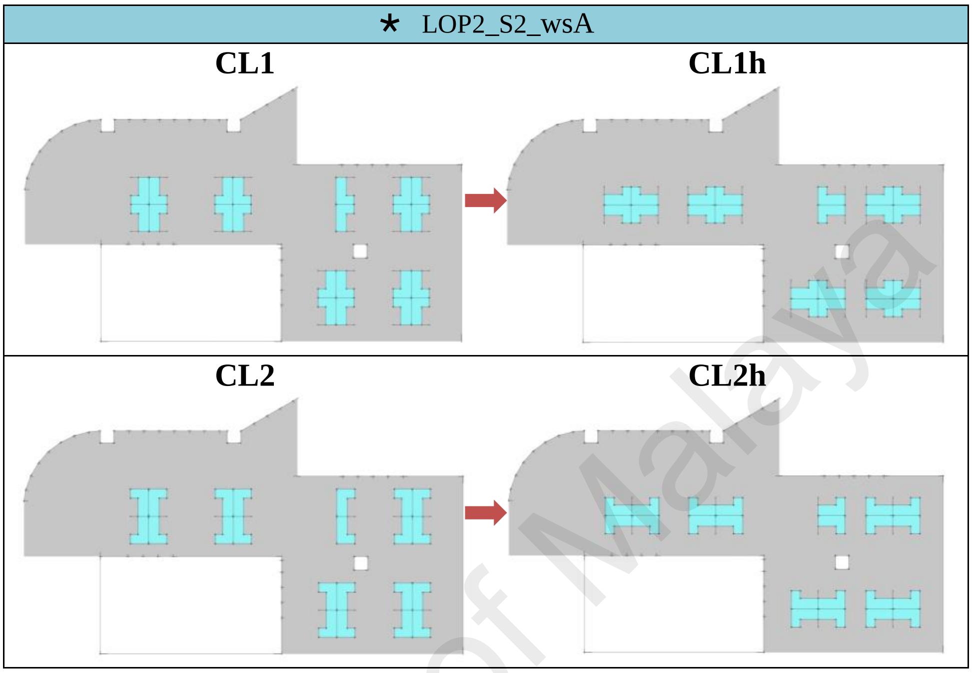


Figure 7.35: Comparison of models' W_{LA} in LOP2_S2_wsA

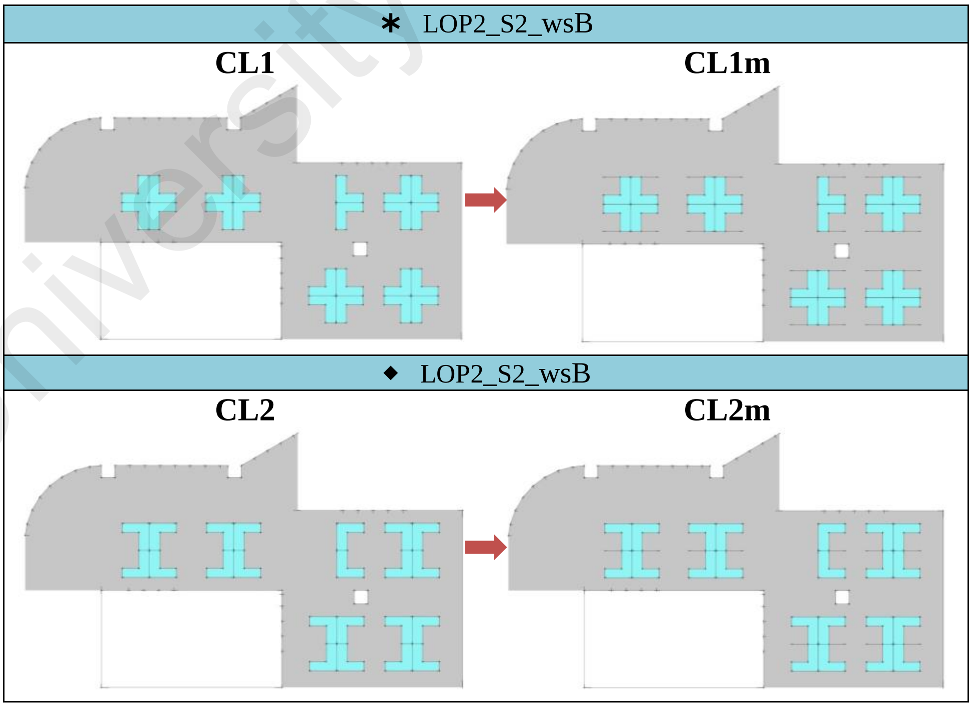


Figure 7.36: Comparison of models' W_{LA} in LOP2_S2_wsB

In term of W_{LA}, it can be seen that the transformation of layout orientation from CL1 to CL1h and CL2 to CL2h in LOP1_S2_wsA (See Figure 7.35) contribute to the average increase of 0.88 dB(A) and 1.89 dB(A) in $L_{p,\mathrm{A,S,4\ m}}$ results as illustrates in Figure 7.32 (See ⋆). This is despite the tiny differences in term of the absorptive surface area between W_{LA} CL1 and CL1h, and CL2 and CL2h.

On the other hand, model LOP2_S2_wsB_CL1m shows an average decreased of 1.48 dB(A) in $L_{p,\mathrm{A,S,4\ m}}$ in comparison to W_{LA} CL1 as it corresponds to the increase of the absorptive surface area as illustrate in Figure 7.36 and Figure 7.32 (See ∗). However, unusual results can be observed between model LOP2_S2_wsB CL2 and CL2m where the $L_{p,\mathrm{A,S,4\ m}}$ actually increases (avg. +1.6 dBA) despite the increasing absorptive surface area particularly in models with P_{HEIGHT} 1.2 and 1.4 (See ◆ in Figure 7.32). This suggests that additional absorptive surfaces should be carefully placed and designed in accordance with the tiny details in the workstations arrangement.

The same finding could also be observed in the results of LOP2_S2_wsB_CL1m vs. CL2m. Despite both models having identical surface areas, $W_{DENSITY\_RATIO}$, W_{SIZE}, and P_{TYPE} (See CL1m and CL2m in Figure 7.36); minor discrepancies between the W_{LA}, where in one layout the desk is arranged in a "T" shape clusters while the other in a "U" shape clusters could contribute to different results in $L_{p,\mathrm{A,S,4\ m}}$ (in this case an increase in CL2m) particularly in models with P_{HEIGHT} of 1.2 m and 1.4 m. Conversely, for model S2_wsB_CL1 and CL2 which do not have an identical surface area but closely similar attributes, the $L_{p,\mathrm{A,S,4\ m}}$ decreases in CL2 ("U" shape cluster) unlike the modified versions of the models (CL1m and CL2m).

(c) ***GOP1***

While design variable W_{SIZE} highly influenced the simulated r_D of GOP1, it was observed that the simulated $L_{p,A,S,4\,m}$ results in GOP1 are influenced by the variables P_{HEIGHT} as presented in Table 7.11. Like LOP1 and LOP2, in comparison to other absorptive partition types, P_{TYPE} P1 continues to positively influence the simulation of $L_{p,A,S,4\,m}$ data. This can be seen in the 'Fair' speech privacy classification plotted in P1 models. However, a slightly significant differences can be seen in design variable P_{HEIGHT} as the results show that models with P_{HEIGHT} 1.0 m consistently recorded 'Poor' $L_{p,A,S,4\,m}$ results throughout all P_{TYPE}.

Table 7.11: Simulated $L_{p,A,S,4\,m}$ for GOP1 models in its speech privacy ratings

GOP1		**P1** (0.75)						**P2** (0.25)					
$L_{p,A,S,4\,m}$ in dB(A)		L	Lhm	CL1	CL1h/m	CL2	CL2h/m	L	Lhm	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	54.63	54.63	55.15	55.32	54.79	55.19	56.44	56.57	56.93	56.80	56.66	56.69
2	S1_wsB_***1.0***	54.86	54.64	55.58	55.32	55.02	54.23	56.42	56.41	56.86	56.70	56.61	56.11
3	S1_wsA_***1.2***	52.58	52.73	53.57	53.71	52.80	53.70	55.21	55.70	56.09	55.92	55.37	55.86
4	S1_wsB_***1.2***	53.09	52.82	54.28	53.79	53.69	52.35	55.40	55.47	56.12	55.81	55.97	55.07
5	S1_wsA_***1.4***	51.11	51.41	52.72	52.60	51.43	52.61	54.53	55.27	55.84	55.50	54.69	55.46
6	S1_wsB_***1.4***	52.02	51.73	53.45	52.88	52.91	50.97	54.91	55.02	55.75	55.39	55.68	54.55
GOP1		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	55.73	55.79	56.25	56.26	55.84	56.14	55.11	55.18	55.65	55.72	55.27	55.59
2	S1_wsB_***1.0***	55.74	55.60	56.27	56.10	55.86	55.32	55.37	55.24	56.08	55.79	55.62	54.80
3	S1_wsA_***1.2***	54.32	54.73	55.27	55.24	54.48	55.18	53.20	53.47	54.22	54.23	53.45	54.22
4	S1_wsB_***1.2***	54.54	54.43	55.39	55.06	55.05	54.07	53.76	53.65	54.92	54.41	54.48	53.10
5	S1_wsA_***1.4***	53.57	54.22	54.94	54.74	53.69	54.69	51.81	52.26	53.46	53.23	52.19	53.24
6	S1_wsB_***1.4***	53.98	53.90	54.93	54.56	54.71	53.45	52.82	52.65	54.18	53.60	53.78	51.89

Comparison of models in GOP1 through $W_{DENSITY\_RATIO}$ cannot be made as the small open-plan office size did not allow for the design variable to be utilised. In term of W_{SIZE}, the effect of the total surface area can be seen as per illustrates in Figure 7.37. It can be observed that with models with W_{LA} L, CL1, and CL2, as the surface area decrease, a slight amount of increase in $L_{p,A,S,4\,m}$ can be detected. The same effect can be observed in W_{LA} CL2h/m but with an opposite result where the $L_{p,A,S,4\,m}$ decrease with the increase in absorptive surface area. Slight divergence can be seen in W_{LA} Lhm and CL1hm where tiny increases in absorptive surfaces resulted in a tiny increment of $L_{p,\mathrm{A,S,4\ m}}$ specifically in models with P_{HEIGHT} 1.2 m and 1.4 m.

On the other hand, the effect of different W_{LA} with similar surface areas can be observed in two instances. One is between GOP1_S2_wsA_CL1h and CL2h, and the other one is between GOP1_S2_wsB_Lhm and CL2m as illustrates in Figure 7.38. In Figure 7.37 it can be seen that for GOP1_S1_wsA_CL1h vs. CL2h (See ⋆ in Figure 7.37), the slight difference in the clustering design of "T" and "U" shapes has no perceptible effect on the $L_{p,\mathrm{A,S,4\ m}}$ results. Meanwhile, for GOP1_S1_wsB_Lhm vs. CL2m (See ∗ in Figure 7.37), the changes in the layout from linear (horizontal) arrangement (Lhm) to "U" shape cluster (CL2m) made a visually noticeable impact on the $L_{p,\mathrm{A,S,4\ m}}$, where it decreases at an average of 0.55 dB(A) in the latter WLA.

