A MODEL FOR PREDICTION OF NOISE LEVELS IN OPEN PLAN OFFICES BASED ON NUMBER OF OCCUPANTS

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ABSTRACT

A MODEL FOR PREDICTION OF NOISE LEVELS IN OPEN PLAN OFFICES BASED ON NUMBER OF OCCUPANTS

Noise is recognized as one of the largest problems in achieving healthy living environments. It is especially critical in working environments which are designed to encourage occupant interactions. While designing spaces, a noise prediction model would be a useful tool for designers. Models for prediction of noise generated by occupants themselves are few. One that has proven effective was developed specifically for eating establishments considering the Lombard effect. This study focuses on the adaptation of this model to open plan offices.

Preliminary measurements were done in two eating establishments, a library study room and an architecture studio confirming the fact that the model is not appropriate for working spaces. Afterwards, measurements were conducted in six open plan offices, based on the measurements, the model parameters were analyzed in detail through optimizations for best-fit. The results indicate that the Lombard slope varies among offices and that spatial density is an indicator of number of simultaneously speaking occupants.

For adapting the model to open plan offices, two modifications were proposed: Introduction of a variable representing the interaction level, and a lookup table for determining the number of simultaneous speakers. Interaction level reflects how careful occupants are in the space not to create noise for others. It changes based on the nature of work. The number of simultaneously speaking occupants depend on how close workstations are. The results indicate that with the proposed adaptations, the model is an adequate prediction tool that can be utilized in the design of open plan offices.

ÖZET

AÇIK PLANLI OFİSLERDE KULLANICI SAYISINA BAĞLI OLARAK GÜRÜLTÜ SEVİYELERİNİ TAHMİN ETMEK İÇİN BİR MODEL

Gürültü, sağlıklı yaşam ortamlarına ulaşmadaki en büyük sorunlardan biri olarak görülmektedir. Gürültü sorunu özellikle etkileşimin desteklendiği çalışma mekanlarında daha önemli hale gelmiştir. Mekanlar tasarlanırken, gürültü seviyesini belirleyecek bir gürültü tahmin modeli tasarımcılar için faydalı bir araç olabilir. Kullanıcıların ürettikleri gürültüyü tahmin eden modellerin sayısı azdır. Etkinliği kanıtlanmış olan ve Lombard etkisini hesaba katan bir model yemek mekanlarına yönelik geliştirilmiştir. Bu çalışma yemek yeme alanları için tasarlanmış modelin açık planlı ofislere uyarlanmasına odaklanmaktadır.

Ön çalışmada, iki yemek yeme mekanı, kütüphanede bulunan bir çalışma salonu ve bir mimarlık stüdyosunda ölçümler yapılmış ve yemek yeme alanları için geliştirilmiş modelin çalışma mekanları için uygun olmadığı gösterilmiştir. Daha sonra ölçümler altı farklı açık planlı ofiste yürütülmüştür, yapılan ölçümlere dayalı olarak modelin parametreleri için en uygun değerler optimizasyonlarla araştırılmıştır. Sonuçlar; Lombard eğiminin ofisler arasında farklılık gösterdiğini ve mekansal yoğunluğun eş zamanlı konuşan kişi sayısı için iyi bir gösterge olduğunu ortaya koymaktadır.

Mevcut modelin açık planlı ofislere uyarlanması için modele iki değişiklik önerilmiştir: Ofislerdeki etkileşim seviyesini temsil eden bir değişken ve eş zamanlı konuşmacıların sayısını belirlemek için bir tablo. Etkileşim seviyesi, kullanıcıların diğer kullanıcıları rahatsız edecek gürültüyü yaratmamak için ne denli dikkatli olduklarını yansıtır. Etkileşim seviyesi işin niteliğine bağlı olarak değişir. Aynı anda konuşan kişi sayısı ise, çalışma masaları arasındaki uzaklığa bağlıdır. Bulgular, önerilen değişiklikler ile modelin açık planlı ofislerin tasarımında kullanılabilecek yeterli bir gürültü tahmin aracı olduğunu göstermektedir.

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LIST OF ABBREVIATIONS

Ap	Amount of Absorption per Person in m^2
c	Lombard Slope
DEU	Dokuz Eylül University
Ee	Eating Establishment
EDT	Early Decay Time
g	Assumed group size N/Ns
HVAC	Heating, Ventilating and Air Conditioning
Hz	Hertz
IEQ	Indoor Environmental Quality
ISO	International Organization for Standardization
IZTECH	Izmir Institute of Technology
LA_{eq}	Equivalent Continuous Sound Level
LE	Lombard Effect
MAPE	Mean Average Percentage Error
Max	Maximum
MD	Main Dining Hall
Min	Minimum
N	Number of People
NR	Noise Rating Curves
OAOs	Open Plan Administrative Offices
OPO	Open Plan Office
OROs	Open Plan Research Offices
RMSE	Root Mean Square Error
RT	Reverberation Time
s	Seconds
SMS	Sound Masking System
SP	Speech Privacy
STI	Speech Transmission Index
STL	Sound Transmission Loss
YM	Yaşam Merkezi
$\sum A$	Total Absorption

CHAPTER 1

INTRODUCTION

1.1. Context

Acoustic performance of rooms is commonly evaluated according to their function, either speech or music. Due to modernization and evolution of spaces recent acoustical studies have been focused on other types of spaces as well. Some examples are shopping malls, airports and eating establishments. They are different in character and require a different approach for acoustic evaluation compared to spaces for speech or music (Schweiker, Wentz, and Taylor 1995, Du, Zhang, and Lv 2020). In the design of such "non-acoustic" environments (Kang, 2006), evaluation of acoustical quality needs to be handled differently than it is in conference halls and concert halls.

The way that researchers evaluate acoustical quality has remained unchanged for quite a while. The one descriptor whose importance cannot be ignored is the reverberation time (RT). Yet, hearing is multi-dimensional and sound has multiple components and more than one descriptor must be examined in studies (C. Svensson & Nilsson, 2008). In order to gain a better understanding of acoustic comfort, besides reverberation time, other objective measures (e.g. Speech Transmission Index, Initial Time Delay Gap, Bass Ratio, etc.) and their correlations to subjective parameters have been investigated. Recommended ranges have been defined.

While room acoustics research defined evaluation criteria, noise control research has been successful in developing standards for noise criteria. Acceptable noise levels have been defined for many contexts and Noise Rating (NR) curves have been developed for defining maximum acceptable sound pressure levels in various spaces. Studies on defining noise and noise problems in public spaces are focused on types and level of noise sources.

However, in most non-acoustic spaces, the source of the noise is the users themselves. It has not been studied in detail how much noise occupants themselves produce while in different spaces. The average sound level of a speaking person is examined, and average values are defined. Those average values are determined regardless of the activity of the space. Because different type of activities take place in non-acoustic spaces, examining noise levels produced by the occupants is difficult.

Furthermore, another factor that makes things even more difficult is the "Lombard effect" which is defined as a result of studies on speech privacy and noise control within buildings. The phenomenon also known as the "Cocktail Party Effect" was first defined in 1911 by Etienne Lombard (Brumm and Zollinger 2011). When number of speaking people increases in an enclosure, people raise their voice inevitably as a reflex in order to preserve speech intelligibility and Lombard effect starts. Lombard effect is a phenomenon where talkers react to increasing noise levels by increasing their own voices to maintain adequate conditions for verbal communication (M. Hodgson et al., 2007). Besides architectural acoustics the effect has been studied in different disciplines such as, in medicine, psychology, and neurobiology as well as in animal behavior. Researches on the Lombard effect study in architecture focus on the relationship between speech levels and background noise level. The ratio of the increase in vocal effort to the increase in background noise level is known as the Lombard slope. In literature various Lombard slopes have been defined (Bottalico 2018).

Rindel (2010) proposed a noise prediction model by using Lombard slope as a variable with an assumed diffuse sound field in eating establishments. In architecture, this effect is mostly studied in eating establishments, not defined and analyzed widely in different environments.

The noise prediction model is developed for eating establishments to increase conversational intelligibility. Applying the model to different spaces rather than eating establishments has not been studied. In this study, the model’s applicability to other types of spaces – in particular open plan offices is investigated. In open plan offices, attitude and purpose of the users are different form eating establishments. Occupants in open plan offices behave more carefully and controlled not to disturb other users. Since, this behavioral difference has an impact on the noise generated per person, for open plan offices, a different noise prediction model is required.

The definition of open-plan office in ISO 3382-3 standards is stated as “spaces where a large number of people can work, have a conversation, or concentrate independently in well-defined work stations” (ISO 2012). Besides, in ISO 3382, it is mentioned that the insufficient acoustic conditions lead to distraction and lack of speech privacy. Furthermore, the difficulty of determining acoustic comfort due to variation of background noise by presence of occupants in the environment is mentioned in standards.

Despite these adverse conditions, open plan offices are still preferred by many organizations due to their advantages such as enabling flexible planning by eliminating corridors, improving collaboration and collective intelligence. Open plan offices also bring cost savings for organizations since worker density can be more than doubled, the number of organizations adopting open plan offices is increasing (Jan et al. 2006, Passero and Zannin 2012).

Technology has allowed architects to design and build large open spaces; however, as the number of occupants increase, background noise level increases and disturbance level due to background noise increases. A model that will predict noise levels in large enclosed spaces based on the number of occupants needs to be developed. The factors such as volume, activity, interior layout, and number of occupants that affect noise levels should be investigated. The aim of our study is to develop a model to predict noise levels based on number of occupants in open plan offices. The model is aimed to be a tool for designers to foresee noise levels based on the number of occupants during planning stage. As a result, architects will be able to determine the maximum number of occupants an open plan office can accommodate while providing acoustic comfort conditions.

1.2. Motivation

Studies on architectural acoustics mainly focus on movement and isolation of sound. Studied room acoustic parameters are not enough to define acoustic quality of various spaces. When previous studies are examined, there is a lack of noise estimation models which is based on the number of occupants and activity of the space. This gap in architectural acoustic studies underpins the major motivation of this study.

Architects and interior designers consider many design decisions and elements while designing spaces. Creating desired acoustical environment in a space with its own unique set of parameters is a complex task. It is common to overlook acoustic properties and its importance on human well-being (Szabó et al. 2018).

Some design decisions may negatively affect indoor comfort parameters in line with the developing and changing spatial needs. For instance, designing large and partition-free spaces and increasing glass surfaces to get more daylight makes it difficult to provide acoustic quality. A noise prediction tool for designers to design partition-free offices with having required acoustic quality based on number of occupants is a need. This study is shaped by taking the mentioned situations into consideration.

1.3. Problem Statement

Maximum recommended background noise levels are used widely for various spaces with specific activities. Standards and regulations mainly focus on sound transmission, insulation and penetration of noise entering the building from outside. Studies on monitoring noise that is generated by the occupants themselves are limited.

Acoustic comfort depends on the noise levels and the activity in a space and there is no guidance for designers to predict noise levels in large enclosed spaces that accommodate a high number of occupants. Currently, there is no single model to predict noise levels due to the occupants in enclosed public spaces with the exception of eating establishments. Technology has enabled architects to design and build large open spaces but, as the number of occupants in a space increase, acoustic comfort rapidly deteriorates. As the designed space gets larger the control of indoor environmental quality gets difficult. This is especially true for work environments. The open plan offices are increasing in numbers despite the acoustic problems they come with.

A model that will predict noise levels in large enclosed spaces such as open plan offices, based on the number of occupants needs to be developed. Such a model can be a tool for designers to predict noise levels based on the planned number of occupants and avoid oversized spaces where comfort conditions are impossible to achieve. For this purpose, how factors such as volume, activity, interior layout, and number of occupants affect noise levels should be investigated.

1.4. Aim

The aim of this study is to analyze acoustic properties of open plan office environments and predict background noise levels based on number of occupants. As the number of people increases, the noise level produced also increases. Since, occupational noise causes distraction and lack of concentration for occupants, and its effect on overall loudness level should be taken into consideration.

In previous studies, the effect of occupant generated noise on background noise levels is not considered. Studies on noise problem are generally focused on reducing background noise level, enhancing speech intelligibility and providing speech privacy. The amount of noise that a single person can produce depending on the ambient noise level and effect of each occupant's noise on ambient noise has not been studied in detail.

In this study, the relationship between the number of users and the total noise level in open plan offices is investigated. The goal is the development of a model for the prediction of noise levels in open plan offices that takes into account the impact of the Lombard Effect and based on the number of occupants.

The research questions about this study may be stated as below:

- Does Lombard effect exist in spaces other than eating establishments?
- Is it possible to estimate background noise level in open plan offices based on number of occupants?
- Is there a relationship between number of occupant and noise level in open plan offices?
- Can Lombard effect be observed in open plan offices? If it can, what is the associated value of the Lombard slope?

1.5. Significance and Limitations of the Study

The noise prediction model that was generated for eating establishments has been researched and tested in several studies and results show that the model works accurately. When predicted and measured noise levels in eating establishments are compared the deviation is very small and acceptable. Yet, occupants in eating establishments can behave more relaxed, and they do not feel the need to control their voice levels, in order not to disturb others while talking. Lombard effect is very much pronounced in such environments. However, in working environments occupants need to focus and concentrate on a task, their behavior patterns need to be different so as not to disturb others.

This study aims to investigate whether Lombard effect is observable in working environments or not. If there is a Lombard effect in working environments, this study focuses on the investigation of the magnitude of the slope. When a reliable model to predict background noise levels based on the numbers of occupants is defined for working environments, designers can find guidance on the maximum number of occupants that working environments should be designed for.

In accordance with this purpose firstly the noise prediction model, which is generated for eating establishments will be studied, and its applicability in open plan offices will be investigated.

The limitations of the study are:

- The maximum number of occupants in the selected spaces ranged from 0-94. The data collected is valid in this range.
- In each selected space, measurements were repeated for 2-3 days. Although, the data does present clear patterns, the reliability would improve with more measurements.
- During measurements the Equivalent Continuous Sound Level (LA_{eq}) logged every 1 minute, logging could be in shorter periods, yet gate counting would be more difficult. Automated tracking based on video surveillance where appropriate should help improve data resolution.
- Through gate counting in some offices, due to the rapid entrances and exits, it was difficult to obtain a high resolution.
- Most measurements were conducted using a single microphone position, after the results of pilot measurements, using two microphone positions showed absolute deviation between the two positions were less than 1 dBA. However, occupant distribution during certain measurement periods was observed to be non-homogeneous.
- The study focuses on open plan offices with a rectangular plan. Different office layouts and types were not considered.

1.6. The Structure of the Thesis

Following the introduction chapter where aim and limitations of the study have been defined. Chapter two will define analyzed concepts; reverberation time, noise criterion curves, vocal effort and Lombard effect. In chapter three, literature review on definition & importance of acoustic comfort, evaluation of open plan offices with its acoustical problems, the methods that have been used to control noise problems are presented. In chapter four, used methods and measurements with their overall results are explained. Also, model development and parameter optimization results are defined. In the fifth chapter results of the study are presented. As conclusion, in the last chapter conclusion and contribution of the study are given with suggestions for further researches.

CHAPTER 2

BACKGROUND

This chapter will present a brief review of concepts, theories, tools, and methods that are employed in this study.

2.1. Equivalent Continuous Sound Level (LA_{eq})

In order to define the concepts that we have included in our study, we first need to analyze, how sounds waves are arriving to ear, heard and interpreted. Sound is generated by vibrating air molecules by wave motion, and when the pressure in the air acts on eardrum the brain senses the sound (Parkin and Humphreys 1969). Human ear is not as sensitive to low frequency sounds as it is to mid and high frequencies. The "A" frequency weighting "filters" out the low frequencies which humans do not perceive. Since the A-weighted decibel (dBA) measurements show good correlation with human hearing, “A” filtered Equivalent continuous level (L_{eq}) is used during noise related measurements.

Equivalent continuous level, L_{eq} is defined as linear averaging over time (Hopkins 2007). If the sound pressure is constant over a period, it will contain same amount of energy during its fluctuation. L_{eq} measurements generally made over 1 hour or 24 hours so they are denoted by L_{eq} (1) or L_{eq} (24). Also, L_{eq} can be measured in dB or dBA (Mehta, Johnson, and Rocafort 1999). In this study equivalent sound level L_{eq} during a given period with A-weighted sound levels in decibels (LA_{eq}) is used.

2.2. Reverberation Time

Reverberation time is probably the most important and critical parameter in architectural acoustics. It describes how reverberant each space is. Reverberation time value of the space enables the designer to determine if the space is suitable for its purpose. It is the time taken for sound level to decrease by 60 dB (Long 2014). For instance, if it takes 1.5 seconds for a sound to decrease from 90 dB to 30 dB, the reverberation time of the room is 1.5 s. Sound absorption properties of materials used on all surfaces, furnishings and people in the space, along with the total volume of the space determine the reverberation time of that space. It can be predicted by using the Sabine equation (Sabine 1964). In Sabine's empirical equation (Eq.1) V is the total volume of the room and ∑A is the total absorption. If the total absorption in the room is higher, the reverberation time will be shorter. However, if the volume of the room is greater the sound rays will less often strike the walls and decay of sound will take more time which leads to a longer reverberation time.

$$Rt = \frac{0.161V}{\sum A} \qquad \textit{Eq. 1}$$

where,

Rt: Reverberation time in s
V: Volume of the space in m^3
A: Total sound absorption in the room in sabins [m^2]

Recommended reverberation time for various activities are studied and even appear in regulations in some countries. For instance Long (2005) listed suggested reverberation time of spaces for various activities (Figure 2.1). According to the figure, such as recording studios has shorter reverberation time and concert halls and opera houses have longer reverberation times.

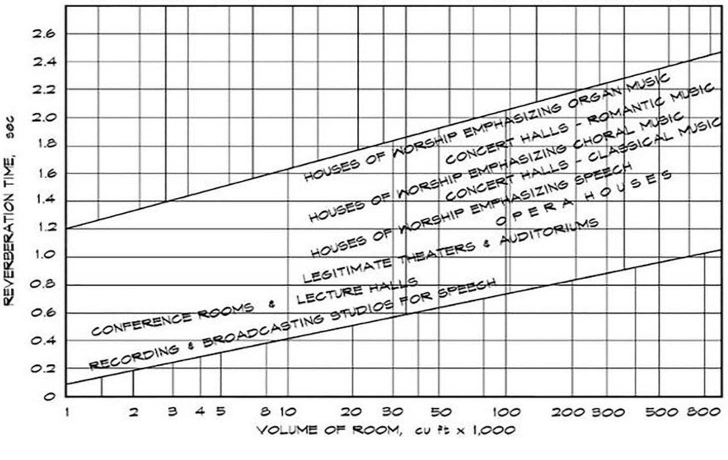


Figure 2.1. Suggested Reverberation Times.
(Source: Long 2005)

Some countries have regulations for recommended reverberation times in spaces with certain activities. According to Turkey's regulation (Environment and Urban Ministry, 2017) maximum allowable reverberation time for various functions are listed with space definitions (Table 2.1). In the list of "Offices and Administrative Buildings" for acoustic performance class of C-D, maximum allowable reverberation time for open offices is defined as 1.0 second.

Table 2.1. Maximum Reverberation Times Allowed for Acoustic Performance Class C-D. (Source: Environment and Urban Ministry 2017)

Function of the Building	Space		Reverberation Time (s)
Houses	Circulation areas		1.2
	Bedrooms		0.5
	Living areas, kitchen		0.8
Education Facilities	Classrooms, Administrative rooms, Reading rooms		0.8
	Sport Halls		1.8
	Circulation areas		1.2
	Kindergartens	Game and eating areas	0.8
		Sleeping areas	0.5
Healthcare Facilities / Nursing Homes	Patient rooms		0.5
	Examination rooms, Operating rooms, Laboratories		0.8
	Multi-bedrooms		1.0
	Circulation areas		1.2
Offices and Administrative Buildings	**Open Plan Offices**		**1.0**
	Meeting – Manager offices Resting areas		0.8
	Teleconference rooms		0.4
	Circulation areas		1.2
	Courtrooms		1.2
Accommodation Facilities	Bedrooms		0.5
	Restaurants		1.0
	Circulation areas		1.2
	Information areas		1.0
Dormitories	Dorms		0.5
	Study rooms		0.8
	Circulation areas, Dining areas		1.2
Cultural Facilities	Museums		1.2
	Libraries		0.8
	Circulation areas		1.2
Commercial Facilities	Stores		1.0
	Shopping malls		2.0
	Post offices, Banks		1.2
	Circulation areas		1.2
Stations	Waiting areas		1.0
	Staff rooms, Resting rooms		0.8
Entertainment Facilities	Restaurants, Eating establishments		1.0
Industrial Facilities	Staff rooms, Resting rooms		0.8
	Circulation rooms		1.2

2.3. Noise Rating Curves

Background noise has several side effects on users. Different spaces, locations, activities, regulations may suggest different acceptable noise levels. For rating background noise level of indoor environments Noise Rating (NR) curves have been developed by Kosten and Van Os (1962). Later NR curves have been adopted by International Organization for Standardization (ISO) as an ambient noise measurement system in indoor environments in 1973. NR curves were defined for rating noise from room mechanical sources in occupied states (Figure 2.2). NR curves are a set of curves where each curve is defined at each octave band. When a measurement is recorded its NR rating is the maximum NR curve it touches across all octave bands.

NR curves are used to define maximum acceptable sound pressure levels for various spaces. Curves range between NR 0 to NR 130. It is recommended that background noise levels should not exceed NR 25 in concert halls. For libraries or executive offices NR 35, and for general offices NR 45 curves are recommended. Some examples of NR values and their applications are listed in Table 2.2.

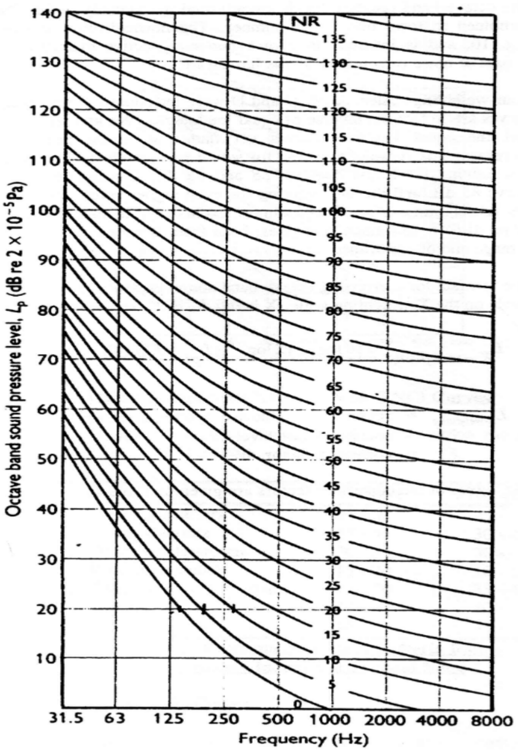


Figure 2.2. Noise Rating Curves.
(Source: ISO 1973)

Table 2.2. Maximum Recommended NR Values with Their Applications.
(Source: ISO 1973)

Noise Rating Curve	Application
NR 25	Concert halls, broadcasting and recording studios, churches
NR 30	Private dwellings, hospitals, theatres, cinemas, conference rooms
NR 35	Libraries, museums, court rooms, schools, hospitals operating theatres and wards, flats, hotels, executive offices
NR 40	Halls, corridors, cloakrooms, restaurants, night clubs, offices, shops
NR 45	Department stores, supermarkets, canteens, general offices
NR 50	Typing pools, offices with business machines
NR 60	Light engineering works
NR 70	Foundries, heavy engineering works

After conducting measurements, background noise levels in unoccupied state of each studied office will be listed and evaluated considering NR curves, whether they are within the specified value ranges suggested by ISO (1973).

2.4. Verbal Communication in Public

Verbal communication studies in architectural acoustics mainly focus on spaces used for speech, such as; conference halls, classrooms and lecture rooms. In those spaces, speech intelligibility is the main criteria for acoustic evaluation. How people talk is an important reference for speech intelligibility and privacy evaluations (Cushing et al. 2011). Importance of vocal effort and speech intelligibility in conference halls, and lecture rooms were studied in several studies (Howard and Murphy 2007, Long 2014) For instance, classroom acoustic design studies aim to improve intelligibility and student-teacher communication to speak comfortably. Such studies show that bad acoustic design of classrooms results with, high background noise levels and teachers adapt their vocal effort to environmental noise. (Balint, Ludwig, and Graber 2017, Carmeliet, Hens, and Vermeir 2003, Cipriano, Astolfi, and Pelegrín-García 2017).

The vocal comfort of a room is directly correlated with speech production and to the perceived support. Vocal effort is characterized by the direct sound level in front of a male speaker 1 meter away from the mouth. In a free sound field, voice has a characteristic spectrum level and directivity factor. In speech analyses average speech spectra of a male speaker is given in Figure 2.3. In order to define the effect of occupants' noise, different vocal efforts of a male speaker measured at 1 m in front of the mouth with their A-weighted speech levels are given in Table 2.3 (ISO 2003).

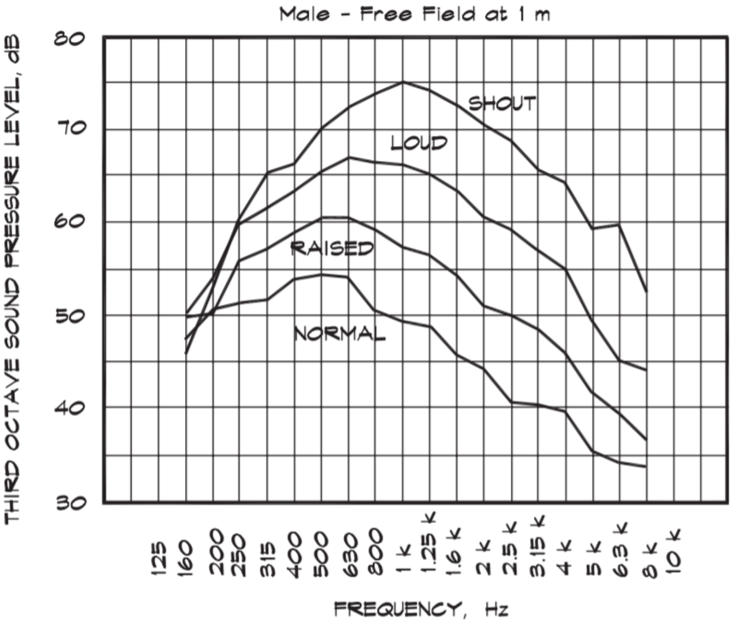


Figure 2.3. Average Peak Male Speech Spectra.
(Source: ANSI 1997)

Table 2.3. Vocal Effort and A-weighted Speech Level.
(Source: ISO 2003)

Vocal Effort	**L $_{S,A,1\,m}$** (dB)
Very Loud	78
Loud	72
Raised	66
Normal	60
Relaxed	54

Defining and applying speech levels as relaxed, normal, raised, loud, very loud in all spaces would ignore behavioral differences in different spaces. Since type of the vocal effort varies depending on the characteristics of the place, specific vocal efforts need to be defined for different activities. Such as in a classroom, a teacher is assumed as a speaker and students are accepted as listeners. Number of speaking people keeps constant. In eating establishments and in open plan offices people communicate with people sitting near them and the number of speaking people is not constant. In order to provide speech intelligibility in eating establishments and in open plan offices speech levels and their increasing rates related with Lombard effect needs to be studied.

Other parameters proposed for the evaluation of speech intelligibility are speech transmission index (STI), clarity (C_{50}) and definition (D_{50}).

- **Speech Transmission Index (STI)**

Speech transmission index is a signal-to-noise ratio expressed as a level. STI is a number between 0 and 1. Closer to zero means more information is lost during transfer. STI is an objective measure used in room acoustics for evaluating speech intelligibility levels in all types of spaces including churches, conference rooms and auditoria (Long 2014).

- **Clarity (C_{50} -C_{80}) and Definition (D_{50})**

Clarity is the balance between the early and late arriving sound energy. Clarity is the ratio of the early sound (energy received by the listener in the first 50 or 80 milliseconds) to the late sound (rest of the energy received) expressed in dB. For speech a 50 ms (C_{50}), for music an 80 ms (C_{80}) limit is used for separating early and late sounds. *Definition* (D_{50}) is similar, but is the ratio of early sound energy (50 ms) to the total energy expressed as a percentage (Vigran 2008, Cavanaugh and Wilkes 1999).

2.5. Lombard Effect (Cocktail Party Effect)

The “Lombard Effect”, also known as the “Cocktail Party Effect” was first described by Etienne Lombard (1869-1920), a French otolaryngologist and surgeon. While he was working in Hôpital Lariboisière in Paris, he demonstrated that patients have increased their speaking volume when noise was introduced. He presented the phenomenon in the paper “Le signe de l’élèvation de la voix” (Lombard 1911). Lombard described the effect as “the adaptation of speech to overcome the deleterious effects of noise, a nonlinear distortion which depends on the speaker voice level, the background noise level and the type of noise" (1911). In order to raise intelligibility in speech, we change our vocal effort while talking in a noisy environment. Since, increased vocal effort of occupants increase ambient noise level and increased ambient noise level influences occupants' vocal effort so, a vicious circle starts. The relationship between vocal effort (A-weighted speaker levels at 1 m.) and ambient noise level (A-weighted) is shown in Figure 2.4. The hatched area shows that the effect starts with minimum 45 dB ambient noise level and minimum 55 dB speech level.

In literature, the Lombard effect phenomena have been defined and studied in different disciplines. The effect is not only useful in medicine but also valuable in neurobiology, psychology, and animal behavior (Brumm and Zollinger 2011). Since the phenomena leads to a vicious cycle where people sharing a room, speak in increasing sound levels to maintain intelligibility, which in-turn leads to higher ambient noise levels, there have been numerous studies on outcomes of the Lombard effect in architecture (Hodgson, Steininger, and Razavi 2007). Studies in architecture that analyze Lombard effect, mostly focused on verbal listener-speaker communication.

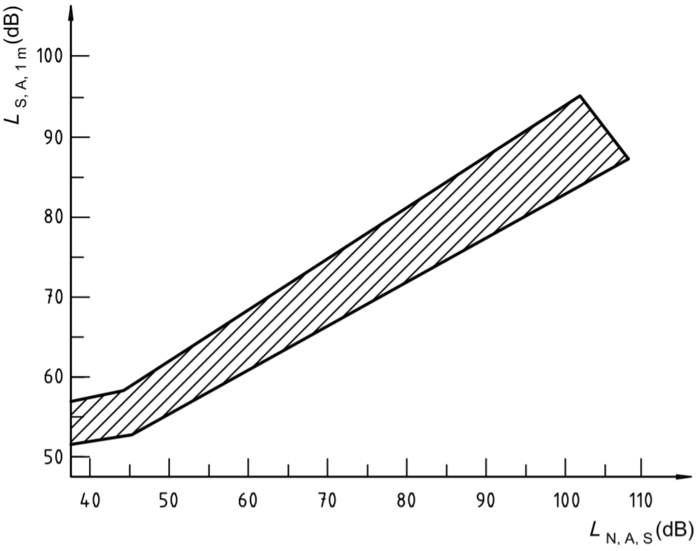


Figure 2.4. Speech Level and Ambient Noise Level Relation.
(Source: ISO 2003)

Lazarus (1986) performed several studies and he concluded that the ratio between speech level and ambient noise level gives a slope and he coined the term "Lombard slope". This slope is usually denoted by "c". Outcomes of studies on Lombard effect in architecture show that slopes vary due to, gender, speech situation (conversing or reading), noise type (speech noise, restaurant noise, wideband noise, or pink noise), vocal effort level (normal or shouting), the listener-speaker distance and the acoustics of the room (Bottalico et al. 2017). For instance, a study by Egan (1972), concluded that men and women are different in the strength of the Lombard effect, women increase their vocal effort more strongly than men.

Different slopes have been defined in literature. Pickett (1958) studied Lombard effect in an anechoic chamber and found 8 dB increases in mean vocal effort with 8 dB increase in noise level which is a Lombard slope of 1 dB/dB. The studies showed the slope could vary between 0.2 and 0.7 dB/dB. Another study by Astolfi and Filippi (2003), studied speech intelligibility and privacy in pizzerias and concluded as better conditions with normal vocal effort can be achieved by increasing area per person from 1 m^2 to 5 m^2. On the subject of increased background level, they took the Lombard effect into consideration. In 1977, (Tang, Chan, and Chan) published a study on a staff canteen that showed when background noise level exceeds 69 dB, people start to raise their voices, and this effect might not be seen when the number of occupants in the space is less than 50.