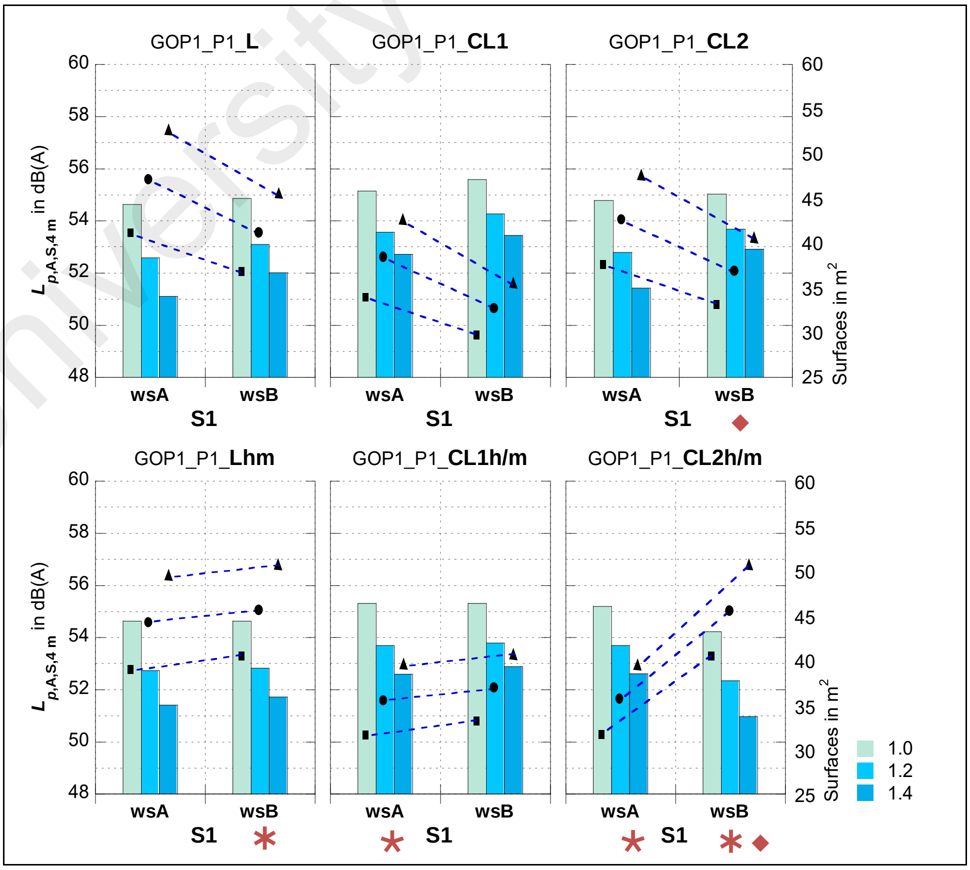


Figure 7.37: Simulated $L_{p,\mathrm{A,S,4\ m}}$ for GOP1 models with P_{TYPE} P1

In the case of GOP1_S1_wsA_CL1 vs. CL1h (avg. +0.16 dBA), and CL2 vs. CL2h (avg. +0.83 dBA), or between GOP1_S1_wsA_CL1 vs. CL2 (avg. -0.8 dBA); it is quite hard to pinpoint if the changes in orientation, arrangement, or clustering shape have any impact on the $L_{p,\mathrm{A,S},4\ \mathrm{m}}$ readings due to the discrepancies in total surface area. Conversely, unlike similar situations found in LOP1 and LOP2, it can be seen that the additional intermediate partitions work in favour of GOP1_S1_wsB_CL2m as the $L_{p,\mathrm{A,S},4\ \mathrm{m}}$ decreases with an average of 1.36 dB(A) in comparison to WLA CL2 which has no barriers present between immediate workstations (See ◆ in Figure 7.37 and Figure 7.38).

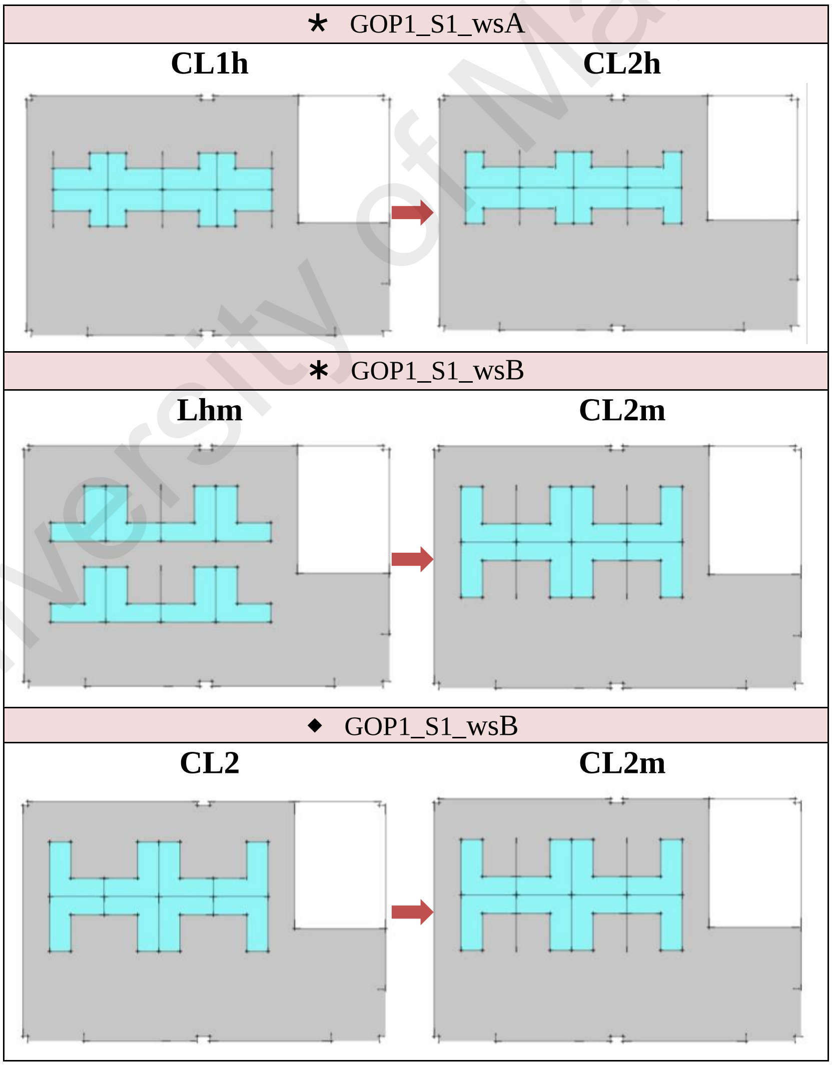


Figure 7.38: Comparison of models' W_{LA} in GOP1_S1_wsA and wsB

(d) ***GOP2***

Much like other open-plan offices, GOP2 models in P_{TYPE} P1 simulates the lowest range of $L_{p,\mathrm{A,S,4\ m}}$ in comparison to identical models in other P_{TYPE}. Correspondingly, P_{TYPE} P2 continues to simulate the highest range of $L_{p,\mathrm{A,S,4\ m}}$ results of within 'Fair' and 'Poor' speech privacy. In term of P_{HEIGHT}, GOP2 models with partition heights 1.2 m and 1.4 m seems to work better as both resulted in lower $L_{p,\mathrm{A,S,4\ m}}$, with P_{HEIGHT} 1.4 m simulates slightly lower $L_{p,\mathrm{A,S,4\ m}}$ than P_{HEIGHT} 1.2 m. Although, the differences are negligible as both results fell under speech privacy classification between 'Fair' and 'Good'.

Table 7.12: Simulated $L_{p,\mathrm{A,S,4\ m}}$ for GOP2 models in its speech privacy ratings

GOP2		**P1** (0.75)						**P2** (0.25)					
$L_{p,\mathrm{A,S,4\ m}}$ in dB(A)		L	Lh	CL1	CL1h/m	CL2	CL2h/m	L	Lh	CL1	CL1h/m	CL2	CL2h/m
1	S1_wsA_***1.0***	52.98	52.60	53.60	53.00	53.58	53.36	54.21	54.39	55.05	54.32	55.07	54.71
2	S1_wsB_***1.0***	52.78	52.62	53.58	52.34	52.87	52.47	54.16	54.10	54.72	53.92	54.35	54.18
3	S2_wsA_***1.0***	53.05	52.68	55.29	53.11	54.05	53.86	54.54	54.40	56.53	54.45	55.38	55.15
4	S2_wsB_***1.0***	53.30	52.79	53.53	52.54	53.44	53.03	54.56	54.12	54.51	54.16	54.94	54.77
5	S1_wsA_***1.2***	50.06	50.52	52.00	51.23	52.06	51.57	52.55	53.48	54.20	53.25	54.29	53.69
6	S1_wsB_***1.2***	50.87	50.95	52.47	50.15	51.15	50.54	52.98	53.26	54.15	52.61	53.37	53.10
7	S2_wsA_***1.2***	50.94	50.71	53.57	51.35	53.10	52.25	53.19	53.53	55.42	53.44	55.16	54.23
8	S2_wsB_***1.2***	51.76	51.16	52.09	50.53	52.61	51.97	53.62	53.26	53.55	53.09	54.83	54.60
9	S1_wsA_***1.4***	48.48	49.19	51.07	49.95	51.12	50.91	51.82	53.13	53.90	52.73	53.92	53.56
10	S1_wsB_***1.4***	49.81	49.85	51.79	48.63	50.13	49.25	52.52	52.82	53.85	51.99	52.89	52.51
11	S2_wsA_***1.4***	49.54	49.23	52.82	50.06	52.30	51.65	52.60	53.09	55.31	52.96	54.84	54.08
12	S2_wsB_***1.4***	51.04	50.02	51.17	49.13	52.11	51.29	53.32	52.76	53.08	52.60	54.70	54.43
GOP2		**P3** (0.25 | 0.75)						**P4** (0.75 | 0.25)					
1	S1_wsA_***1.0***	53.70	53.66	54.47	53.83	54.49	54.22	53.24	53.09	54.01	53.34	53.99	53.72
2	S1_wsB_***1.0***	53.53	53.38	54.18	53.24	53.64	53.41	53.25	53.17	54.03	52.80	53.40	52.98
3	S2_wsA_***1.0***	53.94	53.69	56.07	53.95	54.89	54.67	53.47	53.18	55.62	53.49	54.40	54.23
4	S2_wsB_***1.0***	53.97	53.48	54.06	53.45	54.22	53.99	53.78	53.31	53.92	53.06	54.01	53.58
5	S1_wsA_***1.2***	51.69	52.57	53.50	52.62	53.58	53.04	50.80	51.24	52.55	51.72	52.62	52.09
6	S1_wsB_***1.2***	52.13	52.36	53.50	51.70	52.46	52.15	51.56	51.70	53.04	50.84	51.88	51.25
7	S2_wsA_***1.2***	52.41	52.66	54.78	52.81	54.62	53.61	51.52	51.40	54.02	51.87	53.52	52.76
8	S2_wsB_***1.2***	52.83	52.46	52.97	52.17	54.04	53.76	52.42	51.85	52.60	51.27	53.29	52.64
9	S1_wsA_***1.4***	50.85	52.11	53.13	52.00	53.14	52.88	49.20	50.07	51.74	50.55	51.79	51.50
10	S1_wsB_***1.4***	51.55	51.80	53.13	50.95	51.88	51.44	50.63	50.76	52.43	49.49	50.98	50.09
11	S2_wsA_***1.4***	51.70	52.09	54.73	52.22	54.23	53.43	50.27	50.11	53.35	50.72	52.80	52.22
12	S2_wsB_***1.4***	52.45	51.82	52.42	51.54	53.85	53.52	51.80	50.86	51.79	50.07	52.87	52.06

In term of $W_{DENSITY\_RATIO}$, as seen in Figure 7.39 it can be observed that S2 records a slightly higher $L_{p,\mathrm{A,S,4\ m}}$ than S1 and this was highly influenced by the surface area of each model. Similar to $W_{DENSITY\_RATIO}$, the tendencies of $L_{p,\mathrm{A,S,4\ m}}$ results in term of W_{SIZE} depended mainly on the total surface area of each model. Figure 7.39 shows that for W_{LA} L, Lh, and CL; wsB have somewhat lower surface areas compared to wsA within the same $W_{DENSITY\_RATIO}$ and this made the $L_{p,\mathrm{A,S,4\ m}}$ marginally higher. On the other hand, for W_{LA} CL1h/m, CL2, and CL2h/m; W_{SIZE} wsB has a noticeably higher surface area than models with wsA (within the same $W_{DENSITY\_RATIO}$) which results in a higher $L_{p,\mathrm{A,S,4\ m}}$ accordingly.