2.6. Rindel's Noise Prediction Model for Eating Establishments

Recently, Rindel (2010) proposed a model for predicting the average A-weighted noise level due to several people speaking in a room with assumed "diffuse sound field". The aim of his study was to present a prediction model for design guidelines that can yield satisfactory or good acoustical conditions in eating establishments which takes Lombard effect into consideration.

Rindel's model on background noise due to speech is presented in equation 2.

$$\mathrm{LNA} = \frac{1}{1-\mathrm{c}} \cdot \left(69 - \mathrm{c} \cdot 45 - 10\mathrm{Log}\left(\frac{\mathrm{g}(0.16 \cdot \mathrm{V})}{\mathrm{T0} \cdot \mathrm{N}} + \mathrm{Ap}\right)\right) \ (\mathrm{dB}) \qquad \text{Eq 2}$$

where,

c: Lombard slope (dB/dB)

N: Number of people

g: Assumed group size N/Ns

V: Volume (m^3)

Ap: Amount of absorption per person in m^2 (depending on amount of clothing)

This model takes volume, assumed group size and absorption per person with number of people into consideration, as well as Lombard slope. The equation by Rindel (2010) was suggested to estimate occupant-based noise level in eating establishments.

c: Lombard slope (dB/dB), it has been defined and studied in several studies in literature. There were different values were predicted for Lombard slope (c), such as Rindel suggest 0.5 dB/dB however Picket (1958) suggests 1dB/dB and Lazarus (1986) suggest that slope may vary between 0.5-0.7 dB/dB. Korn (1954) found that speech power increases 0.38 dB with every 1 dB increase in the noise level, which is a Lombard slope of 0.38 dB/dB. In 2004 Whitlock and Dodd (2004) found the rate to be 0.22 with different masking noise effect on 7-9 year old children. Bradley and Sato (2008) found the slope as 0.82 dB/dB in an active class.

N: The total number of people in a venue is indicated by N. The increase and decrease in the value of N is an important determining factor for the total noise level.

g: In each group, it is assumed that one person is a speaker and the others are listeners and g is the total number of people in the group. Therefore, minimum g value can be 2. A study by Navarro and Pimentel (2007) tried to predict noise level in food courts, they applied different values of the group size between 2 and 4 and found that 3 as group size gives the best fit. Another study by Tang et al, (1997) conducted 2.5 hours measurement during lunch time in a canteen and the best overall agreement with the model was 3.5 as g.

Ap: This is the sound absorption provided by the occupants. Occupants are considered both as noise sources and noise absorbers. Besides the absorption value of room surfaces, occupancy absorption is another parameter that needs to be considered. Ap is the total absorption value of each person in square meters. Typical values range from 0.2 to 0.5. Each person's absorption value has a very slight effect on total absorption value in the space. Ap value depends on clothing of occupants and clothing amount depends on climatic conditions. For instance, a study in school cafeterias aimed to find best fit for each parameter and concluded that Ap ranges between 0.15-0.3 m^2 by (Pinho et al. 2018). In another study by Rindel (2010), Ap was accepted as low as 0.2 m^2 in the noise estimation model during summer time.

It is not possible to speak of a certain value for each parameter in the model. For instance, a study in Portugal in six school cafeterias was set to predict noise level by using the model. In their study they tested and optimized all unknown parameters in the model (c, and g), they concluded that under any circumstances, the best fit in all cafeterias has not been achieved. For each cafeteria the set of parameters were different for instance, in one cafeteria best fits were c:0.5 dB/dB and g:4 and for other cafeteria c:0.4 dB/dB and g:3 (Pinho et al. 2018). Another study by Navarro and Pimentel (2007) measured 2 large food courts with ca. 540 and 345 people to show the relationship between measured sound pressure level and number of people (g), and concluded that average group sizes needs to be taken as 2 or 4.

CHAPTER 3

LITERATURE REVIEW

In this chapter, related literature is presented under the following headings: acoustic comfort, acoustic environments of eating establishments, open plan offices and noise control in open plan offices.

3.1. Acoustic Comfort

In developed countries people are spending more than 90% of their time indoors (EPA 2009). Indoor conditions are becoming more important for well-being, health and performance. In order to provide indoor comfort, there are number of physical parameters have been identified and standards on those parameters have been developed to define acceptable ranges. Acoustic comfort is required and essential for every space. Especially spaces include verbal communication and learning, better acoustic design is utmost important for comfort and productivity.

Besides defined standards and studies, not all the users of the space are satisfied with the indoor conditions (Frontczak and Wargocki 2011). However, there are no set of accepted parameters for public or non-acoustic spaces. Non-acoustic spaces are public spaces where occupants can communicate in groups and walk freely. Such as railway stations, shopping malls, libraries, open plan offices, football stadia, swimming spaces, dining spaces, and churches (Kang 2006). Existing parameters are not enough to describe acoustic comfort in those non-acoustic spaces.

In our daily life, we can criticize whether the spaces have good or bad acoustic quality; the subjective impressions of the space may change from one person to another. Also, people can have different impressions on a same signal into same room, which bases on personal considerations (Gramez and Boubenider 2017). Against those subjective impressions, scientists are working on objective parameters. Exclusively, spaces on oral communication require extra attention on signal to noise ratio (S/N) and reverberation time to increase speech intelligibility (Latham 1979). Also another study in urban open public spaces, show that lower background level makes people feel quieter and background sound level found to be an important parameter in soundscape evaluation (Yang and Kang 2005).

Acoustic comfort is generally analyzed and studied in crowded public urban spaces where lots of people gather and try to communicate or focus on a task. Creating a proper acoustical atmosphere for the occupants in non-acoustic spaces is a challenging task for designers. For this purpose, the characteristic, layout and specific noise sources of the space needs to be determined and proposed applications should be suitable and applicable for the space. In order to achieve more robust results on creating better acoustical comfort in eating establishments and in open plan offices, definition, pros & cons, design attitude, noise types of open offices will be elaborated in the following.

3.2. Acoustic Environments of Eating Establishments

Spaces for eating are where conversations take place. People visit diners to eat, but also to meet friends. “Regulation for environmental assessment and management" in Turkey states that maximum acceptable background noise level is 45 dBA in eating establishments. In several studies, measurement results are much higher than this acceptable level of NR 45. Average noise levels in eating establishments can be around 80 dBA and can reach up to 110 dBA (Christie 2004). In diners, verbal communication can be difficult and only be possible with a raised voice level at a close distance. Signal to noise ratio is low and reverberation time is high due to reflective surfaces.

Noise sources that contribute to background noise can be specific to the environment, depending on the activity. In eating establishments, the major noise sources are conversations, eating utensils, and chairs. The acoustical environment of eating establishments is different than other spaces. In most eating spaces, for easy cleaning, smooth surfaces are preferred leading to longer reverberation times and low speech articulation.

For noise control purposes in eating establishments several solutions have been suggested. For instance, Moulder (1993) preferred installation of acoustic ceiling as a way of adding absorptive materials to lower background noise for hearing impaired individuals.

Kang (2002) studied speech intelligibility in dining spaces, he concludes that increasing absorption is more efficient than enlarging the area of the eating establishment.

Also Kang obtained that for increasing speech intelligibility, the ceiling height needs to be decreased. As a result of these and similar studies, increasing the amount of absorptive materials for improving speech intelligibility is a widely accepted strategy.

If speech intelligibility is inadequate in an eating establishment, customers do not enjoy their visit. Lack of speech intelligibility causes tired voice which is a result of the need to raise one's voice to be heard over the noise in order to keep speech intelligibility which is known as the Lombard effect. Rindel's (2010) prediction model estimates the ambient noise level by using Lombard slope (c), Volume (V), Reverberation time in unoccupied state (T0), absorption value per person (Ap), number of people (N), and group sizes (g). By considering occupants' effect on background noise.

Acoustic comfort and acoustic problems in eating establishments have been studied in various studies (Rindel, 2010; Svensson, Jeong, & Brunskog, 2014; White, 1999) in all these studies, noise problems were analyzed by using main objective parameters, for instance, reverberation time, sound pressure level, speech transmission index, and signal to noise ratio. However, total number of occupancy, their absorptive value and their occupational noises were not mentioned or included to studies.

3.3. The Open Plan Office

Where people gather for concentration or cognitive activities, the acoustic quality and suitability of those spaces are utmost important, especially in educational and working environments. The evolution of open office (open-plan office, landscape office) design dates to 1960's, the concept was first revealed by two German furniture manufacturers (Eberhard and Wolfgang Schnelle), and promoted to United States. The main aim was to provide free arrangement in spaces to create unbounded offices with eliminated corridors. By this design, better communication between departments with increasing collaboration, collective intelligence becomes easier to achieve. Besides, open plan offices were providing economic, and managerial advantages (Navai and Veitch 2003). The transition to open plan offices was aimed to increase knowledge sharing and collaboration between workers.

The number of open plan offices has increased irrespective of the job content. The definition of "Open-plan offices" in ISO 3382-3 is described as "offices and similar spaces in which a large number of people can work, have a conversation, or concentrate independently in well-defined work stations" (ISO 2012). According to Van der Voordt (2004), the aim of flexible open-plan offices was to improve labour productivity and make cost savings with designing fewer workspaces in the same space whilst without reducing employee satisfaction. However, when private offices and open offices are compared 20% of occupants in private offices and almost half of the occupants in open plan offices were complaining about existing acoustic conditions. Also, Open office workers are taking extra breaks and experience more stress than private office workers (Haapakangas et al. 2008).

Combining offices into a single open room enables interaction among workers, makes exchange of information easier, nevertheless the new design style reduces co-operation, acoustic comfort and privacy. Besides, in open plan offices, aural distractions and frequent interruption by other employees creates concentration disorder (Liebl et al. 2012, Hedge 1982).

In open plan offices background noise is the most well-known environmental problem (Danielsson and Bodin 2009, Lou and Ou 2019). The main noise sources in an office are; telephone conversations, telephone ringing, typing, machine sound, people talking and moving. American Society of Interior Designers' study (1996) stated that 71% of disturbance in open plan offices is due to noise intrusion. Irrespective of the type of office layout, whether it is enclosed private, enclosed shared, cubicles with high partitions, cubicles with low partitions, and open office with no/limited partitions, the biggest frustration among workers is the lack of sound privacy (Beckerman 2015). According to questionnaire surveys, speech coming from other cubicles or colleagues is the most annoying sound in the environment (Virjonen et al. 2005). Continuous sounds such as HVAC (Heating, Ventilation and Air Conditioning) noise were other disturbing noises in open plan offices (Haapakangas et al. 2008).

According to field surveys, noise problems in open offices dates to early times of its application. Background noise level was as high as 79 dBA around 1970-1980's and the main noise sources were co-worker's conversations and noisy office equipment. Today even as the equipment has become less noisy, the background noise level continues to be primary cause of complaint (Navai and Veitch 2003).

Since sound can transmit effortlessly in open plan offices acoustic comfort problems are common due to the layout. According to S Bradley (2003), the most important design parameters in open plan office design are; layout, height of barriers between work stations and ceiling material. Bradley concludes that attenuation of sound is a challenging task unless the sound is absorbed or contained by an acoustically treated barrier.

Despite these negative effects of open plan offices on workers, the design and application still incrementally continues. In order to provide better acoustic comfort and privacy, there are some precautions and attempts to create better acoustical environment in those types of offices. In the following section some applications to achieve better acoustical comfort in open plan offices will be explained.

3.4. Noise Control in Open Plan Offices

The term noise is generally defined as “unwanted sound” such as loud music coming from a neighbor or sounds coming from nearby construction sites. Besides, the definition can be interpreted differently such as, according to Keizer (2010) noise is “much about what we want as about what we seek to avoid”. A noise can be generated from an internal source such as HVAC or an external source as traffic. The effect of noise on communication affects every person regardless of age, sex, or lifestyle. Noise is one of the biggest problems in open plan offices. When 5 Indoor Environmental Quality (IEQ) (layout, thermal comfort, air quality, lighting and acoustic) parameters in open plan office were analyzed, it was seen that acoustic environment of the offices have the greatest influence on productivity and performance levels (Kang, Ou, and Mak 2017).

In order to identify the noise sources and noise annoyance level between employees in open plan offices in banks, a study shows that; according to staff, the main noise source was commotion of clienteles, which reduces concentration and makes them to spend more effort to understand colleagues’ speech (Trifah et al. 2015).

There are some national and international regulations on noise levels in different environments. The acceptable noise level in offices according to the Ministry of Environment and Forestry's "Evaluation and Management of Environmental Noise" regulation (2010), is 45 dBA when the windows are closed. Also according to noise rating curves, which allow the assessment of acceptable noise levels in volumes depending on frequencies, NR 45 is accepted for general offices (ISO, 1973).

In order to achieve better acoustical environment, decreasing background noise and attaining recommended reverberation time for better speech transmission index and clarity are general precautions in spaces. Furthermore, acoustic comfort in open plan offices is highly affected by total absorption in the space. In order to increase sound absorption, adding extra absorptive materials on the floor and/or ceiling or adding screen panels in the space are some of the priority solutions.

In a study, an office is simulated with 3 different scenarios, those are; first one is the original version of the space. Second one is changing the ceiling into highly reflecting concrete ceiling and the third one is adding extra sound absorbing baffles under the existing acoustical ceiling and adding 1.25 m high screen panels to create a damped atmosphere. The results show that in the second scenario STI goes down with longer reverberation time, and in third scenario the distraction and privacy distances decreases by screen panels (Rindel & Christensen, 2012) . Another study conducted on adding screens with different heights (1.10 m, 1.40 m, and 1.65 m) between workers in open plan offices in Ankara, show that higher partition with 1.65 m is more preferable for privacy. Yet, for lighting 1.10 and 1.40 m height were more preferred (Yıldırım, Güneş, and Yilmaz 2019). In addition, a study was conducted to propose changes in a computational model, study underlines the benefit of increasing sound absorption in the ceiling and inserting dividers between work stations to improve acoustic conditions (Passero and Zannin 2012).

There are many studies on preventing open office noise problems by using sound masking system (SMS). Detrimental effect of noise on workers have been tried to prevent by wearing earphones with masking noises. Field and laboratory experiments show that by using appropriate masking noise, the negative effect of noise on performance and on worker attitude can be prevented (Venetjoki et al. 2006). In contradiction, in another study using modified brown noise through earphones has resulted in discomfort and irritation for workers (Vassie and Richardson 2017). It has been stated that by using SMS speech privacy among workstations can be improved in working environments (Lei and Hodgson 2013).

It can be said that according to field surveys and measurements, acoustic comfort is directly related with offices' productivity and performance. When acoustic comfort deteriorates, productivity of workers diminishes too. Acoustic comfort is affected from many other situations, which are related with IEQ, absorption amount, ceiling type, working styles and layout. Also, studies show that clients' noise is one of the biggest noise problems that effects staff and causes concentration loss and make workers spend extra effort to understand speech in open plan offices. Using masking noise is one of the methods for preventing concentration loss, however; it seems to be not enough (Schlittmeier and Liebl 2015).

Acoustical comfort of a space is generally disregarded, during project planning; in most of the studies, occupant related noise is listed as one of the primary complaints. However increased noise level depending on number of occupants were not seen as a problem in any of the studies. None of the studies in open plan offices focused on noise problems depending on number of occupants and its effect on acoustic comfort.

CHAPTER 4

METHODOLOGY

4.1. Overview

This research has been carried out in three main stages: preliminary measurements, open plan office measurements and noise prediction model development for open plan offices. A flowchart for the processes is given in Figure 4.1.

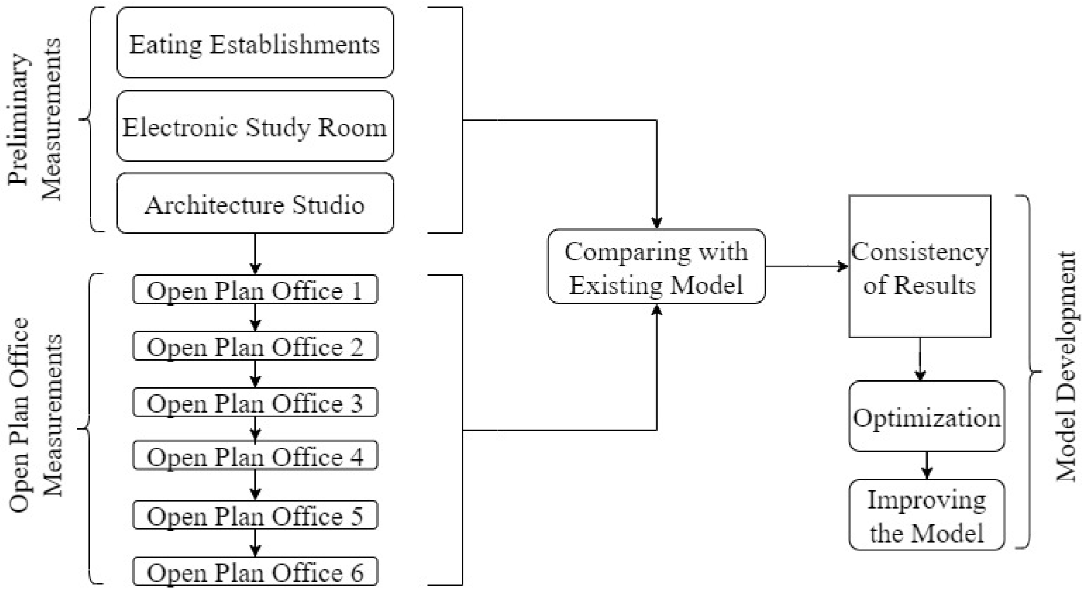


Figure 4.1. Overall Research Workflow.

The measurement workflow is illustrated in Figure 4.2. After obtaining necessary permissions, sites were studied in detail. During site analyses, existing noise sources, and entry points to the space were observed, and measurement points were decided upon. Afterwards, measurements were started with reverberation time measurements. Reverberation time measurements were conducted in unoccupied state following the interrupted method procedures described in ISO 3382-2 (ISO 2008), using Brüel & Kjaer 2260 sound analyzer. Reverberation times used in this study are averages of mid frequencies (400 – 1.25 k Hz).

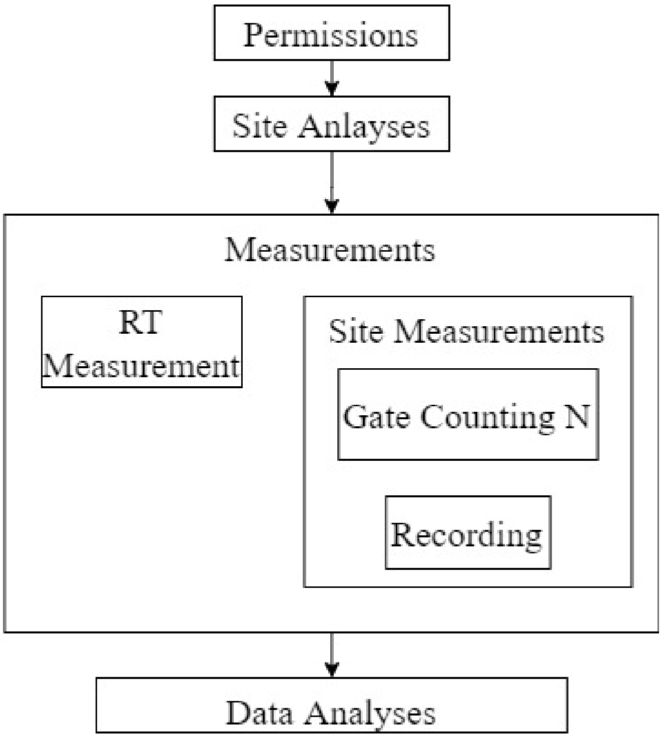


Figure 4.2. Measurement Workflow.

After completing reverberation time measurements, ambient noise measurements covering the whole work day from the beginning of the working shift until the end of the work day were carried out. During measurements HVAC systems were running in the spaces. For each studied open plan office 3 days of measurements were completed, loudness levels for each day are shown in appendix A. During measurements, noise levels are recorded while changes in number of occupants is tracked in one-minute intervals through manual gate counts. Noise level measurements started just before the work shift begins, so the background noise level can be observed until the first users come. Recording time and change of N is shown in Figure 4.3. Microphone was located close to the center of the spaces at least 1.5 meter away from any sources and surfaces.

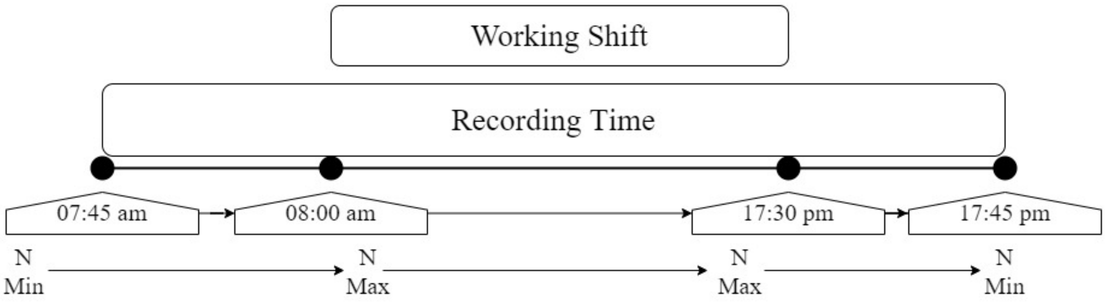


Figure 4.3. Recording Time and Change of N.

After preliminary measurements, the same measurement protocol was used for open plan measurements. After completing the measurement campaign, the measurements were compared to the existing model predictions and subsequently, model development phase focused on optimizing model parameters and modifying the existing model to improve its prediction performance in the context of open plan offices.

4.2. Statistical Evaluation Methods

After conducting measurements and gathering predicted noise levels by using Lombard effect equation (Eq. 2) results will be compared using two regression based statistical comparison methods; Root Mean Square Error (RMSE) and Mean Absolute Percentage Error (MAPE).

In order to see how the residuals, prediction errors are far from the regression line, Root Mean Square Error will be used. For numerical predictions and comparisons, root mean square error is accepted as a good general-purpose error metric in studies (Neill and Hashemi 2018).

Root mean square error compares 2 data sets and their prediction errors, in this study predicted and measured LA_{eq} values of each space will be compared (Eq. 3). Low values of Root Mean Square Error close to 1.0 indicates very good accuracy. Since smaller Root Mean Square Error means predicted value is closer to actual value, the value to be obtained as a result of Root Mean Square Error will give us information about how accurate the results are (Sharif Ahmadian 2016).

$$RMSE = \sqrt{\frac{\sum_{i:1}^{N}(Actual_i - Predicted_i)^2}{N}} \qquad \text{(Eq.3)}$$

For measuring percentage of error between measured and predicted values of each space, Mean Absolute Percentage Error statistical method will be used to test reliability of the model (Eq.4 & 5).

$$PE = \frac{Actual - Predicted}{Actual} \text{x}100 \qquad \text{(Eq. 4)}$$

$$MAPE = \frac{1}{n}\sum_{\text{i}=1}^{n}\left|\frac{[(Actual)i-(Predicted)i]}{[(Actual)i]}\right| x100 \qquad \text{(Eq. 5)}$$

For accuracy of MAPE, some studies accept 10% and around for a threshold (Llinares-Millán et al. 2014). Lewis (1982) suggests following periods for MAPE according to his studies, less than 10% is “highly accurate”, between 10% - 20% is “good”, between 20% - 50% is “reasonable” and greater than 50% is “inaccurate” forecasting.

For each measured space, measured and predicted values will be evaluated according to RMSE and MAPE statistical comparison methods. Whether the results will be above the threshold values, these values are expected to be reduced to the range of the desired values by the optimization method.

4.3. Preliminary Measurements

In order to investigate the research question regarding the existence of Lombard effect in spaces other than eating establishments, first, measurements were carried out in two eating establishments, an electronic study room in library and an architecture studio in Izmir Institute of Technology’s (IZTECH) campus. Measurements were compared and the existing model's suitability and applicability to crowded spaces other than eating establishments were explored.

Eating Establishment Measurements

As eating establishment sites, Main dining hall (MD) and Yasam Merkezi (YM) were selected. MD has a volume of 1724 m^3, a RT of 1.4 s, and a seating capacity of 320.

YM had a capacity of 200 seats with 1372 m^3 and RT of 1.9 seconds. Both dining halls were serving without background music during the measurements. MD has partially applied acoustic tiles on ceiling and laminated wood on the floors. In YM there was an exposed ceiling and marble on the floor (Figure 4.4). Those two spaces were considered as acoustically problematic by the campus community.

For each dining hall two measurements were completed during lunch hours. Each measurement day, recordings were carried out using the same microphone position at 1.2 m height, which was the ear level of a seated person.

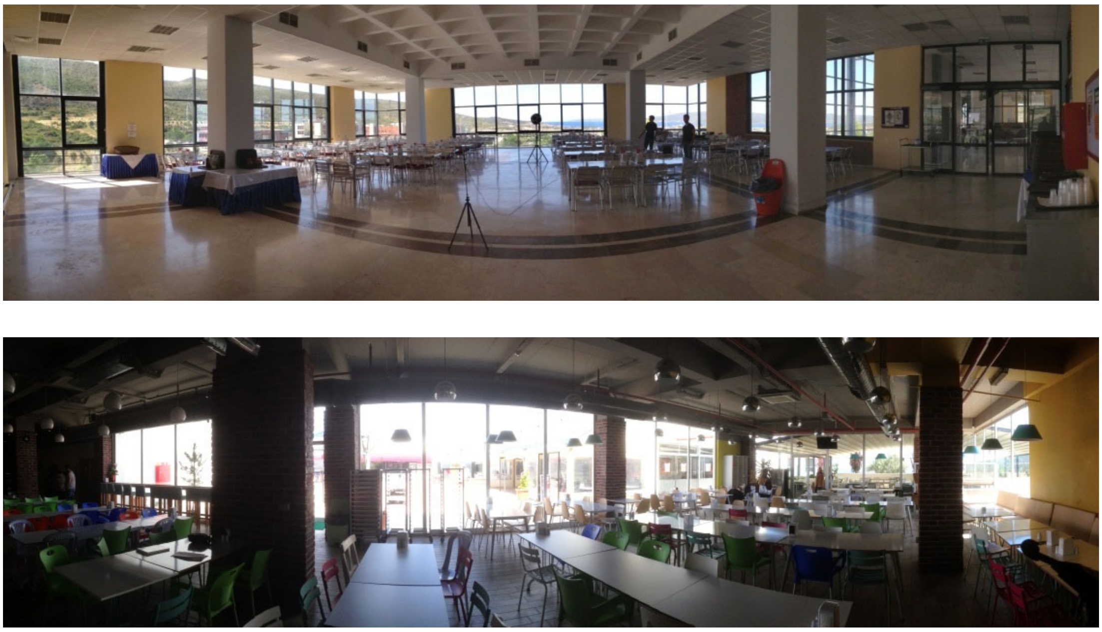


Figure 4.4. Interior of MD and YM.

Predicted LA_{eq} results for MD and YM were obtained using the following values: c: 0.5, g: 3, A_p: 0.3. Measurements in eating establishments completed during spring, so, Ap value was taken as 0.3. Since most of the people were sitting in groups of 4 and 2, average of 3 was accepted for group size, based on observations. Lastly, Lombard slope was assigned as 0.5 according to Rindel's (2010) study for eating establishments. In Table 4.1 and Table 4.2 measured and predicted values for both eating establishments are shown with error rates.

Table 4.1. Predicted Noise Levels of MD.
(c:0.5, Ap:0.3, g:3, V:1724 m^3, RT:1.4 s)

N	**Predicted LA_{eq} (dBA)**	**Measured LA_{eq} (dBA)**	**Deviation (dBA)**
20	63.33	64.27	0.94
30	66.72	63.92	2.80
40	69.09	65.99	3.10
50	70.91	67.00	3.91
60	72.37	68.93	3.44
70	73.59	69.56	4.03
80	74.63	69.92	4.71
90	75.54	70.39	5.15
100	76.34	71.29	5.05
110	77.05	71.29	5.76
120	77.69	71.76	5.93
130	78.28	71.79	6.49
140	78.81	71.82	6.99
150	79.30	71.62	7.68
		Abs. Av. Deviation:	**4.48**
		RMSE:	**5.03**
		MAPE	**6.72 %**

Table 4.2. Predicted Noise Levels of YM.
(c:0.5, Ap:0.3, g:3, V:1372 m^3, RT:1.9 s)

N	**Predicted LA_{eq} (dBA)**	**Measured LA_{eq} (dBA)**	**Deviation (dBA)**
20	66.78	66.97	0.19
30	70.12	67.55	2.57
40	72.43	69.38	3.05
50	74.19	70.99	3.20
60	75.59	74.39	1.20
70	76.76	72.82	3.94
80	77.75	75.09	2.66
90	78.60	76.79	1.82
100	79.36	75.10	4.26
110	80.02	76.59	3.44
120	80.62	76.02	4.60
130	81.16	77.92	3.24
140	81.65	78.31	3.34
150	82.10	78.31	3.79
		Abs. Av. Deviation:	**2.92**
		RMSE:	**1.01**
		MAPE	**0.35 %**

When the results of these two places are compared, absolute average deviation between measured and predicted values in YM (2.92 dBA) is lower than MD (4.48 dBA). RMSE of MD is 5.03 and for YM is 1.01 when the percentage errors are compared MAPE of MD is 6.72% and YM is 0.35%. Both MAPE values are both lower than %10, which is the commonly suggested threshold value (Llinares-Millán et al., 2014).

Also, in Figure 4.5 comparisons of predicted and measured values for both eating establishments are shown. Predicted values calculated by using equation 2, shows good performance with selected dining halls. The values obtained are within the range of values proposed by the literature. After observing the validity of the model in those two eating establishments, model's applicability in working environments will be discussed next.

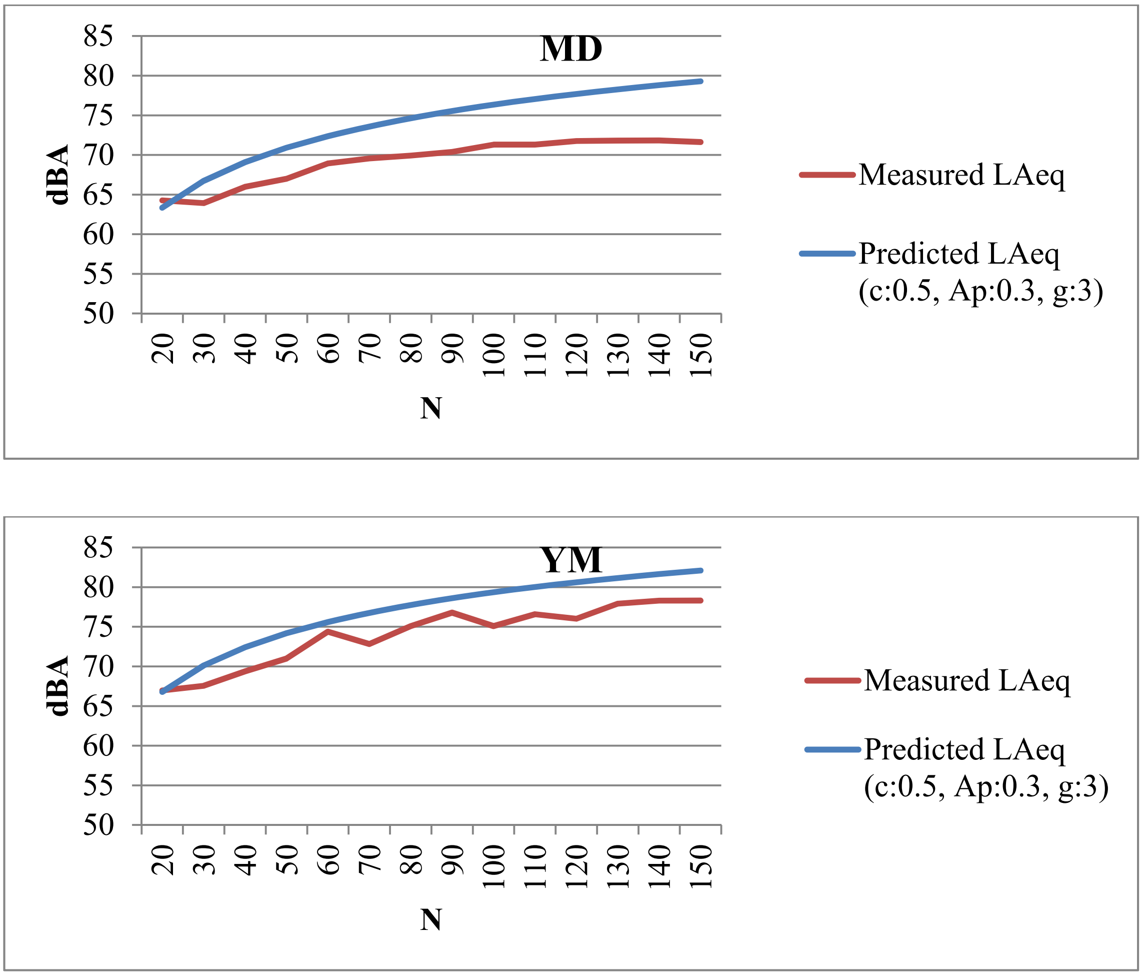


Figure 4.5. Predicted and Measured LA_{eq} of YM and MD.