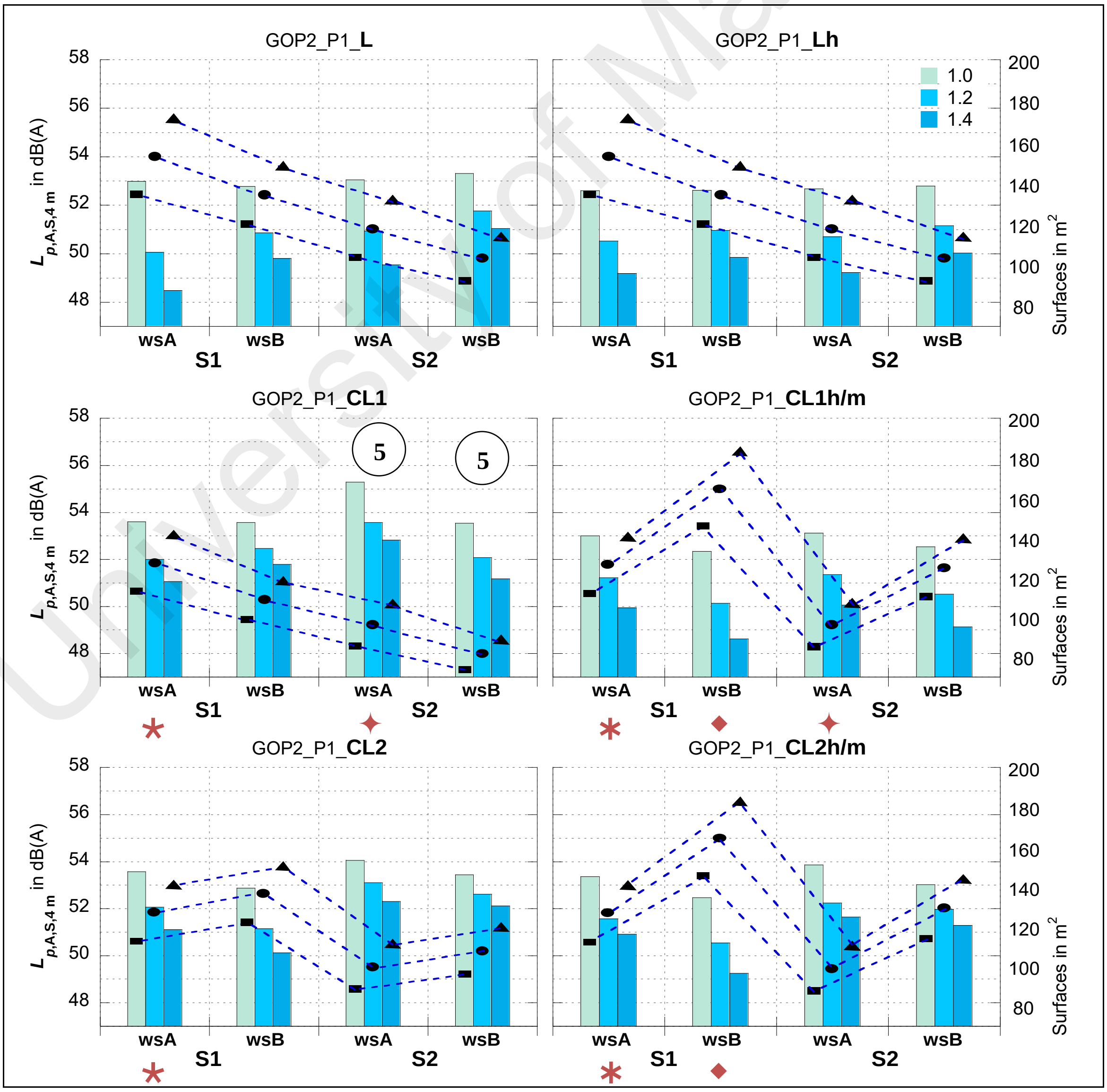


Figure 7.39: Simulated $L_{p,\mathrm{A,S,4\ m}}$ for GOP2 models with P_{TYPE} P1

However, while all the simulated $L_{p,\mathrm{A,S,4\ m}}$ results follow the rule of thumb where; the higher the surface area is, the lower the $L_{p,\mathrm{A,S,4\ m}}$ will be; one small disagreement can be seen in model GOP2_S2_CL1 between the W_{SIZE} wsA and wsB. As illustrates in Figure 7.39 (See to No. 5), it can be seen that even though the total surface area for wsB is clearly lower than that in wsA, the $L_{p,\mathrm{A,S,4\ m}}$ actually decreases, instead of increasing according to the general rule of thumb. Granted, this is not necessarily a bad result as the aim is to achieve low $L_{p,\mathrm{A,S,4\ m}}$. When referring to the layout plans as shown in Figure 7.40, the differences in term of W_{SIZE} can be seen. However, it is a bit difficult to pinpoint the advantages of W_{LA} CL1_wsB compared to wsA as both have similar arrangements.

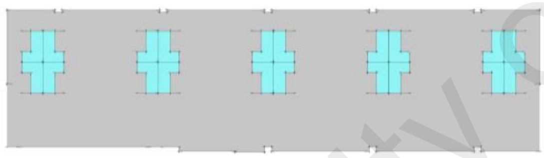
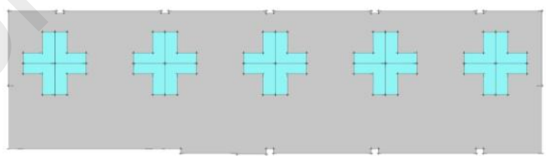
(5) GOP2_S2_CL1	
wsA	**wsB**
	

Figure 7.40: Comparison between models' W_{SIZE} in GOP2_S2_CL1

In term of W_{LA}, from Table 7.12 it can roughly be seen that W_{LA} L, Lh, CL1h/m, and CL2h/m work quite well in delivering low $L_{p,\mathrm{A,S,4\ m}}$ with "Good" rating speech privacy, especially when combined with P_{HEIGHT} 1.2 m and 1.4 m. Comparison between $L_{p,\mathrm{A,S,4\ m}}$ results in all four W_{LA} L models and Lh models are made as they possessed identical surface area within their own $W_{DENSITY\_RATIO}$ and W_{SIZE} combination. As overall, it can be observed that for models with P_{HEIGHT} 1.0 m, W_{LA} Lh records an average decrease of 0.36 dB(A) in $L_{p,\mathrm{A,S,4\ m}}$ in comparison to W_{LA} L. Meanwhile, for L and Lh models with P_{HEIGHT} of 1.2 m and 1.4 m, similar tendencies can be seen where Lh models in $W_{DENSITY\_RATIO}$ S1 (both wsA and wsB) record an average increment of 0.27 dB(A) and 0.37 dB(A) for P_{HEIGHT} 1.2 m and 1.4 m respectively. On the other hand, models in the

$\mathrm{W}_{\mathrm{DENSITY\_RATIO}}$ S2_wsA and wsB record lower $L_{p,\mathrm{A,S},4\ \mathrm{m}}$ with an average decrease of 0.42 dB(A) and 0.67 dB(A) respectively for $\mathrm{P}_{\mathrm{HEIGHT}}$ 1.2 m and 1.4 m.

Another pair of models with a similar surface area are GOP2_S1_wsA_CL1 and CL2. Despite the similar surface area, the arrangements of WLA differ in term of the clustering where CL1 is arranged in ‘T” shape clusters and CL2 in “U” shape clusters as per illustrates in Figure 7.41. This minor tweak results in a tiny increase of $L_{p,\mathrm{A,S},4\ \mathrm{m}}$ in models with $\mathrm{P}_{\mathrm{HEIGHT}}$ 1.2 m and 1.4 m, and a decrease in $\mathrm{P}_{\mathrm{HEIGHT}}$ 1.0 m. However, the increase/decrease is insignificant as it is imperceptible (See ⋆ in Figure 7.39). On the other hand, for models GOP2_S1_wsA_CL1h and CL2h, the transformation of the horizontal clusters from “T” to “U” clusters also record a small increase in $L_{p,\mathrm{A,S},4\ \mathrm{m}}$ of below 1 dB(A) (See ∗ in Figure 7.39 and Figure 7.41).

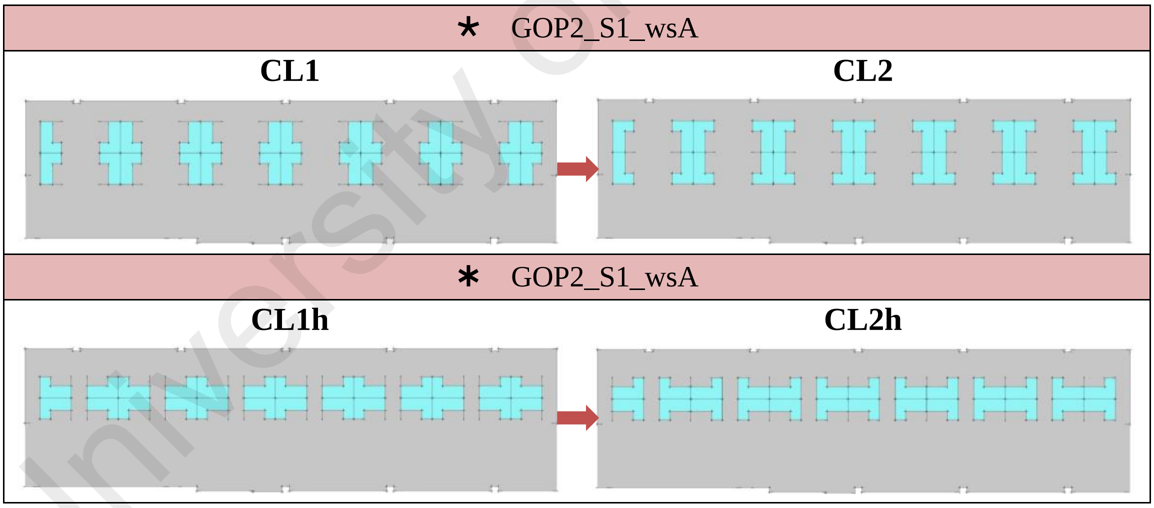


Figure 7.41: Comparison of models’ W_{LA} in GOP2_S1_wsA

It should be noted that models GOP2_S1_wsA_CL1h and CL2h are actually the horizontally arranged version of models GOP2_S1_wsA_CL1h CL1 and CL2 respectively. While they do not possess identical surface area, the total surface areas are very close to one another. The alteration of arrangement from CL1 to CL1h and CL2 to CL2h can be observed in Figure 7.41. From Figure 7.39, it can be seen that the changes do affect the $L_{p,\mathrm{A,S,4\ m}}$ where it visibly decreases in CL1h and CL2h models with an average decrease of 0.83 dB(A) and 0.31 dB(A) respectively.

Other models with an identical surface area are model GOP2_S1_wsB_CL1m and CL2m. Figure 7.42 illustrates the changes between the two W_{LA} where the clustering of the workstations changes from “T” to “U” shape. Much like models in Figure 7.41, this tweak in arrangement also increases the $L_{p,\mathrm{A,S,4\ m}}$ results (See ◆ in Figure 7.39) with an average increment of 0.38 dB(A).

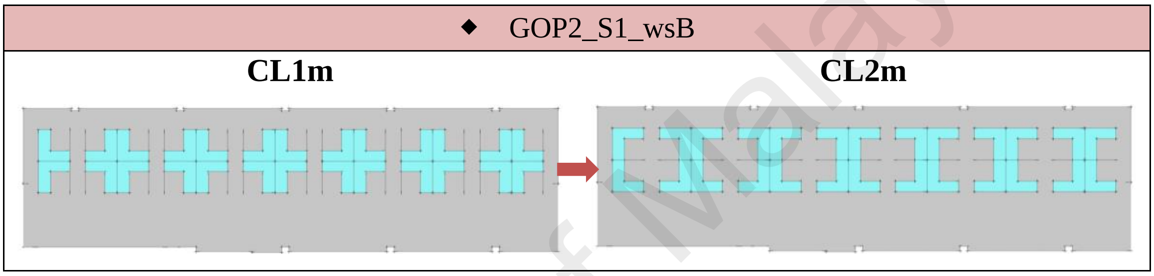


Figure 7.42: Comparison of models’ W_{LA} in GOP2_S1_wsB

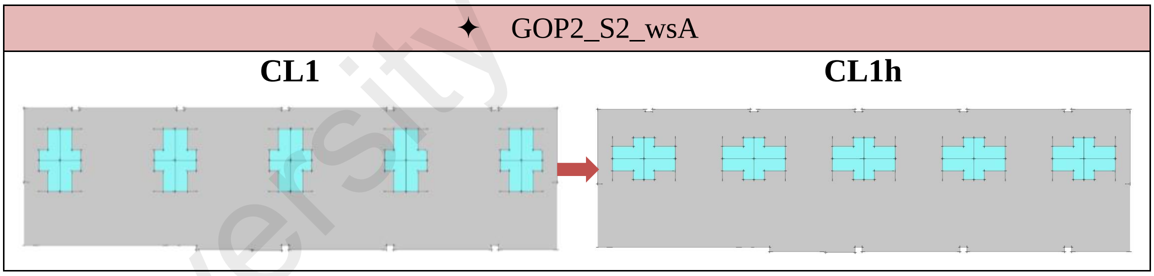


Figure 7.43: Comparison of models’ W_{LA} in GOP2_S2_wsA

Another pair of models with an identical surface area is models GOP2_S2_wsA_CL1 and CL1h. As illustrates in Figure 7.43, it can be seen that model CL1h was basically a horizontal version of CL1 models with five clusters of workstations. The changes of W_{LA} from CL1 to CL1h resulted in a substantial difference in $L_{p,\mathrm{A,S,4\ m}}$ results with an average decline of 2.38 dBA (See ✦ in Figure 7.39).

In the case of model pairings with similar characteristics, but altered in term of arrangement or modified through additional partitions, which also have a substantial change in the surface area; the increase or decrease in $L_{p,\mathrm{A,S,4\ m}}$ between the models cannot be clearly subjected to any alteration in term of design as the additional amount of surface area plays a major role in the readings of $L_{p,\mathrm{A,S,4\ m}}$. However, it can be seen that additional partitions between the workstations, especially if it crossed the measurement line; works well in reducing the $L_{p,\mathrm{A,S,4\ m}}$ results (S1_wsB_CL1 vs. CL1m, S1_wsB_CL2 vs. CL2m, S2_wsB_CL1 vs. CL1m, and S2_wsB_CL2 vs. CL2m). The change in arrangement from linear to horizontal layout could also assist in bringing down the $L_{p,\mathrm{A,S,4\ m}}$ (S2_wsA_CL2 vs. CL2h). Changing in workstation clustering from "T" to "U" could assist in decreasing the $L_{p,\mathrm{A,S,4\ m}}$ as well (S1_wsB_CL1 vs. CL2, S2_wsA_CL1 vs. CL2). Nonetheless, when the workstations were modified, the "T" clustering worked better than "U" clustering in GOP2 models.

7.1.4 Spatial Decay Rate of Speech ($D_{2,\mathrm{S}}$) in dB(A)

A-weighted SPL of speech at a distance of 4m ($L_{p,\mathrm{A,S,4\ m}}$) and spatial decay rate of speech ($D_{2,\mathrm{S}}$) are basically obtained from the same graph of SPL versus Distance (meter) as discussed in Chapter 2. While all open-plan offices recorded a reasonably acceptable $L_{p,\mathrm{A,S,4\ m}}$, it recorded poor $D_{2,\mathrm{S}}$ results. As discussed earlier, an ideal spatial decay rate of speech ($D_{2,\mathrm{S}}$) according to ISO 3382-3 (2012) should be equal to or above 7 dB(A).

Simulated $D_{2,\mathrm{S}}$ for all open-plan offices show disconcerting results as all models from all open-plan offices recorded a $D_{2,\mathrm{S}}$ of way below the recommended value of 7 dB(A). An exception can be made for two models from LOP2 (LOP2_S2_wsA_1.4_CL2h_P2 and P3) which recorded $D_{2,\mathrm{S}}$ of 7.12 dB(A) and 7.19 dB(A) respectively. Figure 7.44, 7.46, 7.48, and 7.50 illustrates the of simulated $D_{2,\mathrm{S}}$ results for models in LOP1, LOP2, GOP1, and GOP2 in a graphical description.

Each open-plan offices data are divided into their particular number of graphs according to its $W_{DENSITY\_RATIO}$, W_{SIZE}, and P_{HEIGHT}. The *y*-axis of each graph represents the spatial decay rate of speech ($D_{2,S}$) value in dB(A), and the *x*-axis represents the six variations of workspace layout arrangement (W_{LA}) of linear and cluster arrangements. The three columns of graphs separate the models into the three variable of P_{HEIGHT} of 1.0 m, 1.2 m, and 1.4 m. Meanwhile, the three (LOP1 and LOP2), two (GOP1), and four (GOP2) rows of graphs divide the models into their respective $W_{DENSITY\_RATIO}$ and W_{SIZE}. Each of the graph categorises the data into four different P_{TYPE} according to different colour codes of Blue (P1), (Pink) P2, (Green) P3, and (Orange) P4.

Observation on Figure 7.44, 7.46, 7.48, and 7.50 shows that in term of P_{TYPE}, P1 consistently recorded higher $D_{2,S}$ among all the P_{TYPE}. Nevertheless, it can also be observed that P_{TYPE} P2, P3, and P4 simulated $D_{2,S}$ results with similar tendencies to P1 in their respective group of $W_{DENSITY\_RATIO}$, W_{SIZE}, W_{LA}, and P_{HEIGHT}. Hence, Figure 7.45, 7.47, 7.49, and 7.51 illustrates the simulated $D_{2,S}$ data extracted from models with P_{TYPE} P1 only so that comparison of $W_{DENSITY\_RATIO}$, W_{SIZE}, W_{LA}, and P_{HEIGHT} can be concentrate on only one P_{TYPE}.

Figure 7.45, 7.47, 7.49, and 7.51 divides the $D_{2,S}$ data into three graphs of P_{HEIGHT} 1.0 m, 1.2 m, and 1.4 m accordingly. The *x*-axis of each graph represents the six variations of W_{LA} and the *y*-axis represents the spatial decay rate of speech ($D_{2,S}$) value in dB(A). Each graph shows the results of $D_{2,S}$ according to their $W_{DENSITY\_RATIO}$ and W_{SIZE}, distinguished using different shades of blue plotting lines (represents P_{TYPE} P1).

(a) ***LOP1***

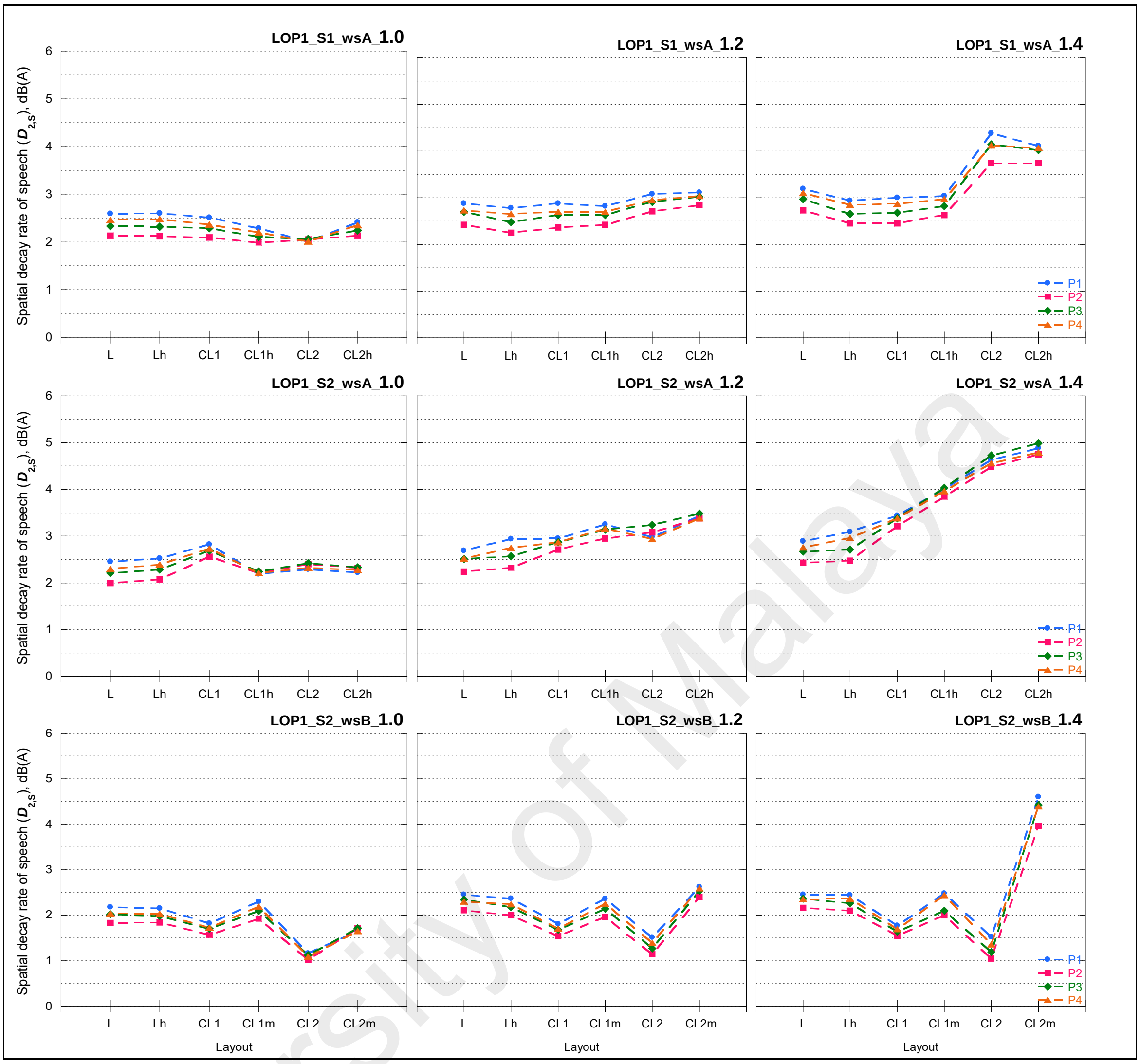


Figure 7.44: Simulated $D_{2,S}$ for LOP1 models

In Figure 7.45, it can be seen that models with P_{HEIGHT} 1.0 consistently recorded the lowest $D_{2,S}$ among the three P_{HEIGHT}. It can also be observed that the $D_{2,S}$ results gradually increases as the P_{HEIGHT} increases from 1.2 m to 1.4 m accordingly.

Overall comparison of $W_{DENSITY\_RATIO}$ and W_{SIZE} illustrated in Figure 7.45 shows that models with W_{SIZE} wsA records higher $D_{2,S}$. Meanwhile, between $W_{DENSITY\_RATIO}$ S1 and S2 (wsA_S1 vs. wsA_S2), $W_{DENSITY\_RATIO}$ S2 records slightly higher results than S1 as observed in models with P_{HEIGHT} 1.4 m. Between models with P_{HEIGHT} 1.0 m and 1.2 m, the differences are not too apparent as some models of S1_wsA record higher $D_{2,S}$ than S2_wsA models.

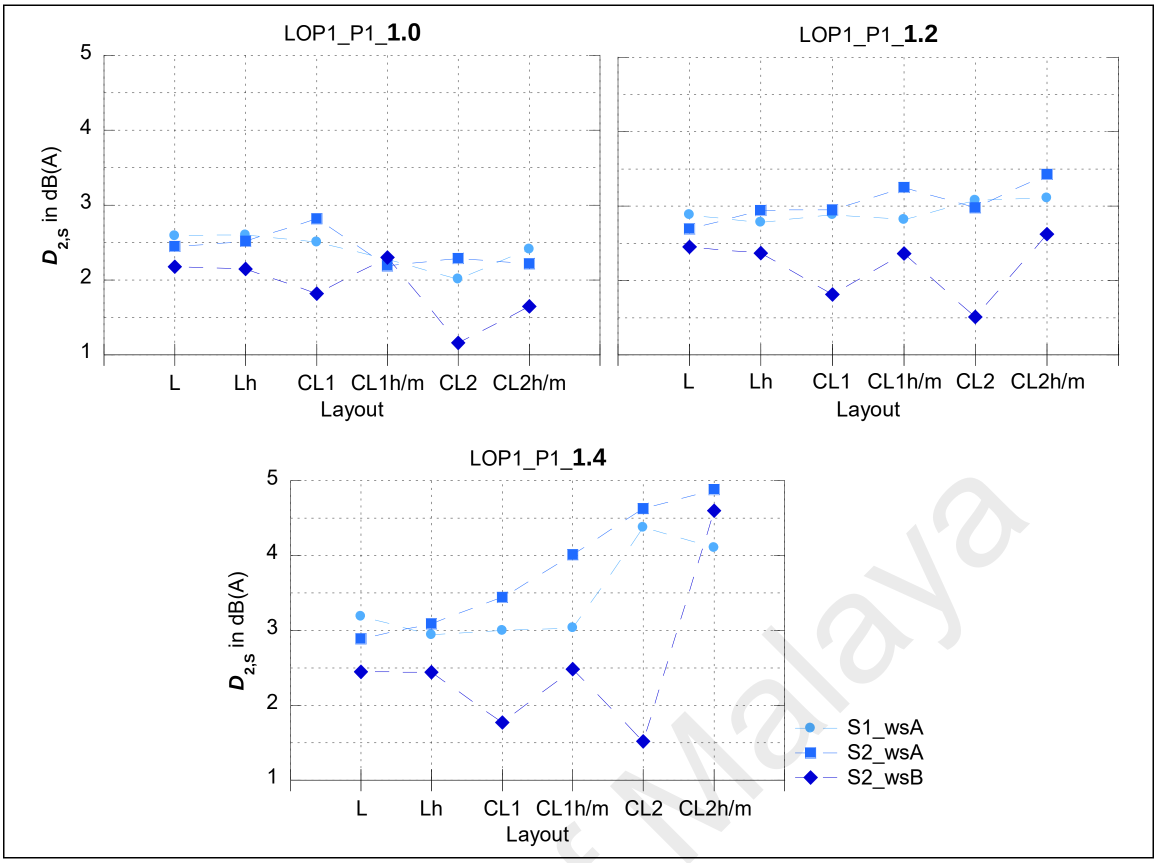


Figure 7.45: Simulated $D_{2,S}$ for LOP1 models with P_{TYPE} P1

Comparison between the W_{LA} shows that the $D_{2,S}$ of models S2_wsB_CL1 and CL2 decline remarkably in all P_{HEIGHT}. Comparison of the W_{LA} plans of models in S2_wsB show that the decline in $D_{2,S}$ are caused by the lack of partitions between the intermediate and adjacent workstations. It could also be seen that when the two models (CL1 and CL2) are modified into CL1m and CL2m using additional partitions, the $D_{2,S}$ results immediately increases as shown in Figure 7.45.