Library Measurements

Study halls require a quiet environment. Noise in any form is unwanted. A calm and quite environment conducive to focused work is sought. Some research outcomes conclude that cognitive task performance such as students' concentration and librarian's consultation is distracted by background noise (Aremu, Omoniyi, and Saka 2015). Low background noise can make the slightest sound noticeable, while high background noise may lead to annoyance (Hodgson and Moreno 2008). Modern libraries host different spaces for work, study, meeting spaces and electronic study rooms with access to internet and multimedia services. For comprehension and skill development, established acceptable noise levels in libraries range between 35 - 45 dBA, with low reverberation time.

In order to investigate the presence and strength of the Lombard effect in places where users are more careful about noise, library spaces are discussed. One expects that library users stay quiet even if the number of occupants increase. Recently, electronic study rooms in libraries are becoming more popular, in those spaces users are relatively more relaxed and talk more comfortably with less self-control, so background noise levels can be higher. Conversational and electronic equipment noises are common noise sources in electronic study rooms.

Figure 4.6. Interior of Electronic Study Room.

The electronic study room chosen has a floor volume of 948 m^3 with 70 seats. There were both individual seating units and tables eligible for group studies. Reverberation time was 0.8 s with 42 dBA background noise level in its empty state.

Predicted LA_{eq} results for electronic study room and architecture studio were obtained using the following values: c: 0.5, g: 3, A_p: 0.3 same as in eating establishments. Measurements in electronic study room and architecture studio completed during final exam week of the University. Ap value was taken as 0.3 based on observations. Lastly, Lombard slope was assigned as 0.5 according to Rindel's (2010) study for eating establishments. In Table 4.3 and Table 4.4 measured and predicted values for electronic study room and architecture studio are shown with error rates.

Table 4.3. Calculated Noise Levels for Electronic Study Room.
(c:0.5, Ap:0.3, g:3, V:948 m^3, RT:0.8 s)

N	Predicted LA_{eq} (dBA)	Measured LA_{eq} (dBA)	Deviation (dBA)
35	68.31	48.34	19.97
40	69.41	48.68	20.73
45	70.37	49.20	21.17
50	71.22	47.82	23.40
55	71.98	49.24	22.74
60	72.68	50.28	22.40
65	73.31	49.53	23.78
		Abs. Av. Deviation:	**22.03**
		RMSE:	**22.07**
		MAPE	**14.26 %**

According to the results, absolute average deviation was 22.03 dBA with 22.07 RMSE and 14.26% MAPE (Table 4.3). Measured and predicted noise levels are shown in Figure 4.7.

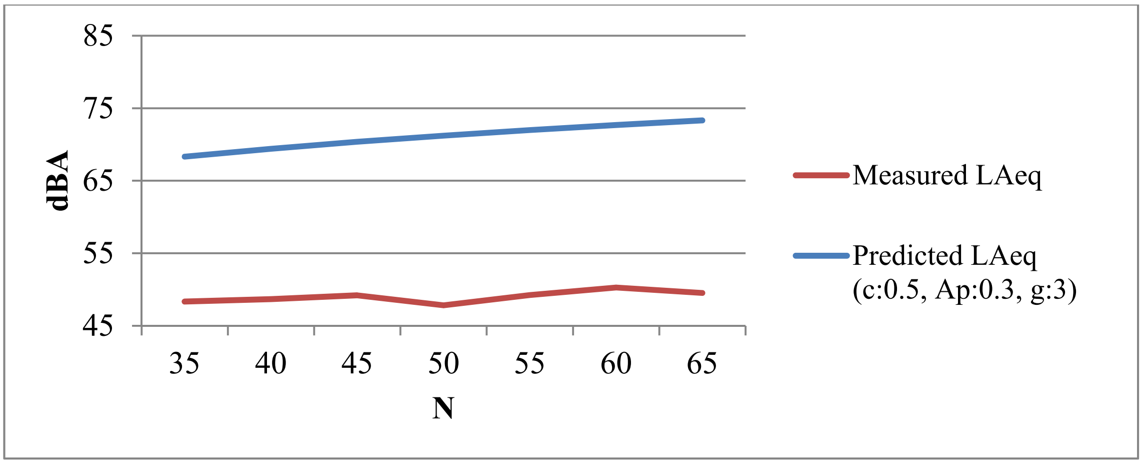


Figure 4.7. Predicted and Measured LA_{eq} of Electronic Study Room.

Architecture Studio Measurements

Architecture studios are workspaces where students work, learn and explore a set of skills. The exploration in the studio can be with or without the presence of an instructor (Lueth 2008). The type of the learning method may vary in accordance with the project. Learning experience type can be; reviews/juries/critiques, group projects, pin-ups, lectures, one-on-ones, and other interactions. Since number of speakers changes in each method, noise level varies. During juries and lectures one speaker is to be expected, therefore, noise level would be low and any form of sound generated by students would be considered as noise. However, during group projects and individual study periods background noise level can be high and any form of sound such as music, phone ringing and conversations would not be considered as noise.

Architecture studios are different than other study environments. The expectations from occupant behavior are more flexible than in other spaces and depends on the tasks undertaken in architecture studios.

The volume of the studio in IZTECH was 633 m^3, RT was 0.9 s. with a capacity of 45 students. Measurements were taken from 9:00 am to 4:00 pm during measurements students completed their work by individual or as a group work. It was observed that even though the space is a study area that needs concentration, students did not feel the need to control their voices.

Table 4.4. Calculated Noise Levels for Architecture Studio
(c:0.5, Ap:0.3, g:3, V:633 m^3, RT:0.9 s).

N	**Predicted LA$_{eq}$ (dBA)**	**Measured LA$_{eq}$ (dBA)**	**Deviation (dBA)**
10	62.20	54.54	7.66
15	65.61	53.12	12.49
20	68.00	54.58	13.42
25	69.83	60.91	8.92
30	71.31	57.48	13.83
35	72.54	57.60	14.94
40	73.59	53.42	20.17
45	74.51	59.61	14.90
		Abs. Av. Deviation:	**13.06**
		RMSE:	**13.77**
		MAPE	**13.76 %**

When average loudness levels are analysed, no continuous increase is observed based on the number of people (Figure 4.8). Like in the electronic study room, in the architecture studio the prediction model developed for eating establishments does not perform well. Between measured and calculated values there is an average of 13.06 dBA difference.

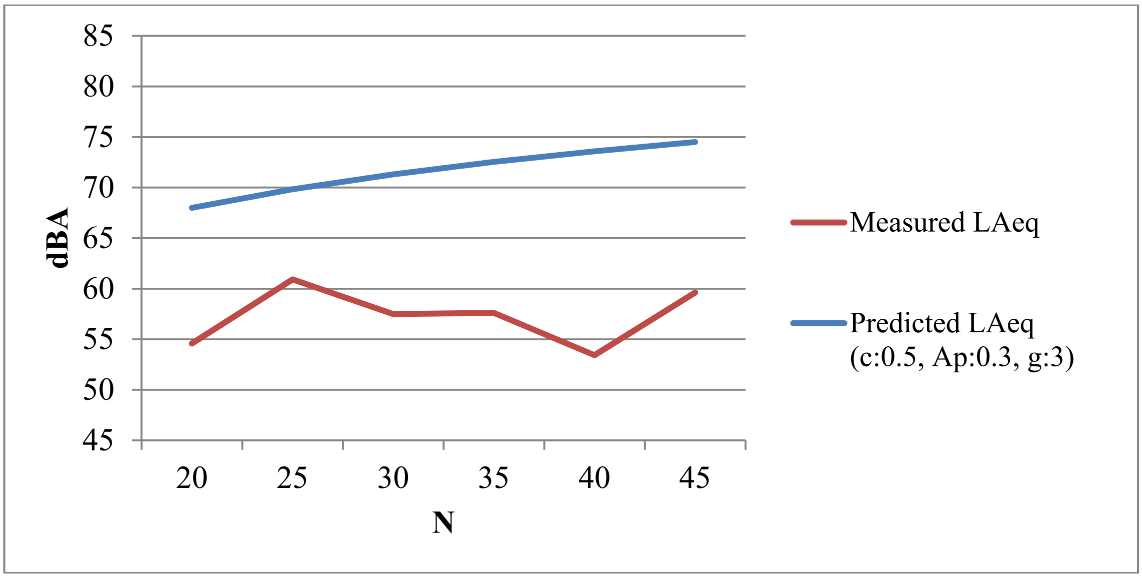


Figure 4.8. Predicted and Measured LA$_{eq}$ of Architecture Studio.

Preliminary Measurement Results

In order to explore the validity of the noise prediction model for spaces other than eating establishments, preliminary measurements were completed in two eating establishment, and two working environments. Eating establishments were Main Dining hall and Yaşam Merkezi, working environments were electronic study room in a library and architecture studio in the same University Campus.

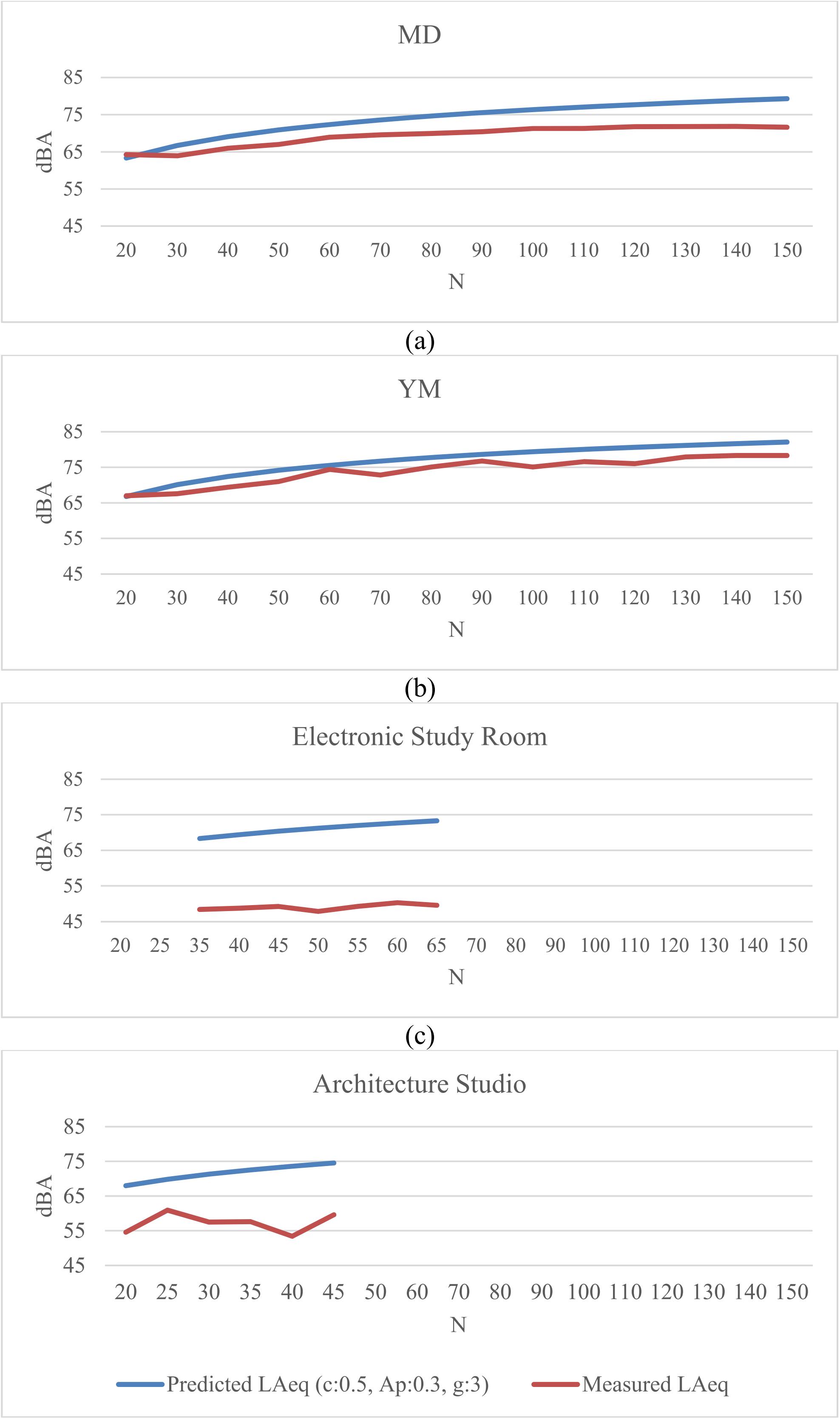
When measured and predicted background noise levels are compared, their results can be summarized as shown in Table 4.5. The preliminary studies in eating establishments, show that predicted and measured values are very close with low error rates. However, in studio and electronic study room, measured and predicted values were not close and error rates were high.

Table 4.5. Deviation and Error Rates of Preliminary Measurements.

		Ave. Deviation	RMSE	MAPE
Eating Establishment	MD	4.48 dBA	5.03	6.72%
	YM	2.92 dBA	1.01	0.35%
Working Environments	Electronic Study Room	22.03 dBA	22.07	14.26%
	Architecture Studio	13.06 dBA	13.77	13.76%

After completing preliminary measurements, it was observed that in eating establishments noise prediction model is very successful in estimating LA_{eq} levels. However, in working environments predicted and measured values were not close to each other and exploring the Lombard effect in these spaces was not possible (Figure 4.9).

For more detailed study in working environments the study turned to open plan offices. Open plan offices are spaces where people concentrate on a task and talk with more self-control over their voice levels than in eating establishments. Yet, in most open plan offices there is a regular regime and noise levels can be monitored through the working day, allowing investigation of the relationship between number of occupants and noise levels. By completing background noise level measurements in open plan offices whether there is an observable Lombard effect or not in these places was investigated.



(a)

(b)

(c)

(d)

Figure 4.9.a,b,c,d. Measured and Predicted LA_{eq} Values in Preliminary Measurements.

4.4. Open Plan Office Measurements

Measurements of our study were conducted in different open plan offices. Studied open plan offices were examined and offices were classified based on their working styles. In choosing office spaces, the working style, density of occupants and plan scheme of the spaces were the decisive factors. In all selected spaces, employees were working on a task individually or interacting with their colleges for idea sharing. Furthermore, during work hours, occupants were meeting for co-working purposes. In some offices where visitors from the outside are allowed, meeting also took place with outsiders.

There were some constraints while deciding on spaces, such as number of occupants should be at least 45 and, in an effort, to monitor incoming and outgoing occupants it is preferred to select spaces with a single entrance. Also, the placement of the working units should be balanced on the floor. In some offices there were meeting rooms, hot desks or game rooms which were located within the space or in adjacent rooms.

In accordance with the above constraints of our study, there were 6 open offices chosen and analyzed during our study. They were designated as OPO (Open Plan Office) and numbered as OPO I, OPO II, OPO III, OPO IV, OPO V, and OPO VI. Some of these offices belong to the same company in the same building, while some were offices of different companies in the same building with similar layouts.

For instance, open plan office I and II offices were in the same building with similar layouts for the same company whereas open plan office IV and V were from different companies and had similar layouts in the same building with different furnishing and layout styles. An overview of the offices, their institutions, volume, RT and maximum number of occupants are presented in Table 4.6.

Table 4.6. Selected Offices.