(b) ***LOP2***

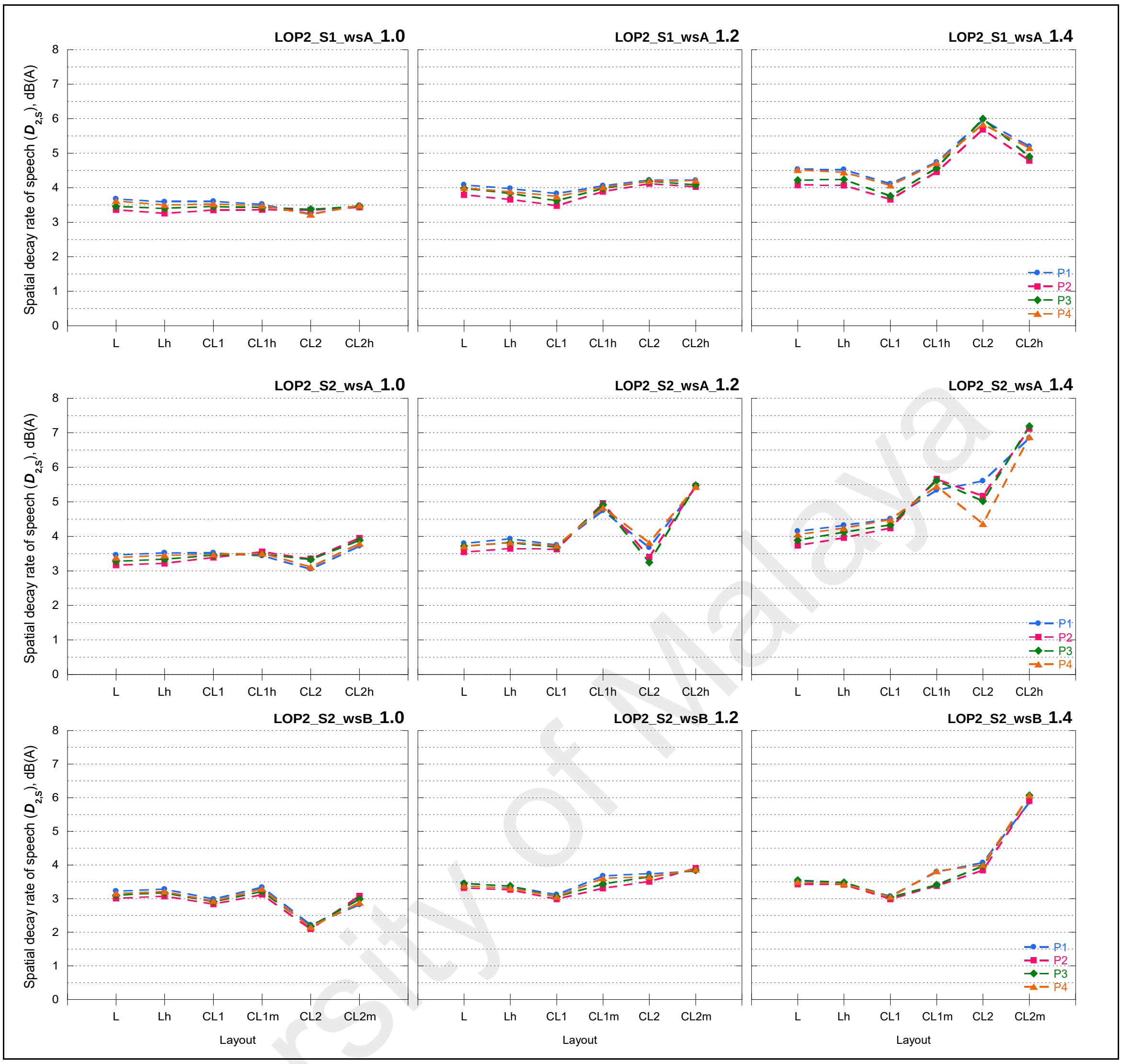


Figure 7.46: Simulated $D_{2,S}$ for LOP2 models

Figure 7.46 illustrates the simulated $D_{2,S}$ for LOP2 models. In term of P_{HEIGHT}, it can be seen that P_{HEIGHT} 1.0 m recorded the lowest $D_{2,S}$ compared to models constructed with P_{HEIGHT} 1.2 m and 1.4 m. It can also be observed that the $D_{2,S}$ gradually increases as the P_{HEIGHT} increases from 1.0 m to 1.2 m to 1.4 m. Comparison between $W_{DENSITY\_RATIO}$ S1 and S2 is done by comparing the simulated $D_{2,S}$ results of models S1_wsA and S2_wsA. Figure 7.47 shows that the two mostly recorded similar $D_{2,S}$ results, especially models with P_{HEIGHT} 1.0 m and 1.2 m. Models with P_{HEIGHT} 1.4 m show a little discrepancy between the two, but the differences could be considered negligible.

On the other hand, between S2_wsA and wsB, it can be seen that models with W_{SIZE} wsB constantly recorded lower $D_{2,S}$ compared to S2_wsA models. The most differences can be observed in models with P_{HEIGHT} 1.4 m.

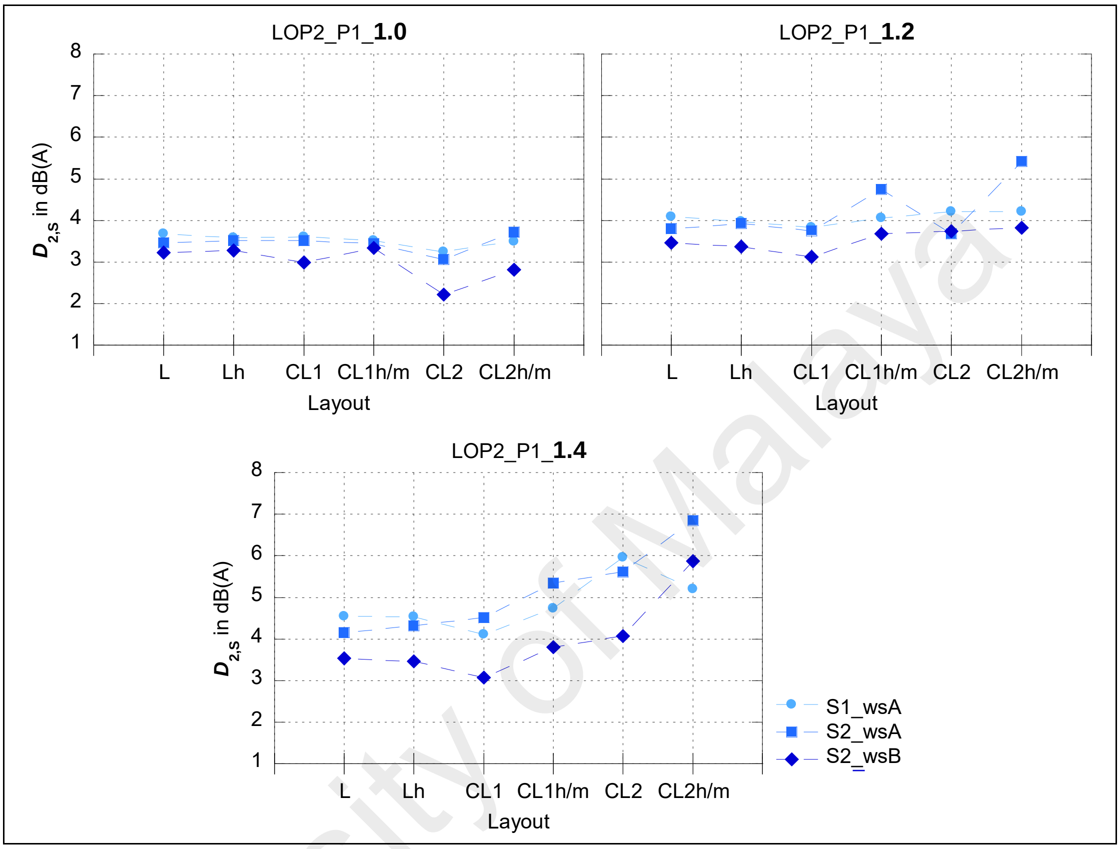


Figure 7.47: Simulated $D_{2,S}$ for LOP2 models with P_{TYPE} P1

Among the six W_{LA}, Figure 7.47 shows that most models with similar W_{LA} in each P_{HEIGHT} graphs recorded similar tendencies. Some apparent discrepancies that can be observed are in graph LOP2_P1_1.2, where model S2_wsA_CL1h and CL2h record an increasing $D_{2,S}$ in comparison to its origin models (S2_wsA_CL1 and CL2). Observation on the W_{LA} shows that models S2_wsA_CL1h and CL2h are arranged horizontally which causes the existing partitions in the workstation clusters to run more frequently along the measurement lines compared to models S2_wsA_CL1 and CL2 (Refer Figure 7.35).

(c) ***GOP1***

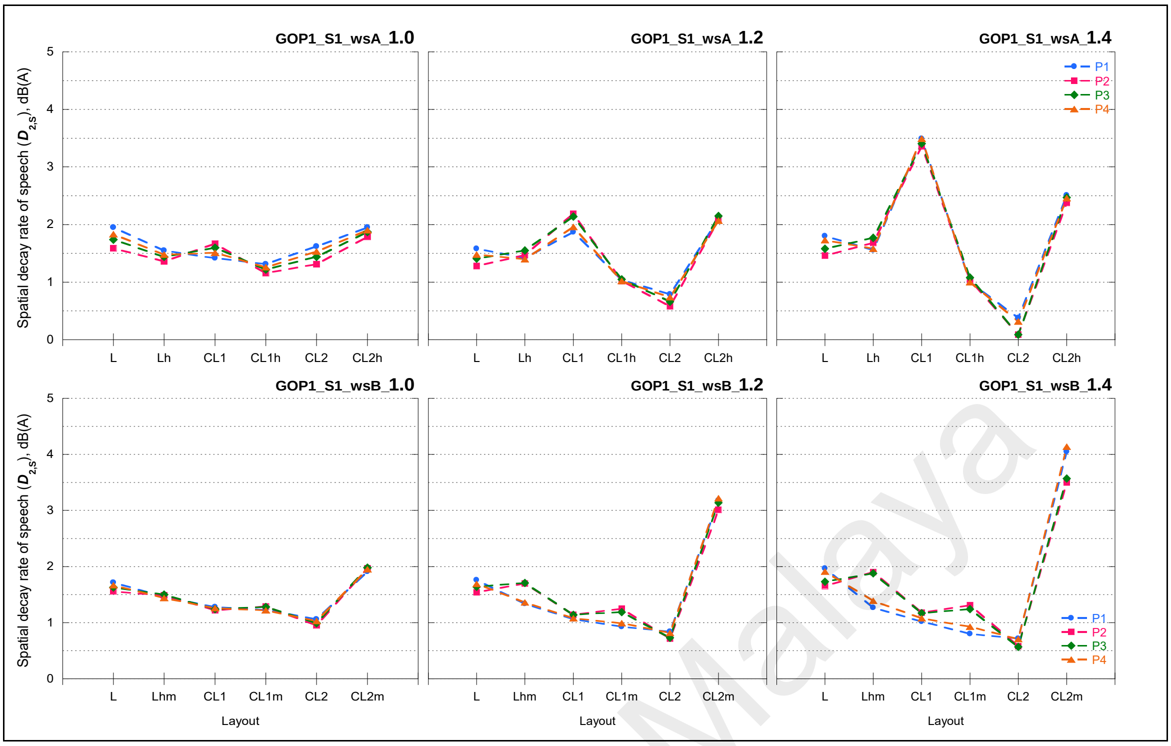


Figure 7.48: Simulated $D_{2,S}$ for GOP1 models

GOP1's simulated $D_{2,S}$ results are as illustrated in Figure 7.48 and Figure 7.49. Comparison in term of P_{HEIGHT} shows that there are not many differences between the three P_{HEIGHT} 1.0 m, 1.2 m, and 1.4 m. However, it can be observed that while some models record an increase in $D_{2,S}$ with the increment of P_{HEIGHT}, some actually record lower $D_{2,S}$ despite the increasing P_{HEIGHT}. Similar to the P_{HEIGHT}, the comparison between W_{SIZE} wsA and wsB also shows similar tendency where there are not many differences in $D_{2,S}$ results between models with wsA and wsB. Although, it can be argued that S1_wsA generally records a slightly higher $D_{2,S}$ than wsB.