Selected Offices	Name and Affiliated Company	N Max	Volume (m^3)	RT (s)
OPO I	Izmir Water and Sewage Administration	85	765	0.45
OPO II	Izmir Water and Sewage Administration	62	1029	0.55
OPO III	Technology Firm in Aegean Free Zone	65	1325	0.5
OPO IV	Software Company in a University Techno Park	94	1760	1.15
OPO V	Software Company in a University Techno Park	74	1573	0.71
OPO VI	Software Company in a University Techno Park	50	1105	0.72

Reverberation times of the offices were very close to each other between 0.45 s to 0.72 s except for open plan office IV which had a reverberation time of 1.15 s. Reverberation time of open plan office IV was higher than other offices since the ceiling of this office was an open ceiling design, without an acoustic ceiling. Number of people working in selected offices were between 50 to 94 people. Details of RT measurements are in Appendix B.

For predicted results by using Rindel's (2010) model, Lombard slope was assigned as 0.5, similar to numerous prior studies. Secondly, since open plan office measurements were taken during spring and summer seasons and users' clothes were light and Ap was assigned as 0.3. Lastly g was taken as 3, same as in preliminary studies. The values that were used in in open plan offices are presented in Table 4.7.

Table 4.7. Used Values for the Model.

Parameter	Predicted Value
c	0.5
g	3
Ap	0.3

4.4.1. Open Plan Office I

Open plan office I is a rather crowded office. The office belongs to Izmir Water and Sewage Administration. It is located in Konak, Izmir and it has 8 floors. The most important feature of the building is; it has open plan offices on every floor for different departments. Based on our interview, employees stated that there were 2 noisy and problematic floors in the building. Measurements were conducted on open plan office I and open plan office II which were the mentioned acoustically problematic floors. Open plan office I was located on ground floor where visitors were entering and inquiring information from the employees. On the ground floor, present services were; tender deliveries, cashiers, and petitions for complaints and requests.

Open plan office I was 765 m^3 and designed for several departments in an open plan office layout (Figure 4.10). The floor was designed for 50 employees yet, during measurements maximum number of occupants was 85, due to visitors from the outside.

There were several noise sources in the environment; workers and occupants' noise were changing time to time; however, printer and security door beeping were constant. Reverberation time of the floor was 0.45 s (400 - 1.25 k Hz) and detailed reverberation time results are presented in the appendix B.

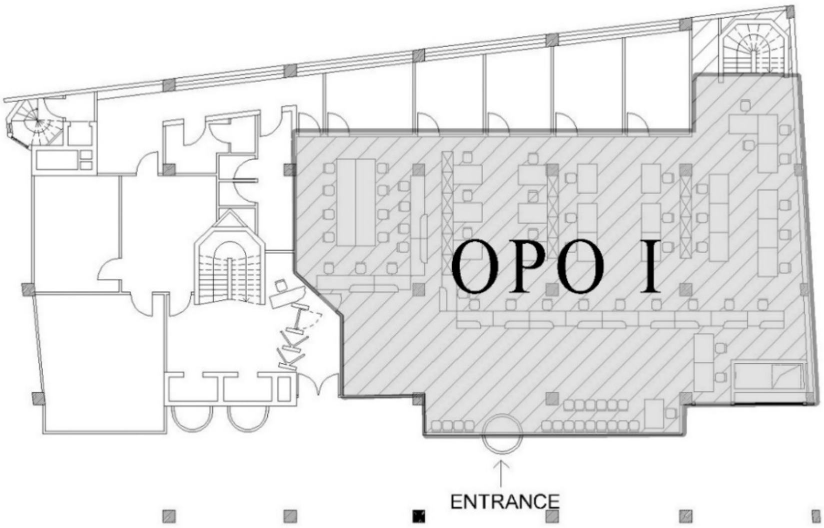


Figure 4.10. OPO I Plan Layout.

As seen in Figure 4.11 the ceiling is covered with acoustic tiles. The floor is covered with linoleum sheet. There were no screen panels between workstations for privacy and sound absorbance. Workstation layout was dense.

Figure 4.11. Interior of OPO I.

In Figure 4.12 each data indicates one-minute intervals, and for each minute, existing number of occupant and dBA levels are shown. According to the figure it can be inferred that the density of data was among 20-60 occupants with 54 dBA - 64 dBA background noise level ranges. According to the results, the maximum number of occupants on the floor reaches up to 85.

Background noise level in unoccupied state of the floor was 34.96 dBA which was lower than the limits of recommended noise levels for offices. According to standard of “Evaluation and Management of Environmental Noise” by Environment and Forestry Ministry (2010) background noise level in open offices stated that it can be maximum 45 dBA.

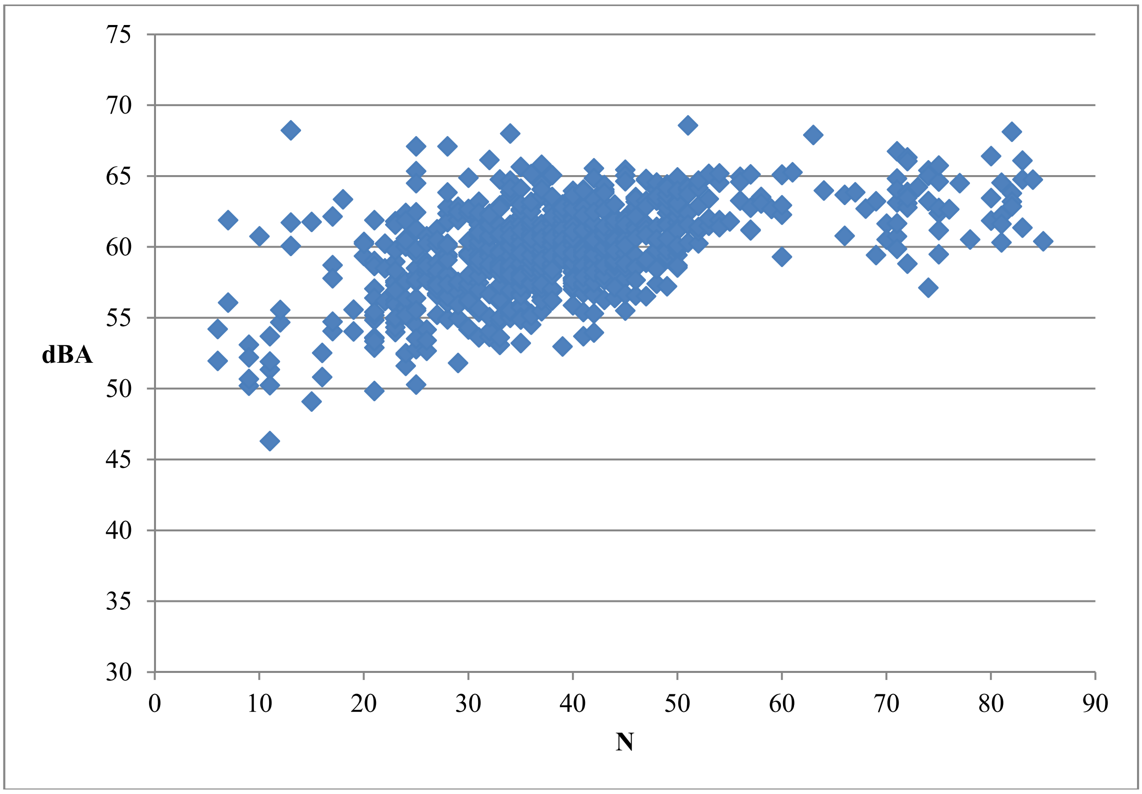
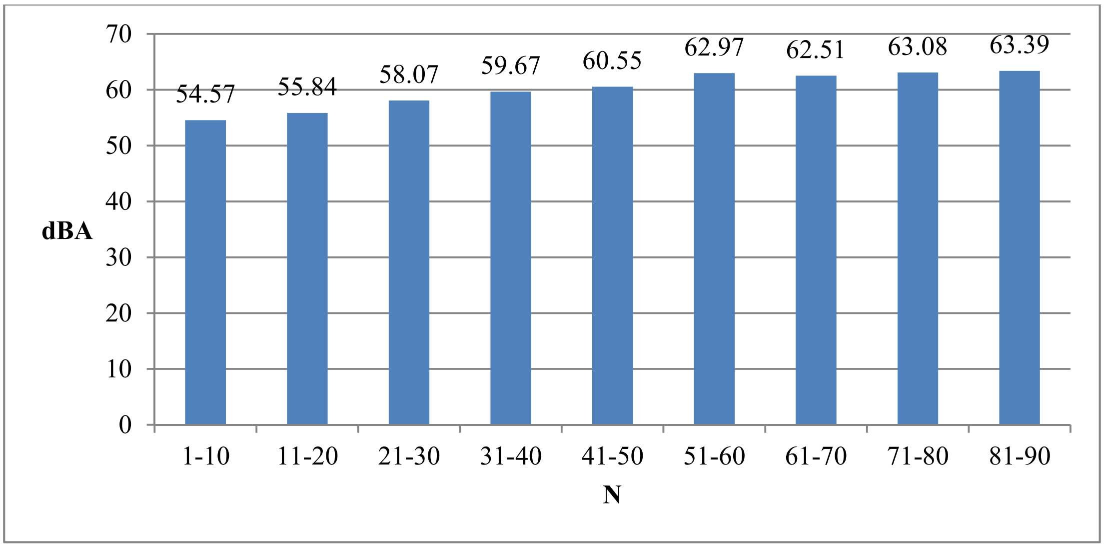
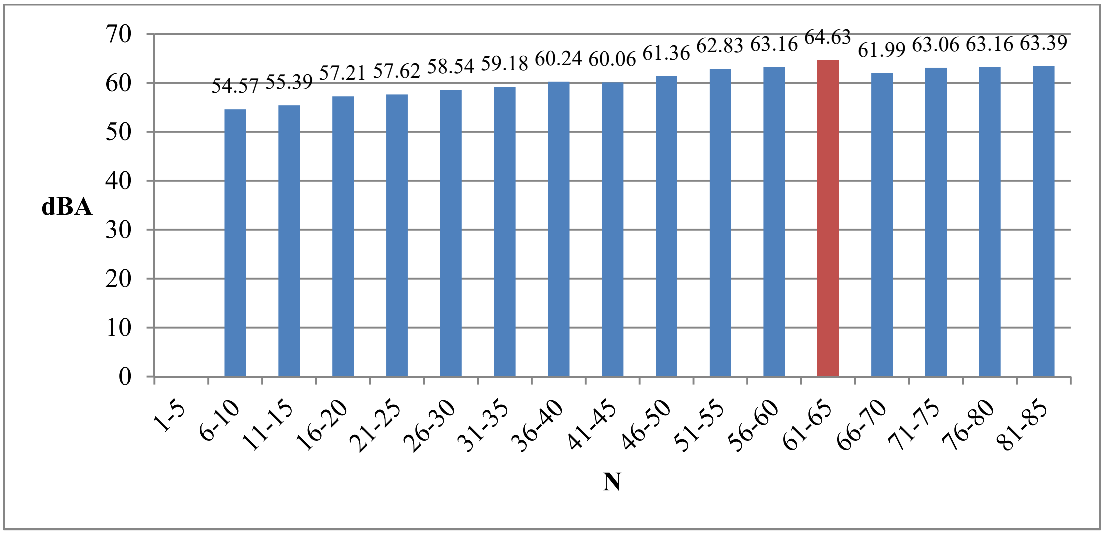


Figure 4.12. Measured Data Log in OPO I Measurement.

After logging LA_{eq} value and existing number of occupants for each minute collected data is categorized in groups of 5 and 10 occupants, the results are shown in Figure 4.13 a and b. Background noise level increases from 54.57 dBA to 63.39 dBA and maximum LA_{eq} was observed as 64.63 dBA within 61-65 occupants.



(a)



(b)

Figure 4.13 a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

Upon general evaluation of the data, Rindel's model was applied to open plan office I. The average and predicted LA_{eq} values were compared and presented in Table 4.8 Predicted LA_{eq} values were calculated using the following parameter values: Lombard slope, c: 0.5, Ap: 0.3, and g: 3. Measured and predicted values with their average deviation, RMSE and MAPE are tabulated in Table 4.8. When the results were analyzed, the minimum deviation between two values is 3.39 dBA with (N:20) and the maximum is 9.19 dBA (N:85). The absolute average deviation among all the results was 6.76 dBA. According to results, RMSE was 6.96 and MAPE was 11 %.

Table 4.8. Application of Rindel's Model to OPO I c:0.5, Ap:0.3, g:3 (V: 765 m^3, RT:0.45).

N	Predicted LA_{eq} (dBA)	Measured LA_{eq} (dBA)	Abs. Deviation (dBA)
20	60.60	57.21	3.39
25	62.49	57.62	4.82
30	64.03	58.54	5.49
35	65.32	59.18	6.14
40	66.43	60.24	6.19
45	67.41	60.06	7.35
50	68.28	61.36	6.92
55	69.06	62.83	6.23
60	69.77	63.16	6.61
65	70.42	64.63	5.79
70	71.02	61.99	9.03
75	71.58	63.06	8.52
80	72.09	63.16	8.93
85	72.58	63.39	9.19
		Average Dev.:	6.76
		RMSE:	6.96
		MAPE:	11 %

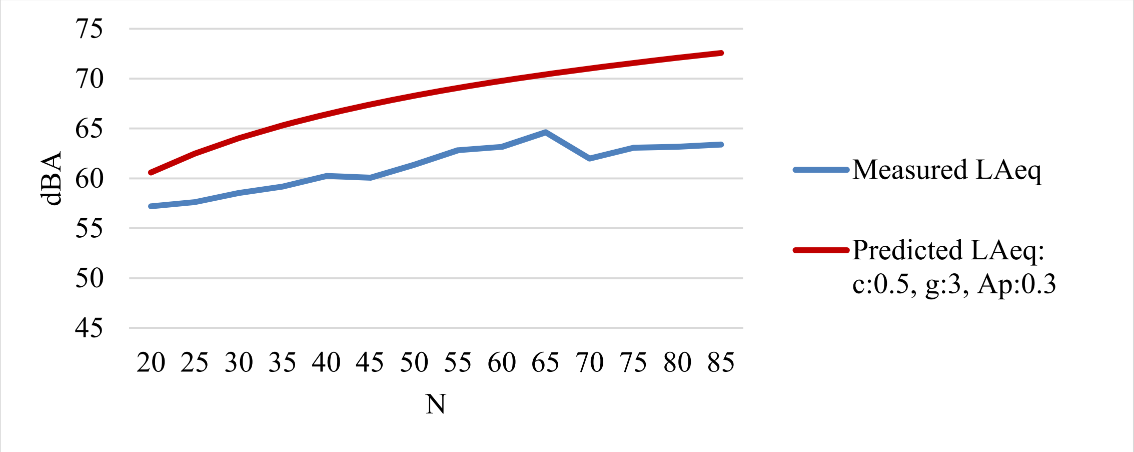


Figure 4.14. OPO I Predicted and Measured LA_{eq}.

In Figure 4.14 measured and predicted values are shown for each number of occupants. In open plan office I as number of occupants increases, noise level increases as expected.

4.4.2. Open Plan Office II

The second open plan office that was investigated in the same building was open plan office II which was on the 2nd floor. Open plan office II was an accounting department, companies or individuals who have problems with their accounts come to get information and make payments. Volume of the space was 1029 m^3 and it was designed for 55 employees. It was relatively larger than open plan office I (Figure 4.15).

Main noise sources on the floor were occupant-based noises and footsteps. Also, the employees were complaining about a noisy printer which was located at the center of the office. Reverberation time of the space was 0.55 s detailed reverberation time results are shown in Appendix B.