It can also be observed that the simulated $D_{2,S}$ for GOP1 models depends mostly on the W_{LA}. This is because even though most of the models between the different P_{HEIGHT} and W_{SIZE} show almost similar results, discrepancies between the individual W_{LA} can be seen more clearly. One instance is in model S1_wsA_CL1 in P_{HEIGHT} 1.2 m and 1.4 m where the $D_{2,S}$ fluctuate in comparison to models with W_{LA} Lh and CL1h/m. When referring to the layout plans, it can be seen that the increase in $D_{2,S}$ in models S1_wsA_CL1 happen because of the layout arrangement in CL1 where each workstation is more isolated from each other compared to CL1h/m. Another discrepancy can be observed in model S1_wsB_CL2m where the $D_{2,S}$ is recorded to be the highest one especially with the model in P_{HEIGHT} 1.4 m. The layout plan of W_{LA} CL2m show that the increase in $D_{2,S}$ in comparison to W_{LA} CL2 could be caused by the extra partitions added in between the intermediate workstations (See Figure 7.38 in page 246).

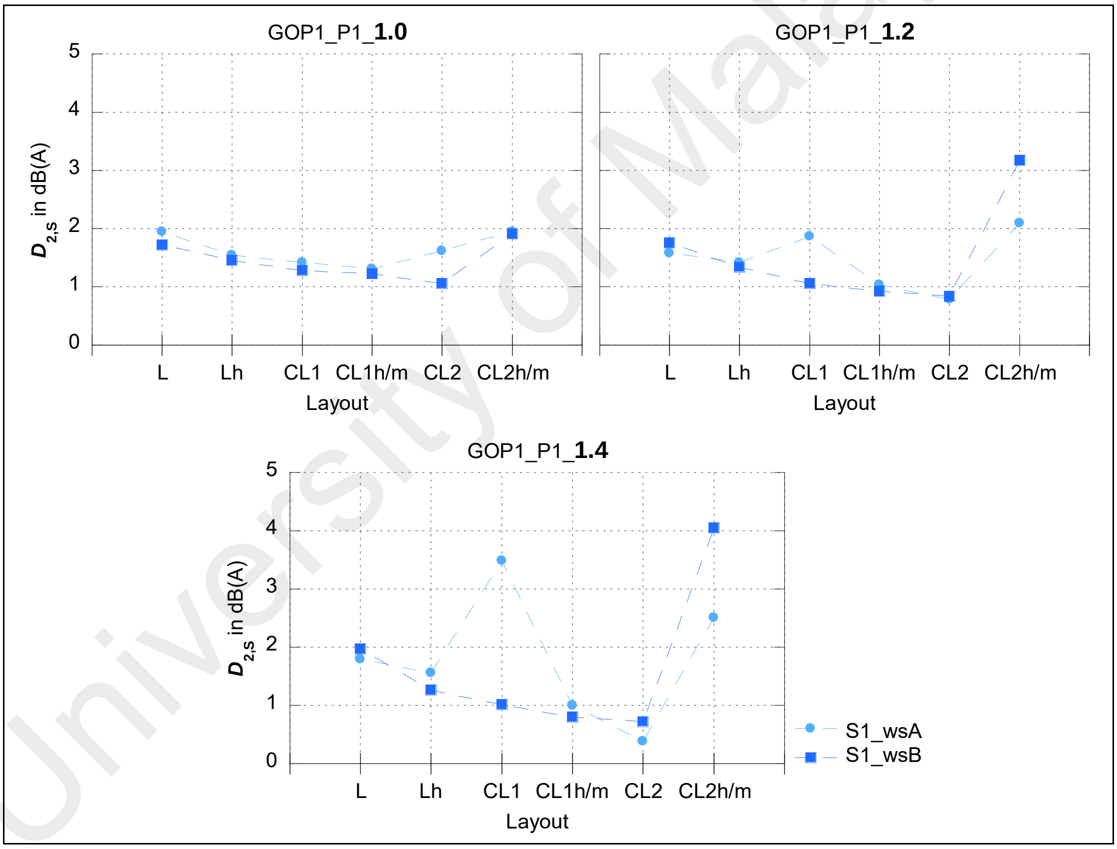


Figure 7.49: Simulated $D_{2,S}$ for GOP1 models with P_{TYPE} P1

(d) ***GOP2***

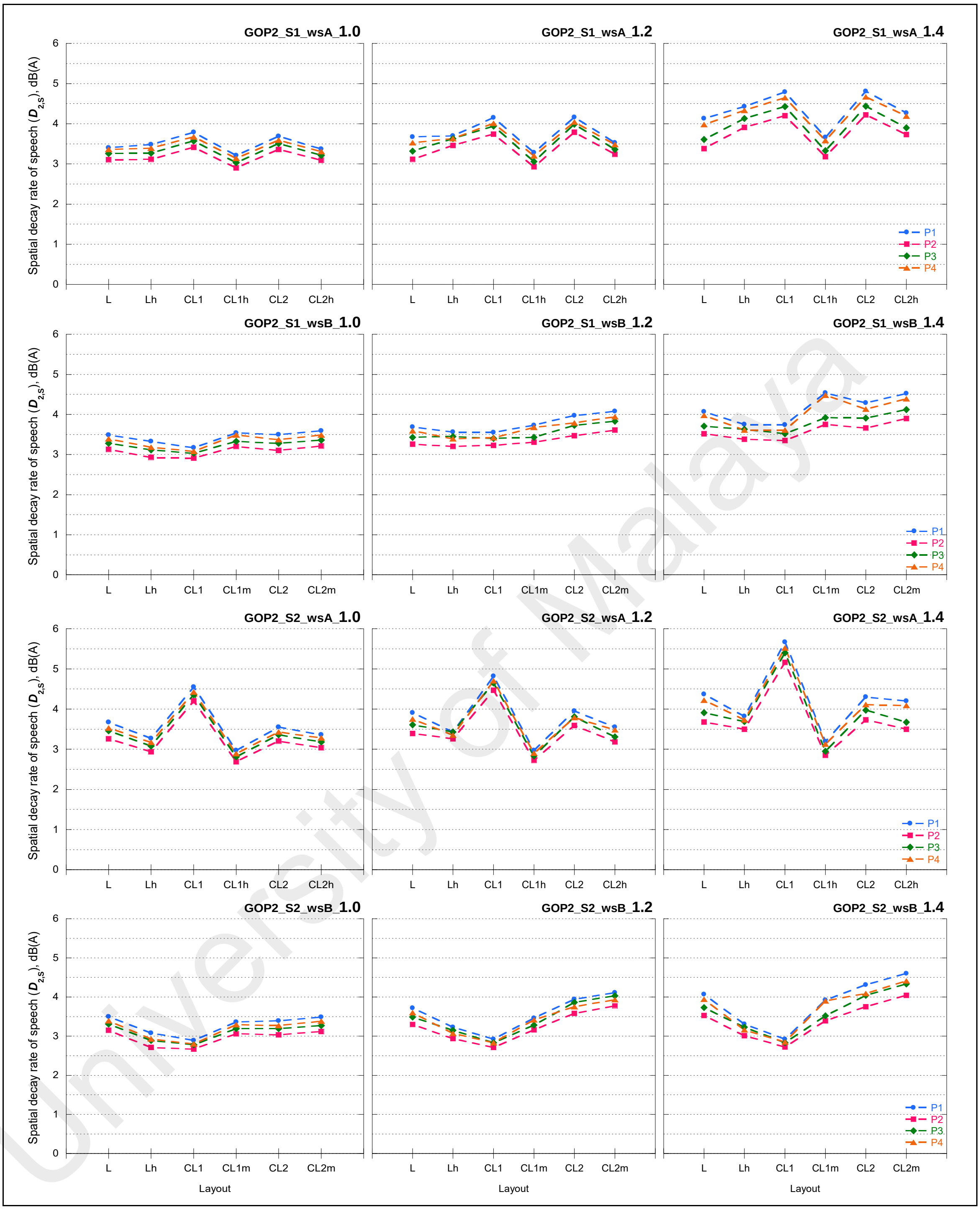


Figure 7.50: Simulated $D_{2,S}$ for GOP2 models

In term of P_{HEIGHT} it can be observed in Figure 7.50 that the $D_{2,S}$ results for models in GOP2 generally increases with the increment of P_{HEIGHT} from 1.0 m to 1.2 m to 1.4 m. In Figure 7.51, it can be observed that the tendencies of the simulated $D_{2,S}$ is highly dependent on the individual W_{LA}. Between the $W_{DENSITY\_RATIO}$, it is quite hard to tell which $W_{DENSITY\_RATIO}$ recorded higher or lower $D_{2,S}$, but between the two W_{SIZE}, it can be seen that wsA records higher $D_{2,S}$ in comparison to models with W_{SIZE} wsB. The most obvious $D_{2,S}$ result discrepancies between the W_{LA} can be seen in W_{LA} S2_wsA where there is a huge gap between the $D_{2,S}$ recorded by W_{LA} CL1 in comparison to W_{LA} CL1h.

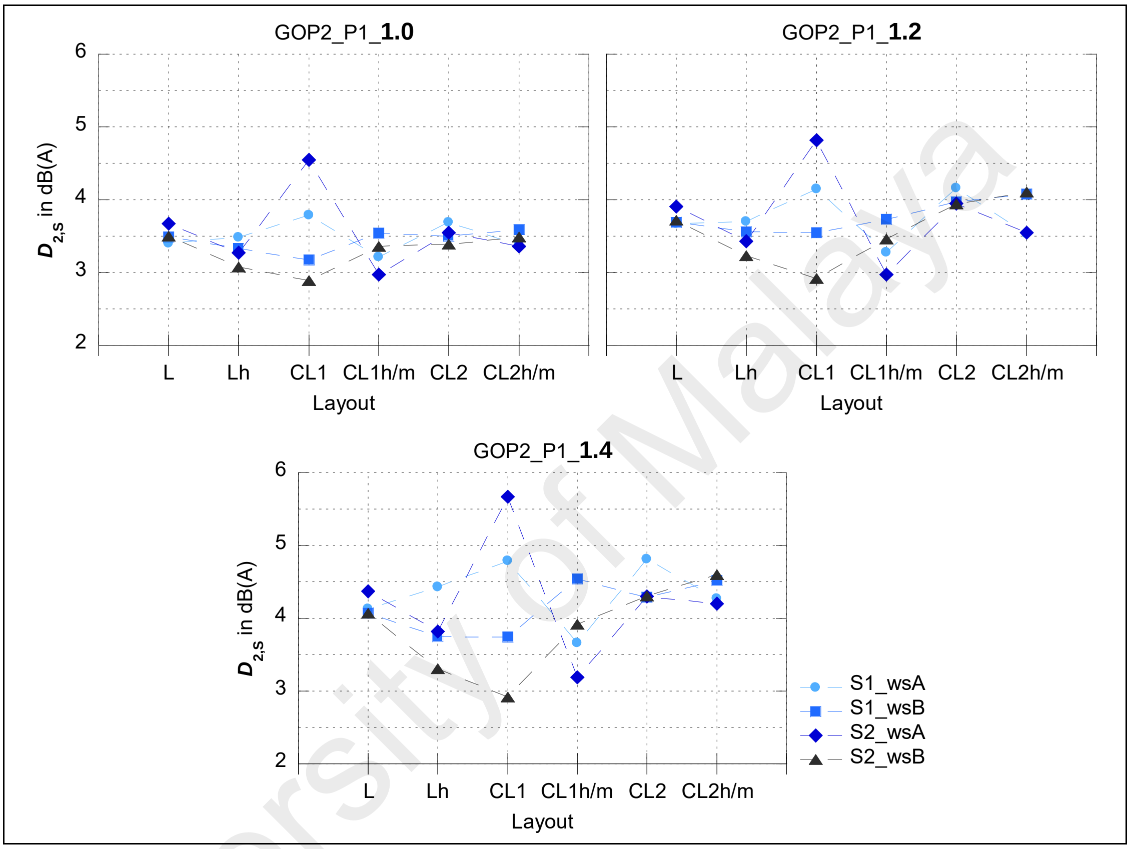


Figure 7.51: Simulated $D_{2,S}$ for GOP2 models with P_{TYPE} P1

7.2 Summary

This stage of the study experimented with five internal design variables namely the workspace density ratio ($W_{DENSITY\_RATIO}$), the workstation size (W_{SIZE}), the workspace layout arrangement (W_{LA}), the partition height (P_{HEIGHT}), and last but not least the absorptive partition type (P_{TYPE}). These design variables were constructed into four existing open-plan offices in two green office buildings. Although the importance and significance for implementing these design variables have been deliberated earlier in Chapter Three, data findings show that not all design variables work well for the four acoustic parameters measured in this study. The four acoustic parameters namely speech transmission index (STI) in the nearest workstation, distraction distance (r_D), spatial decay rate of speech ($D_{2,S}$), and A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\ m}$) are considered as important descriptors in identifying the level of acoustic quality in open-plan offices.