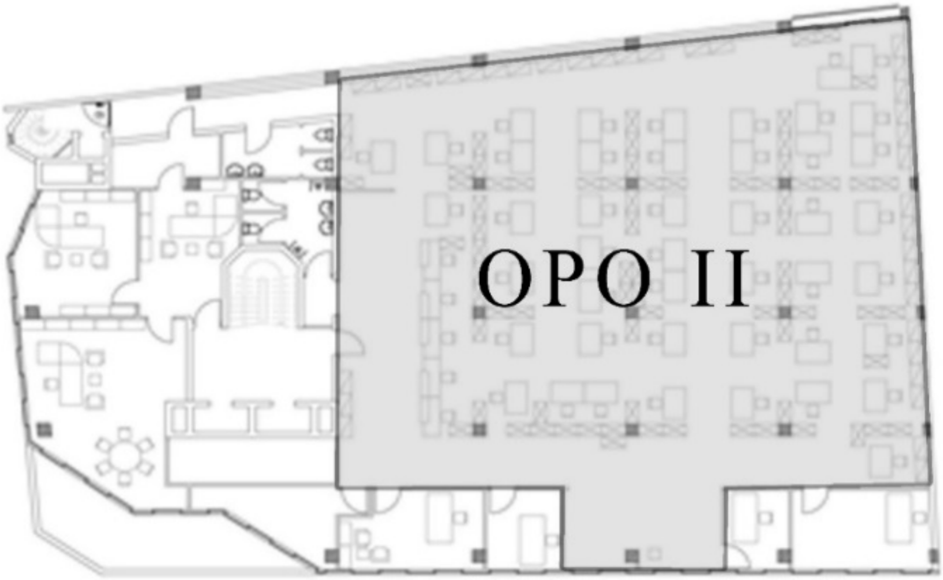


Figure 4.15. OPO II Plan Layout.

The interior photos of open plan office II are shown in Figure 4.16. Finishing materials that were used in the office were same with open plan office I as, the floor was covered with linoleum, and ceiling was covered with acoustic tiles. There were no screens between workstations for privacy and sound absorbance, same as open plan office I.

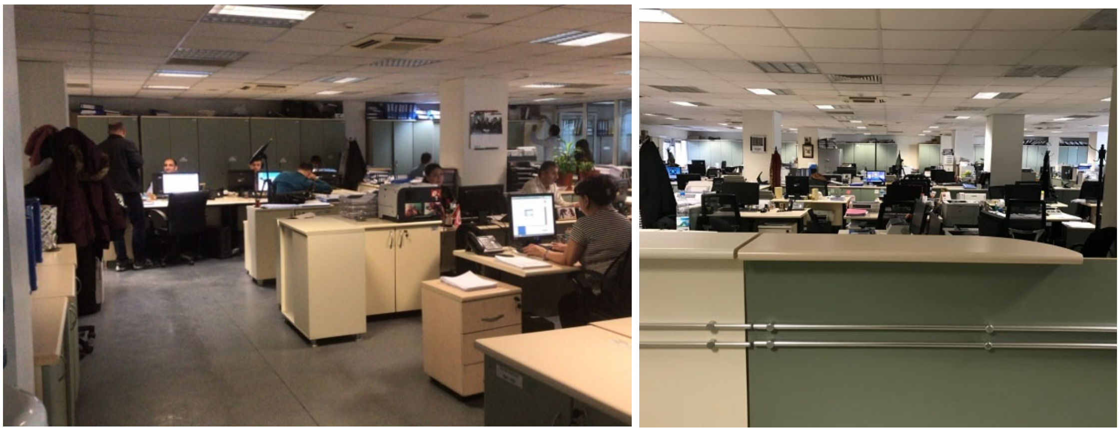


Figure 4.16. Interior of OPO II.

When the intensity of each measured minute is examined the density of gathered data was among 40-62 occupants between 50 dBA - 65 dBA background noise level (Figure 4.17).

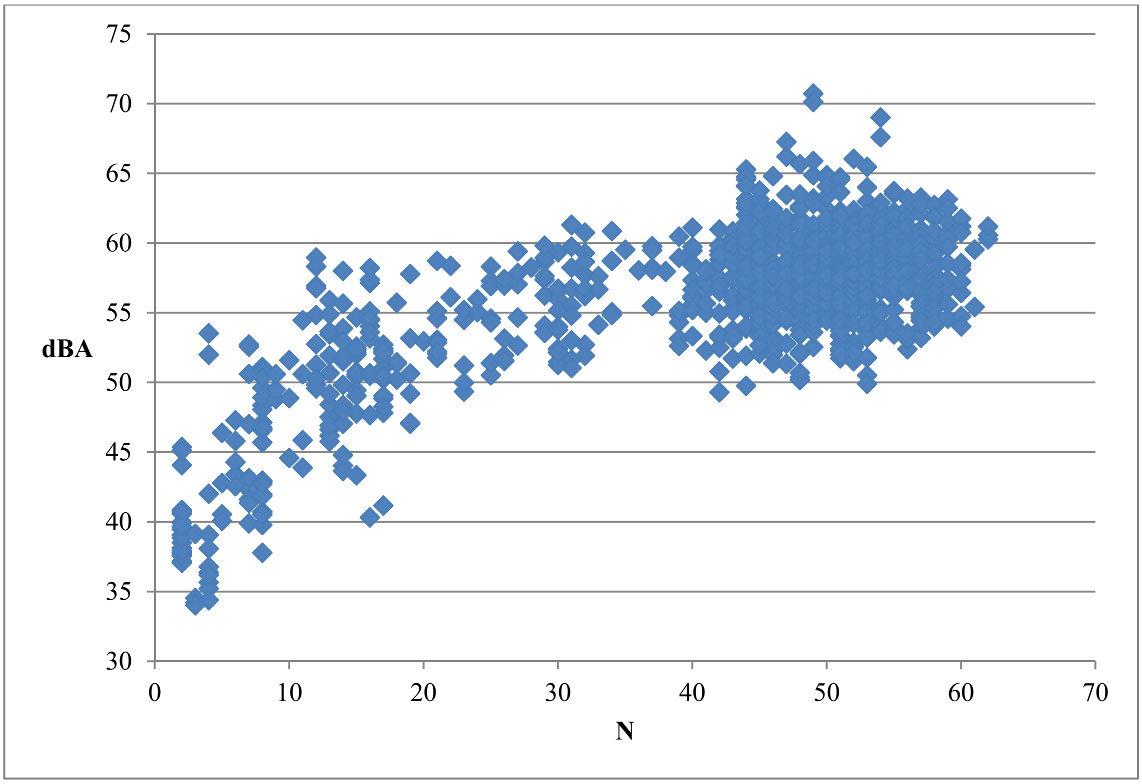
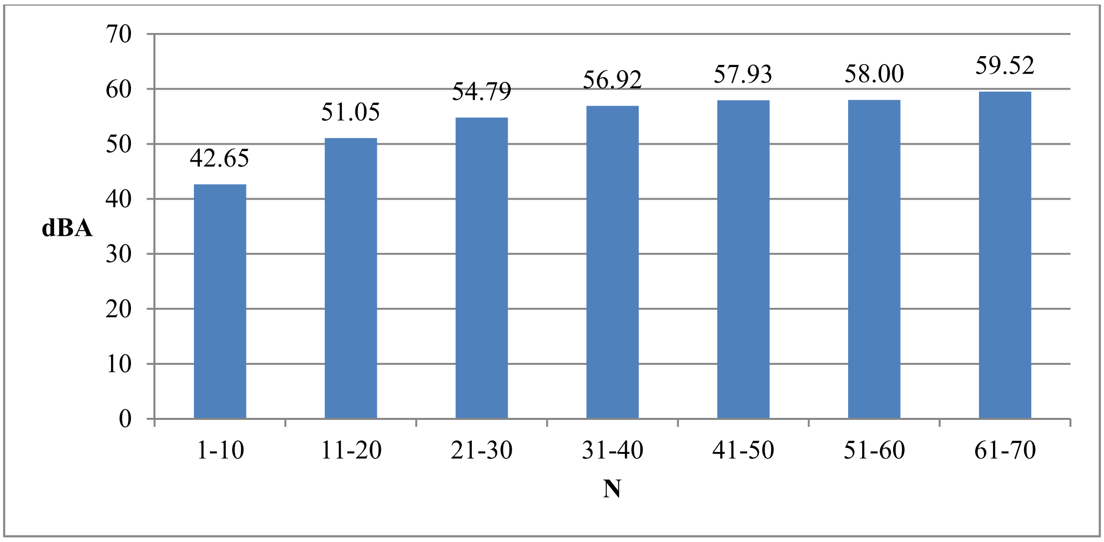
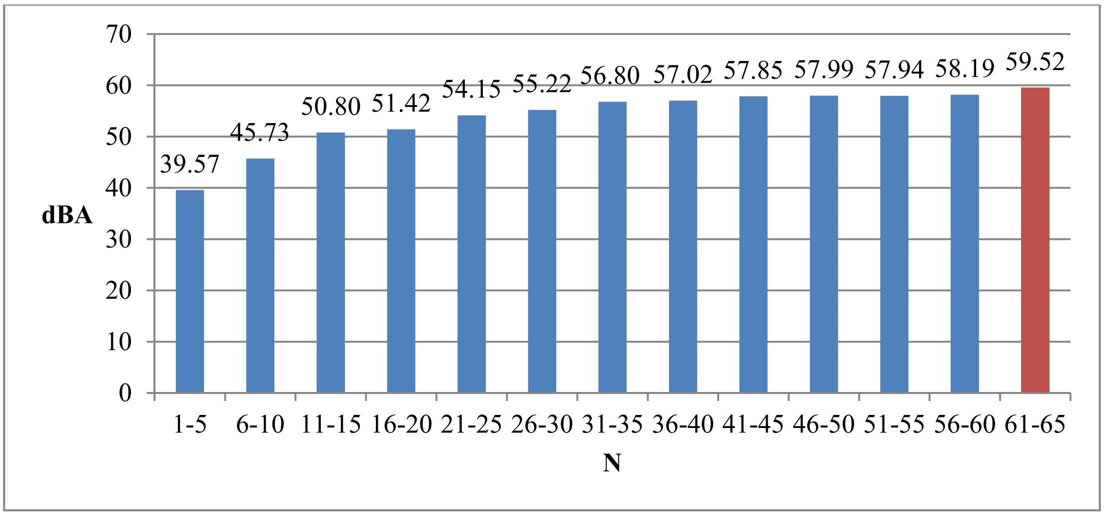


Figure 4.17. Measured Data Log in OPO II Measurement.



(a)



(b)

Figure 4.18. a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

Figure 4.18 a, b, shows aggregated number of occupants and average noise levels. When the periods were analyzed it can be said that when number of occupants increase, noise level increases form 39.57 dBA to 59.52 dBA. After examining and grouping each logged data by groups of 10 and 5 occupant, maximum LA_{eq} was seen among 61-65 N with 59.52 dBA. In Table 4.9 minimum deviation between predicted and measured LA_{eq} values is 7.53 dBA (N:25) max deviation is 10.80 dBA (N: 60) and average deviation is 8.97 dBA. RMSE of the results is 9.04 and MAPE is 15.83%.

Table 4.9. Application of Rindel’s Model to OPO II
c:0.5, Ap:0.3, g:3 (V:1029 m^3, RT:0.55).

N	**Predicted LA$_{eq}$ (dBA)**	**Measured LA$_{eq}$ (dBA)**	**Abs. Deviation (dBA)**
20	8.97	51.42	8.36
25	9.04	54.15	7.53
30	63.22	55.22	8.00
35	64.52	56.80	7.72
40	65.63	57.02	8.61
45	66.62	57.85	8.77
50	67.49	57.99	9.50
55	68.28	57.94	10.34
60	68.99	58.19	10.80
65	69.64	59.52	10.12
		Average Dev.:	8.97
		RMSE:	9.04
		MAPE:	15.83 %

In Figure 4.19 the interval between measured and predicted LA$_{eq}$ is shown, the difference seems almost constant in each groups of N.

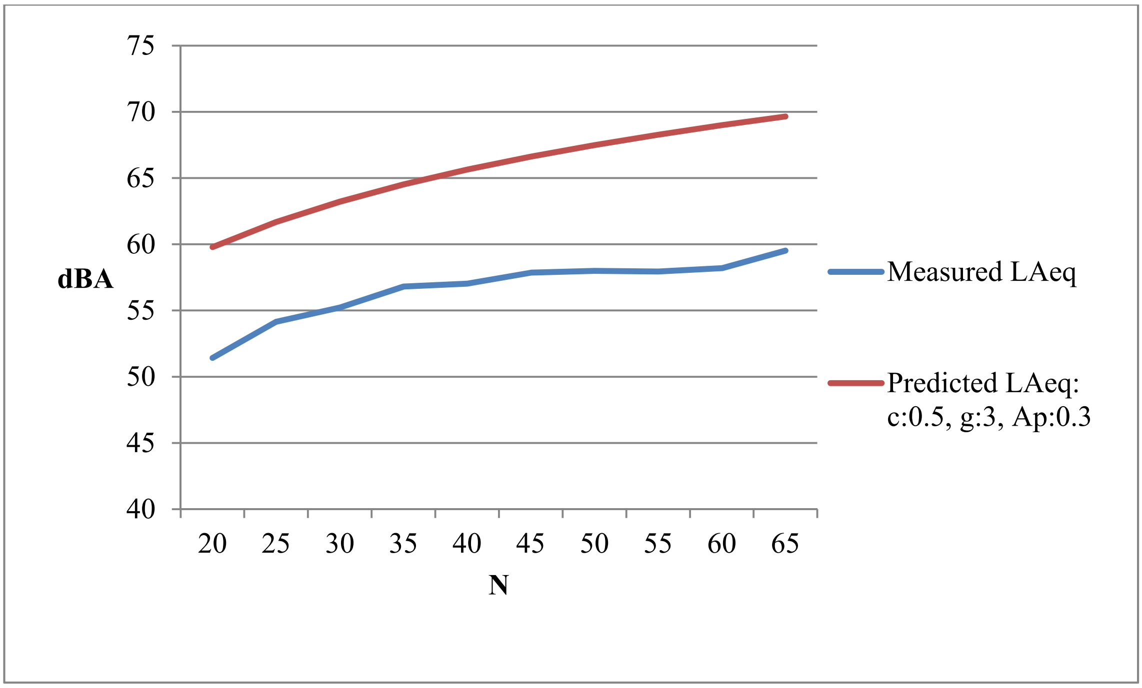


Figure 4.19. OPO II Predicted and Measured LA$_{eq}$.

4.4.3. Open Plan Office III

Open plan office III is an open plan office that is located in the Agean Free Trade Zone in Izmir. The building where open plan office III was located includes production facilities, individual offices and a common open office for different departments. Open plan office III was located on the first floor of the building. Seating capacity of the office was 64 with 1325 m^3 volume. Reverberation time was 0.5 s. Detailed RT measurement results of the open plan office III is given in Appendix B. The office has a rectangular floor plan; a corridor separates the office from meeting rooms and wet areas (Figure 4.20). Most complained of noise sources were occupant related voices, footsteps, and chatting sounds of passersby from the corridor.

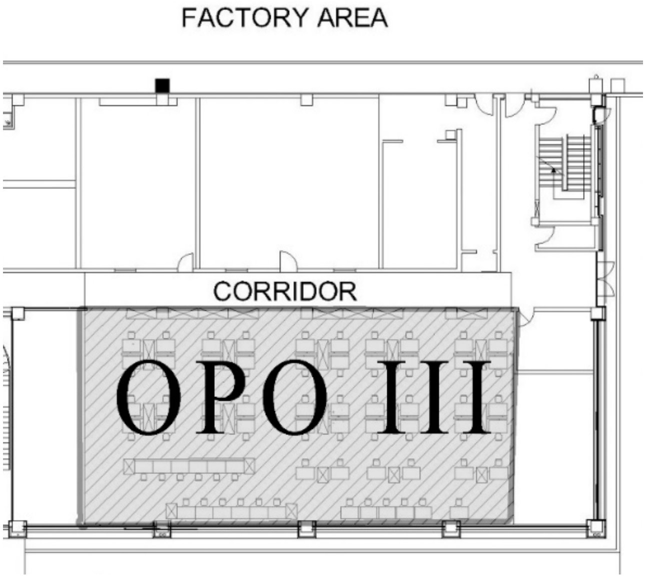


Figure 4.20. OPO III Plan Layout.

In OPO III 1.60 m high partition screens were used (Figure 4.21). The overall open plan office was surrounded with meeting rooms and managers' offices. Most of the workers were sitting in cubicles, the boundaries of cubicles were defined with cabinets to ensure privacy, and concentration. Additionally, some occupants were sitting next to each other all along the window. The ceiling was covered with acoustic ceiling tiles and the floor was covered with ceramic tiles. Also, working environment was surrounded by windows and manager's glass cubicle offices.