As overall, it can be seen that the most significantly evident design variable that shows clear variances in acoustic parameters results is the P_{TYPE}. Among the four acoustic quantities, P_{TYPE} consistently shows notable results. It is observed that while partition with a lower absorption coefficient (0.25α) which is P_{TYPE} P2 is highly influential towards the simulation results of STI and r_D; it is not working well for the other two parameters ($D_{2,S}$ and $L_{p,A,S,4\ m}$). Meanwhile, P_{TYPE} P1 which has a higher absorption coefficient (0.75α) shows the opposite tendencies from P_{TYPE} P2 as it turned out to be positively effective for $D_{2,S}$ and $L_{p,A,S,4\ m}$ instead of STI and r_D. The other two absorptive partition types, P3 (0.25|0.75α) and P4 (0.75|0.25α), which are a modified version of P1 and P2, do not contribute in any distinctive enhancement or impairment towards any of the four acoustic parameters.

The second most significant design variable can be identified through the consistent results from the variation of partition height (P_{HEIGHT}). The results show that P_{HEIGHT} 1.2 m and 1.4 m record better r_D and $L_{p,A,S,4\ m}$ results in comparison to P_{HEIGHT} 1.0 m. Although the results for STI and $D_{2,S}$ are recorded way higher (in STI) and lower (in $D_{2,S}$) than their desired target values, observations on the results show that higher P_{HEIGHT} does sway the results tendency toward its respective target values.

In term of workspace density ratio ($W_{DENSITY\_RATIO}$), workstation size (W_{SIZE}), and workspace layout arrangement (W_{LA}), it is found that the three design variables contributed to the same characteristics namely the distance, the in-between barriers (between the SS and receiver points), and the amount of surface area.

In the case of STI, the simulated results are highly influenced by the varying distances which occurred due to differences in $W_{DENSITY\_RATIO}$, W_{SIZE}, and W_{LA}. It is observed that when the $W_{DENSITY\_RATIO}$ changes to S2 (which resulted in fewer workstations and hence more distance between the SS and receiver point), the STI tends to drop. The same tendencies can be observed when the W_{SIZE} and W_{LA} resulted in more distances between the SS and receiver points.

Unlike STI, it is observed that distances and the presence of in-between barriers do not play a major role in the simulated results of distraction distance (r_D). It can be seen that r_D is more influenced by the individual W_{LA}.

The amount of surface area resulted from the modification of $W_{DENSITY\_RATIO}$, W_{SIZE}, and W_{LA} is observed to be a significant influencer in the simulation of A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\text{ m}}$). The physical layout changes in W_{LA} also give massive effect on the $L_{p,A,S,4\text{ m}}$. Like the r_D, the distance between the SS and receiver points do not give any significant influence on the simulated $L_{p,A,S,4\text{ m}}$.

Pinpointing the design variables that are most influential towards the spatial decay rate of speech ($D_{2,S}$) is quite impossible as all the data show a low value of $D_{2,S}$ which translated into ‘Poor’ speech privacy. Although, minor tendencies can be observed where the differences in $W_{DENSITY\_RATIO}$, W_{SIZE} and W_{LA} do result in different $D_{2,S}$. However, they do not show any viable inclinations and are highly inconsistent.

CHAPTER 8: CONCLUSION

This chapter would discuss the conclusions of the research through deliberation of the four research objectives formulated at the beginning of the study. Recommendation for future studies in regards to the context of this research would also be made. The conclusion would highlight the general issue of how and where the findings of the research can be applied to.

8.1 Discussion

The study was derived from the issues of how acoustic quality and satisfaction in green office buildings deteriorate in comparison to the acoustic quality and satisfaction in non-green office buildings. This issue was identified as being unintentionally created due to the lack of awareness on the importance of good acoustic quality in the office environment. The lack of awareness on the matter caused green building rating tools (GBRTs) to give minimal attention towards this aspect of the office design, and when that happened, implementation of green building design features which were done for the improvement of other green building aspects accidentally aggravates the acoustical environment of the offices.

At the beginning of the thesis, the lack of research done on this topic specifically in the context of green office buildings in Malaysia gave birth to few research questions. To understand the previously deliberated acoustic dilemma, but in the context of green office buildings in Malaysia, questions such as below were posed:

1. What is the current situation on acoustical performance in open-plan offices in green office buildings in Malaysia?
2. Which green building design elements contribute to the current acoustic quality in open-plan offices in green office buildings in Malaysia?

3. What kind of design strategies that could assist in the acoustic design of open-plan offices in green office buildings in Malaysia?
4. How to improve the acoustic design of open-plan offices in green office buildings in Malaysia?

The questions were answered through four research objectives as will be discussed below:

8.1.1 Research Objective 1

To evaluate the level of acoustic quality in selected open-plan offices.

The evaluation of the level of acoustic quality was carried out using the method of acoustic measurement in selected open-plan offices. Three acoustic parameters were measured to assess the acoustic quality of these open-plan offices; the background noise (BN) level, the reverberation time (RT), and the speech transmission index (STI). From the data collected through the measurement of BN and STI, two other parameters namely the noise criteria (NC) and distraction distance (r_D) were derived respectively. Table 8.1 summarised the data findings of the field measurements.

Field measurement results revealed that half of the open-plan offices have 'Low' BN level (< 35 dBA). Even though another half of the open-plan offices managed to obtain 'Optimum' BN level (35 to 45 dBA), they were at the bare minimum of the scale. Also, the NC results showed that all open-plan offices have 'Low' NC levels. NC level relates closely to the mechanical sounds originated from fans or the air-conditioning systems in the room. The low NC level suggested that the measured open-plan offices have muted mechanical systems which resulted in the low BN and NC level. While the measurement of reverberation time (RT) showed that the open-plan offices have 'Low', 'Optimum', and 'High' RT; it was considered as acceptable as the lower and higher RT recorded were not low or high enough to affect the acoustic environment in the spaces. On the other hand, measurement of STI which bears the results for distraction distance (r_D) showed varied results whereas both DOP1 and DOP2 in Diamond building recorded 'Poor' r_D while open-plan offices in LEO and GEO building recorded r_D values in the range of 'Fair' and 'Good' category. Nonetheless, none of the open-plan offices achieved 'Excellent' r_D.

Albeit not excellent, it can be determined that the selected open-plan offices have an acceptable level of acoustic quality; with some recorded better acoustical quality than the other. The outcome would serve as a good base in the determination of basic design elements for the acoustical design in open-plan offices.

Table 8.1: Summary of field measurement findings

No	Building / OPO	Code	BN (dBA)	NC	RT (s)	r_D (m)
Diamond Building						
1.	Open-plan office 1 (Lvl 4)	DOP1	30.28	NC-25	1.50	11.5
2.	Open-plan office 2 (Lvl 6)	DOP2	36.77	NC-31	0.70	15.5
LEO Building						
3.	Open-plan office 1 (Lvl 2)	LOP1	37.29	NC-30	1.41	-
4.	Open-plan office 2 (Lvl 3)	LOP2	31.79	NC-25	0.71	10.8
GEO Building						
5.	Open-plan office 1 (Lvl 2)	GOP1	36.33	NC-32	1.09	5.5
6.	Open-plan office 2 (Lvl 2)	GOP2	35.00	NC-28	1.12	9.0

BN/NC/RT class: Low, Optimum, High

r_D class: Excellent, Good, Fair, Poor

Through the method of acoustic measurement, the actual quality in selected open-plan offices was analysed efficiently. By measuring the basic acoustic parameters such as the background noise (BN) level and the reverberation (RT), and specific parameters such as the speech transmission index (STI); the overall acoustic conditions of the spaces were able to be identified. Studying the selected open-plan offices' layout plans beforehand, and off-site preparation of the measurement procedures, equipment, and locations of specific measurement points helped in expediting the measurement work tremendously.

8.1.2 Research Objective 2

To identify the green design elements that influences the acoustic quality in selected open-plan offices.

The intention of identifying the green design elements that influence the acoustic quality in selected open-plan offices was mostly done to recognise the green design elements that can be manipulated for the purpose of acoustic enhancement, without compromising the other IEQ elements. The identification process focused on four major design elements identified at the beginning of the research. The four design elements are the type of ventilation system used, daylight harvesting, reduced finishes, and open-plan office layout.

Table 8.2: Green design approaches in the three green office buildings

Green Design Strategy	**Green Office Building**		
	Diamond	**GEO**	**LEO**
Radiant Cooling	✓	✓	✗
Daylighting	✓	✓	✓
Reduced finishes	✓	✓	✗
Open-plan office layout	✓	✓	✓

Table 8.2 summarised the green design approach in the three selected green office buildings. In the case study, it was found that Diamond and GEO building have a similarity in term of the usage of the radiant cooling system as their primary means of ventilation, and the extensive daylight harvesting effort. To complement the radiant cooling and the daylight harvesting system, the two buildings were also designed with

fewer finishes, mainly in the ceiling area so that the painted concrete ceiling could double as a cooling medium for the ventilation system and work as reflective surfaces for the daylight harvesting system.

LEO building, on the other hand, employed conventional ventilation system of centralised A/C, but with special treatment to reduce the energy consumption, which resulted in minimal mechanical noise. Much like all the spaces in the entire LEO building, both selected open-plan offices in LEO building were installed with acoustical ceiling tiles. Daylighting effort in LEO building was mainly focused on the internal perimeter of both open-plan offices using curtain glass walls without any additional reflective mechanism. The similarities for all the selected spaces in the three green office buildings can be seen through the part where the internal office spaces were all designed as open-plan offices.

By analysing the data findings from the field measurement and the case study, it was found that the green design element that highly influenced the acoustic quality in the open-plan offices was the usage of quiet ventilation systems (radiant cooling in Diamond and GEO, and specially designed conventional A/C system in LEO) which resulted in low BN and NC levels in all the open-plan offices.

It should be noted that even though all open-plan offices recorded low BN and NC levels, measurement of distraction distance (r_D) showed different results. This was especially obvious for Diamond and GEO buildings where both green buildings employed similar green building design strategies, and both recorded low BN levels, but only GOP1 and GOP2 in GEO building managed to record an acceptable range of r_D. These inconsistencies can be credited to the discrepancies in the office space and building geometry, and also the internal design of the spaces.

It was discussed earlier that the green design elements were intentionally implemented to improve on other IEQ elements in green office buildings such as the indoor air quality (IAQ), visual comfort, and thermal comfort. Also, the implementation of the green design elements also assisted in the overall energy efficiency (EE). Case in point, the usage of radiant cooling and daylight harvesting aided in reducing the amount of energy needed to ventilate, cool, and illuminate the internal spaces; and reducing the interior finishes assisted in reducing the amount of maintenance needed.

On that note, for overall IEQ objective, it was determined that the cooling and ventilation system should not be compromised as the systems were chosen to assist in the enhancement of IAQ and thermal comfort specifically. On the other hand, daylight harvesting was purposely utilised for visual comfort in the office spaces. Moreover, reducing the finishes on specific surfaces such as the ceilings was deliberate as it acted as a design mechanism for the ventilation and daylight harvesting systems. Therefore, it was determined that the green design element that ought to be manipulated for the purpose of acoustic enhancement should be the design of open-plan office layouts.

The method of case study and observations on the design features and elements applied to achieve the second objective needed some severe literature reviews and secondary data research. Studying previous literature written about the subjects provided an advantage in the form of a checklist, which can be used during the case study and observation work. The process of specifically connecting the acoustic measurement data with the observation findings needs a serious theoretical understanding of how room acoustic work. By studying the basics of acoustics, specifically room acoustics, a proposition on what causes the acoustic in the open-plan offices to occur the way it was can be done appropriately.

8.1.3 Research Objective 3

To investigate a workable alternative of design strategies that could assist in achieving an acoustically comfortable open-plan office (within the structural parameters of selected open-plan offices).

Identification of design elements that could assist in providing good acoustic quality for open-plan offices was made through the simulation of experimental open-plan office layouts. Four selected open-plan offices namely LOP1, LOP2, GOP1, and GOP2 from LEO and GEO building were selected to be the “backdrop” for the design experiments to retain that controlled green-office environment for the simulation work. Five internal design strategies were chosen to be part of the design experiment. They were:

1. Workspace density ratio ($W_{DENSITY\_RATIO}$)
2. Workstation size (W_{SIZE})
3. Workspace layout arrangement (W_{LA})
4. Partition height (P_{HEIGHT})
5. Partition type (P_{TYPE})

The effect of the five design strategies were analysed on four acoustic parameters namely: STI (in the nearest workstation), distraction distance (r_D), spatial decay rate of speech ($D_{2,S}$), and the A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\ m}$). These four parameters are a relevant indicator of acoustic quality in open-plan offices as it covers the measurement of speech privacy (through STI and r_D) and speech decay (through $L_{p,A,S,4\ m}$ and $D_{2,S}$).

Table 8.3 provided a summarised indicator on which design strategies that have an influence on speech privacy based on its effect on the four acoustic parameters.

Analysis of the simulated results from the experimental open-plan office layouts using the five internal design strategies revealed that:

1. The level of absorption coefficient (α) in the form of partitions between the workstations is crucial for the design of speech privacy in open-plan offices.
2. The height of partitions is also a significant design element in open-plan offices, and it should be explored in order to achieve the much-desired speech privacy.
3. Carefully design workspace layout arrangement could assist in achieving speech privacy in open-plan offices.
4. The measurement of workstation sizes could assist in achieving a certain degree of speech privacy in open-plan offices.
5. Workspace density ratio is helpful in creating distance between workstations, but it would not make any significant impact on the speech privacy in open-plan offices as a whole.

Table 8.3: Specific design strategies to be considered for the acoustic design in open-plan office

Acoustic parameter	**Design Strategies**				
	P_{TYPE}	P_{HEIGHT}	W_{LA}	W_{SIZE}	W_{D_RATIO}
STI	O	O	O	O	O
r_D	O	O	O	O	×
$L_{p,A,S,4\,m}$	O	O	O	×	×
$D_{2,S}$	O	O	O	×	×

Legend:
O YES
× NO

For design experimentation containing many strategies with several numbers of variables such as presented in this study, computer simulation tool should be a very convenient way to assess the effectiveness of the design variables and their respective combinations. Nevertheless, it should be noted that the crucial part of the simulation work began even before the simulation work itself. The models used in the simulation work needs to be constructed carefully and furthermore verified to ensure that the models used would be comparable to a real room condition. Model verification is an essential step in the preparation of the 3D models, as the exactitude of the models would establish the accuracy of the simulation results later on.

Additionally, the process of designing the experimental design layouts using the five chosen strategies should be done with some predetermined limitations so that the variables and the combination of the design strategies would not be overwhelming. This process involved some major study on the appropriate, and relevant design strategy and variables to be used in the experimentation.

Furthermore, having a particular list of intended acoustic parameters to be simulated would assist in determining the vital model settings and input. Also, having well thought out ideas of how the results would be analysed and presented would aid in the process of results extraction.

8.1.4 Research Objective 4

To recommend relevant acoustic parameters and design strategies to be considered for the design of acoustically comfortable open-plan offices.

To design an acoustically comfortable open-plan office, the primary purpose of offices, open-plan or otherwise, should be understood. Office spaces were designed for cognitive work, which relates closely to the multifaceted thinking process. Acoustically comfortable open-plan office equals to spaces that provides adequate aural privacy which would support these cognitive processes in order for occupants to get their work done efficiently.

It was well established that factories and technical workrooms experienced acoustic problems in the form of excessive sound level from machinery noises. However, open-plan offices did not suffer the same problems. Open-plan offices do not generally contain heavy machinery that would raise the noise level of the office. In fact, office tools are getting smaller and quieter. Hence, instead of loud noises, the most dangerous type of acoustic problem faced in open-plan offices is speech noises. Intelligible speech noises contain information, which could interfere with occupants' cognitive performance and furthermore affect the occupants' ability to work efficiently.

Acoustically comfortable open-plan offices should provide adequate speech privacy for the occupants. To avoid and/or tackle the issue of the lack of speech privacy, assessment on acoustical quality in the open-plan office should be done through the evaluation of not only the background noise (BN) level, but also through the measurement of STI, distraction distance (r_D), spatial decay rate of speech ($D_{2,S}$), and the A-weighted SPL of speech at a distance of 4m ($L_{p,A,S,4\,m}$).

Below is the summary of basic target values for the acoustic parameters that should to be considered to achieve acoustically comfortable open-plan offices.

Table 8.4: Basic acoustic parameters and target values to be considered for the design of acoustically comfortable OPO

No	Acoustic parameter	Target values
1.	Background noise (BN) level	35 to 45 dB(A)
2.	Speech transmission index (STI) in the nearest workstation	≤ 0.5
3.	Distraction distance, r_D	≤ 5 m (max 11 m)
4.	A-weighted SPL of speech at a distance of 4m, $L_{p,A,S,4\,m}$	≤ 48 dB(A) (max 54 dBA)
5.	Spatial decay rate of speech, $D_{2,S}$	≥ 7 dB(A)

Acoustic should be an integral component during the early stage of open-plan office design. Through experimental designs of the five design strategies, design effects on the relevant acoustic parameters were identified as per illustrated in Table 8.4. However, to achieve the desired target values for each parameter, the design approaches might not all be similar as STI and r_D, and $L_{p,A,S,4\ m}$ and $D_{2,S}$ have different roles in regulating the speech privacy. Table 8.5 specified the particular design approach that should be considered to achieve the target values for each specific acoustic parameter.

It should be noted that besides utilising the internal design strategies, consideration on the shape and geometry of the space, the type of work carried out in the office, as well as the intended office dynamics between occupants are also significant to achieve an acoustically comfortable open-plan office.

Table 8.5: Specific design approach to be considered for each design strategies

Acoustic parameter	**Design strategies / approaches**	
STI (in the nearest workstations)	P_{TYPE}	Use partitions with low absorption coefficient (α)[1]
	P_{HEIGHT}	Use partitions with ≥ 1.2 meter high[2]
	W_{LA}	Strategic layout planning[3]
	W_{SIZE}	Use bigger size workstations[4]
	$W_{DENSITY\_RATIO}$	Reduce the density ratio of occupants in the OPO[4]
r_D	P_{TYPE}	Use partitions with low absorption coefficient (α)[1]
	P_{HEIGHT}	Use partitions with ≥ 1.2 meter high[2]
	W_{LA}	Strategic layout planning[3]
	W_{SIZE}	Use bigger size workstations[5]
$L_{p,A,S,4\ m}$	P_{TYPE}	Use partitions with high absorption coefficient[6]
	P_{HEIGHT}	Use higher partitions[7]
	W_{LA}	Strategic layout design[8]
$D_{2,S}$	P_{TYPE}	Use partitions with high absorption coefficient[6]
	P_{HEIGHT}	Use higher partitions[7]
	W_{LA}	Strategic layout design[8]

[1] Partitions with low absorption coefficient (α) assist in reflection of SPL = raised RT = low speech intelligibility
[2] Equivalent or higher than occupants' sitting height partition = indirect sound
[3] Layout arrangement depends on the intended office / work dynamic and the geometry of the open-plan office
[4] Bigger workstations / reduce occupants = more space in the OPO = increase distance between speaker and listeners
[5] Bigger size workstation provide more containment which constrain the sound propagation between workstations
[6] Partitions with high absorption coefficient (α) assist in reducing the SPL
[7] Higher partitions = higher amount of absorptive surfaces = reduced SPL
[8] Layout design refer to the positioning of partitions specifically between and surrounding the workstations

Simulation results in Chapter Six showed that it would be impossible to achieve the target values for all four acoustic parameters simultaneously as different design strategies would affect the parameters differently. Even though there are four acoustic parameters proposed for the assessment of acoustic quality in open-plan offices, it is not necessary to achieve all the target value for all acoustic parameters simultaneously. Different type of work needs different type of office dynamic and therefore different type of layouts and specifications. As stated previously, different parameters have a different influence on speech privacy. While $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$ works to measure the attenuation level of speech noises, STI and r_{D} measure the intelligibility of the speeches.

In designing open-plan offices that cater to individual works, consideration should focus towards achieving the target value for the acoustic parameter STI (in the nearest workstation). This is because the parameter STI would focus more on the acoustic measurement between adjacent workstations rather than measuring the acoustic quality of the whole office. Considering the design strategies and approaches as per illustrated in Table 8.5 will help in designing a workspace with adequate speech privacy in each workstation.

Meanwhile, for offices that accommodate more towards group collaboration, the acoustic parameter distraction distance (r_{D}) would be a more suitable parameter to be considered during the design process. Consideration on the r_{D} would assist in designing each group's work area and the distance between two adjacent groups.

On the other hand, controlling the level of speech attenuation between adjacent workstations and between group areas can be done by observing the target values for $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$. Even though the design experimentation showed that the target value for the parameter $D_{2,\mathrm{S}}$ was somewhat impossible to be achieved, the results still showed some degree of speech attenuation and hence should be considered as satisfactory.

Ultimately, the main acoustic problem in open-plan offices is the intelligibility of speech sounds, which could impair occupant's cognitive performance. Hence, it would be considered acceptable to focus on the STI and the r_{D} as the primary acoustic requirements, while the $L_{p,\mathrm{A,S,4\ m}}$ and $D_{2,\mathrm{S}}$ to be considered as the accompanying requirements.

8.2 Contribution to Knowledge

The outcome of the study contributed to two area of knowledge. The first outcome was directed towards improving the acoustical assessment (specifically for open-plan offices) in Malaysia's GBRT the GBI. Currently, with only one (1) credit point for acoustic under the assessment criteria indoor environmental quality (IEQ), the GBI only considered the basic acoustic parameter, which is the BN level. Even though the parameter is a vital one especially for general room acoustic, the parameter articulates nothing about the acoustic quality which relates to open-plan offices' need namely the speech privacy. Henceforth, the outcome highlighted on the usage of relevant acoustic parameters for the assessment of speech privacy in open-plan offices. Basic target values for each of the acoustic parameters were also summarised and tabulated for easy references.

The second contribution to knowledge was the guideline for the design of workspace layouts in open-plan offices as presented in Table 8.5. The design guideline specified the design strategies to be taken for the design of acoustically comfortable workspace in open-plan offices. Unlike previous studies related to the acoustic design in open-plan offices, the guideline also identified the specific design direction and approaches to be taken for the design of acoustically comfortable open-plan offices in relation to specific acoustic parameters associated to speech privacy. The guideline should be a helpful tool in the prediction of acoustic quality in open-plan office during the design stage.

8.3 Recommendation for Future Study

As this study focused on the topic of acoustic design in open-plan offices in green office buildings in Malaysia, the scope of which the study covers are still very limited. Further exploration of research area regarding acoustic in open-plan offices should be done to ensure a deeper understanding of the subject. Continuation and future studies of the subject shall be done through:

i. The acoustical assessment of more open-plan offices in green office buildings to further develop a proper understanding and generalisation for acoustic quality in green office buildings in Malaysia's green building context.
ii. The assessment of acoustic performance in offices through psychological assessment of building occupants' satisfaction.
iii. The exploration of more relevant design variables in a controlled simulated environment.

8.4 Conclusion

One fundamental misconception made by green building designers and architects is that they pride themselves when they successfully provided the working spaces with very low background noise (BN) level. Even though low BN level is desirable, very low BN is, in fact, a problem when it comes to open-plan offices. Like the domino effect, very low BN would result in good speech transmission index (STI), which is very problematic especially in open-plan offices as it would cause an issue of speech privacy. This issue is not relieved by the fact that green building rating tools (GBRTs) only fixated on the level of background noise (BN) level in their checklist when it only covers half of the acoustical equation that needs to be resolved. To achieve acoustically comfortable open-plan office in green buildings, the role of GBRTs should be appropriately exploited. The design guidelines specified in GBRTs should highlight on the acoustic parameters which are relevant to the specific type of spaces.

Data findings on the acoustical performance in selected open-plan offices in green office buildings in Malaysia showed that design features in green office buildings often unintentionally interferes with the acoustic quality in the office spaces. However, these interferences could be prevented or refurbished through careful planning and implementation of appropriate internal design elements. In fact, the acoustic quality in open-plan offices depends highly on the internal design details rather than the structural design features.

In overall, as people spend most of their time working in the office, and open-plan offices being the most popular and thriving type of office design, the issue of acoustic comfort in the office should not be disregard. It is hoped that this study would bring awareness on the issues of acoustic quality and the importance of acoustic design in the workplaces, especially in open-plan offices.

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LIST OF PUBLICATIONS AND PAPERS PRESENTED

(a) ***Journal Publication / Chapter in Book***

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(b) ***Conference Papers / Proceedings***

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