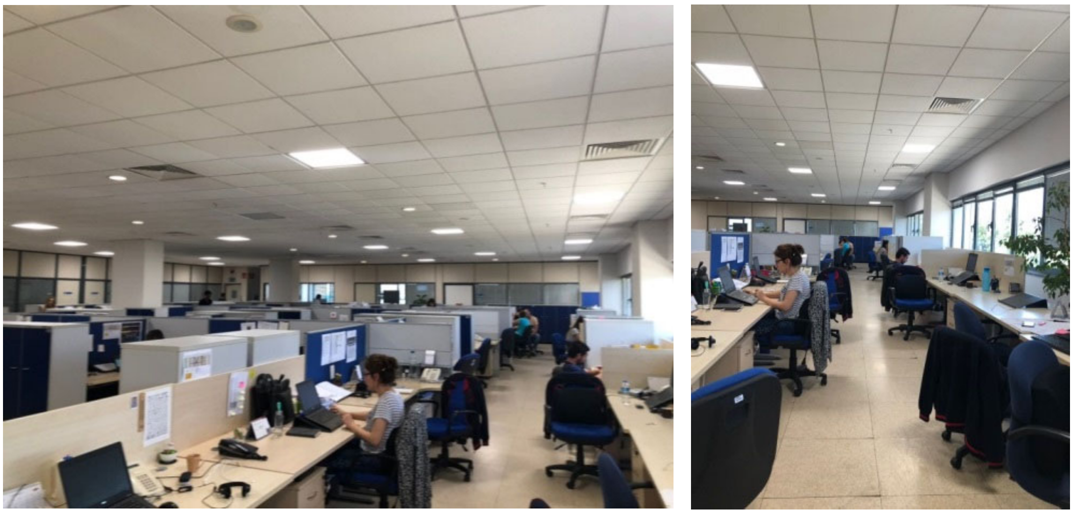


Figure 4.21. Interior of OPO III.

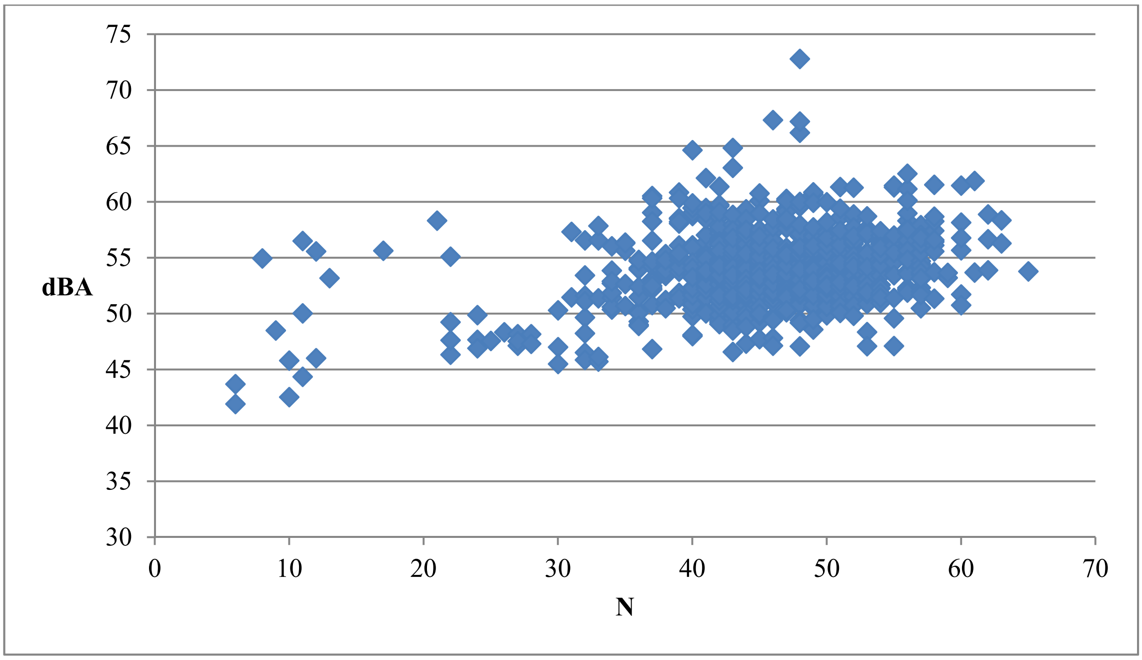
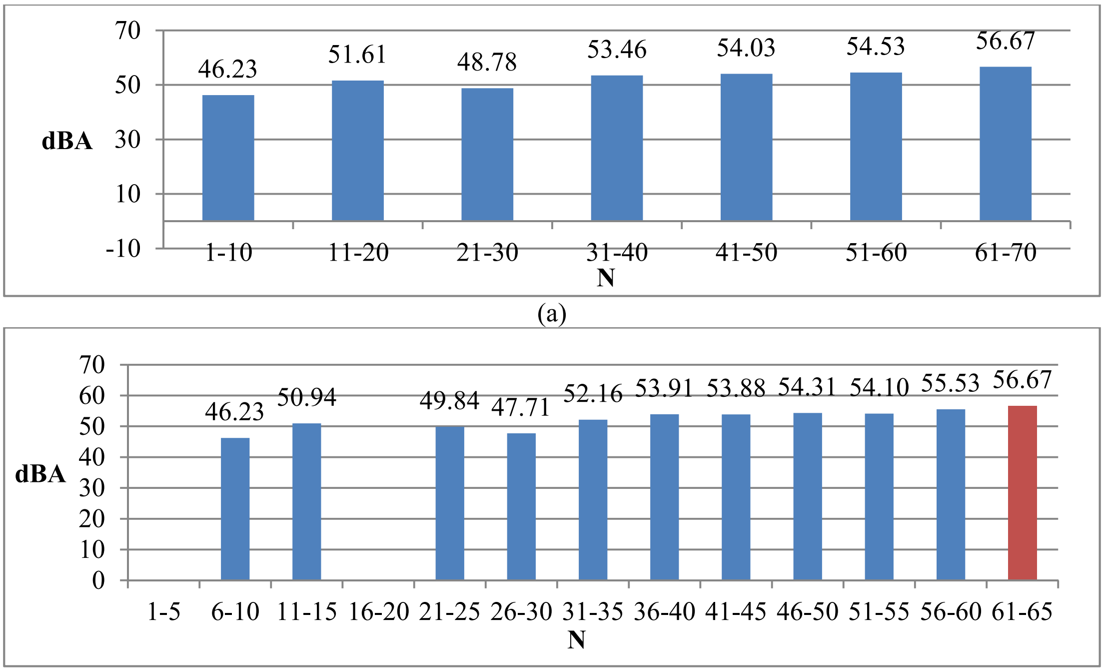


Figure 4.22. Measured Data Log in OPO III.

In Figure 4.22 measured data for each minute are shown. It can be said that density of number of occupants is observed among 45-55. In Figure 4.23 a and b, logged data are categorized in the groups of 5 and 10 occupants. Noise level increases from 46.23 dBA to 56.67 dBA when there were 65 occupants on the floor.



(a)

(b)

Figure 4.23 a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

In Table 4.10 measured and predicted results are tabulated. Results show that minimum deviation between measured and predicted value is 1.19 dBA (N:20), maximum deviation is 12.56 dBA (N:30) and average deviation is 9.29 dBA. RMSE is 9.74 and MAPE is 17.56%.

Table 4.10. Application of Rindel's Model to OPO III
c:0.5, Ap:0.3, g:3 (V:1325 m^3, RT:0.5).

N	**Predicted LA$_{eq}$ (dB)**	**Measured LA$_{eq}$ (dB)**	**Abs. Deviation (dBA)**
20	56.81	55.62	1.19
25	58.72	49.84	8.88
30	60.27	47.71	12.56
35	61.58	52.16	9.42
40	62.71	53.91	8.80
45	63.70	53.88	9.82
50	64.59	54.31	10.28
55	65.39	54.10	11.29
60	66.11	55.53	10.58
65	66.78	56.67	10.11
		Average Dev.:	9.29
		RMSE:	9.74
		MAPE:	17.56 %

The difference between measured and predicted LA_{eq} is shown in Figure 4.24, as number of occupants increases, noise level increase as expected.

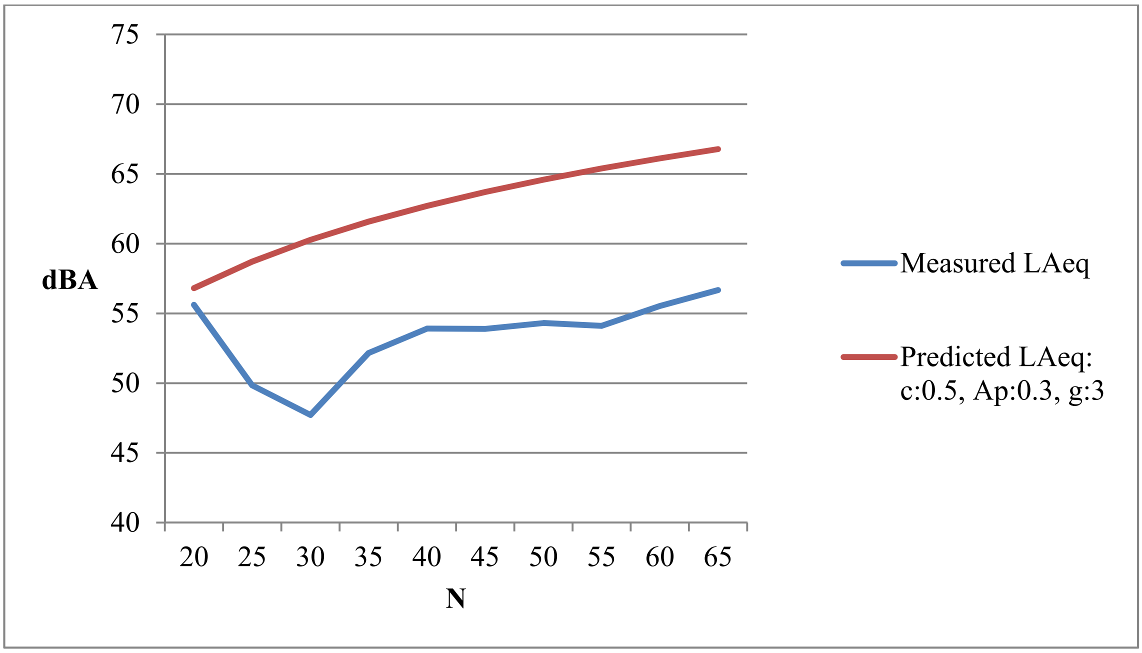


Figure 4.24. OPO III Predicted and Measured LA_{eq}.

4.4.4. Open Plan Office IV

Open plan office IV is located at Dokuz Eylül Üniversity’s (DEU) campus in Izmir. The building where OPO IV is located, is the Dokuz Eylül Technology Development Zone building housing multiple companies. The capacity of open plan office IV was 74 and the volume of the office was 1760 m^3. During measurements it was seen that maximum number of occupants was 94. The reverberation time of the space was 1.15 s. Details of reverberation time measurement are provided in Appendix B. Plan layout of the office is shown in Figure 4.25. According to employees the main sources of noise complaints are occupant-based noises such as keyboard and phone conversations of co-workers.

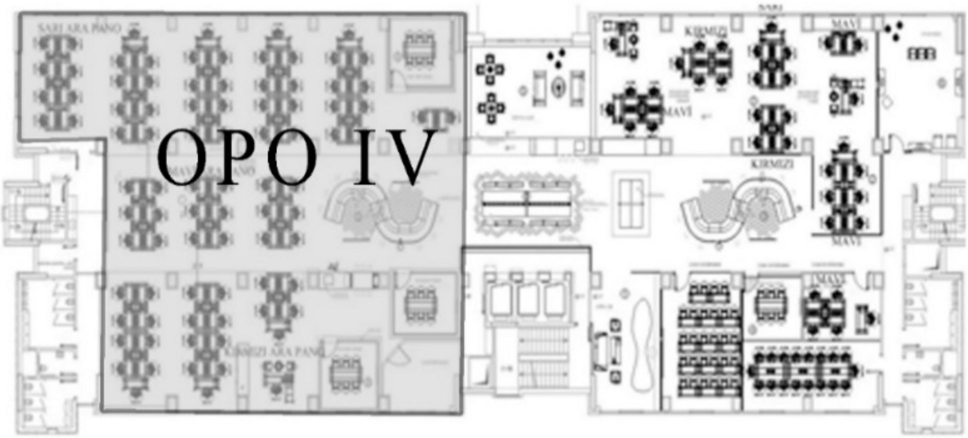


Figure 4.25. OPO IV Plan Layout.

The office had a rectangular floor plan with several working stations next to each other. Also, there was another open plan office for the same company on the same floor next to the measurement site. Between two offices, there was a chilling out area and a hot desk that separates two offices from each other. As finishing materials, laminated wood and carpet tiling were used on floors; exposed ceiling was preferred where structural and mechanical systems were visible. The two sides of the office were surrounded by windows letting in natural light. Also, there were glass enclosed meeting rooms located at the sides of the office. Some interior photos are shown in Figure 4.26.

As it is seen in Figure 4.26, occupants were sitting side by side and there was no other furniture other than tables and chairs in the working area. It was observed that, occasionally colleagues from the neighboring office came for discussions or co-working. Consequently, maximum number of occupants reached up to 95. Measured and logged minutes are shown in Figure 4.27 the occupancy changed mostly between 40-85 occupants.

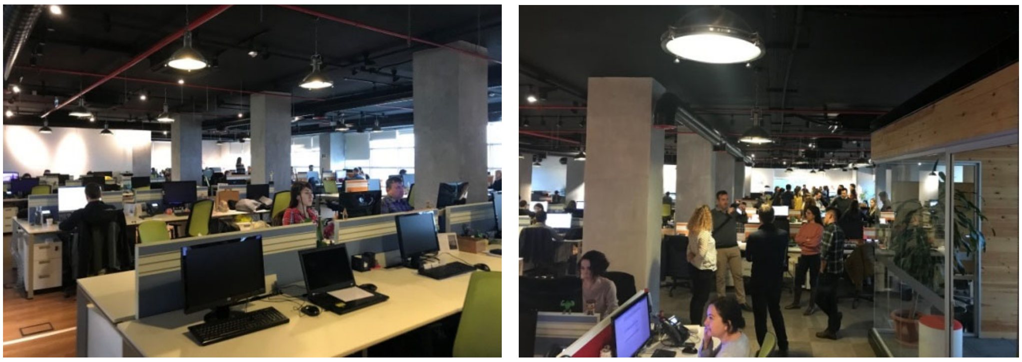


Figure 4.26. Interior of OPO IV.

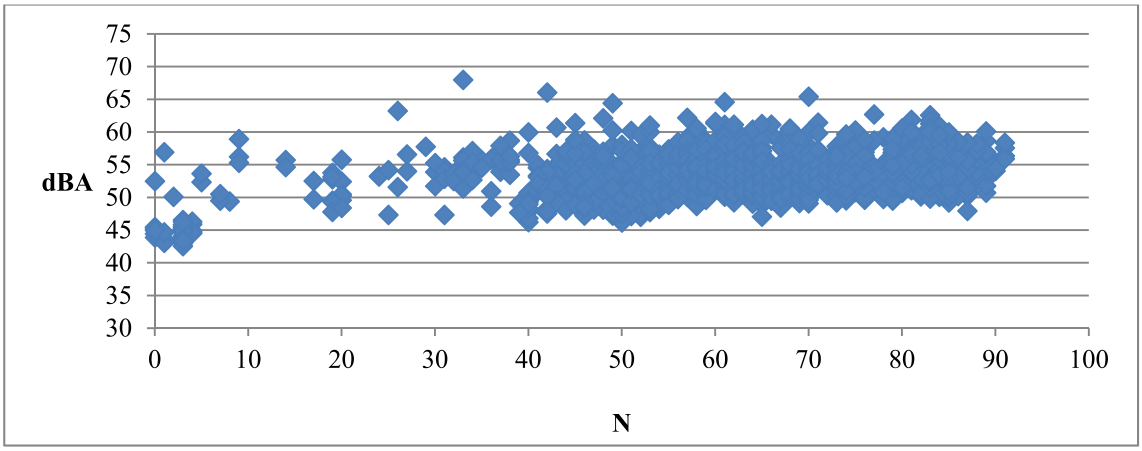
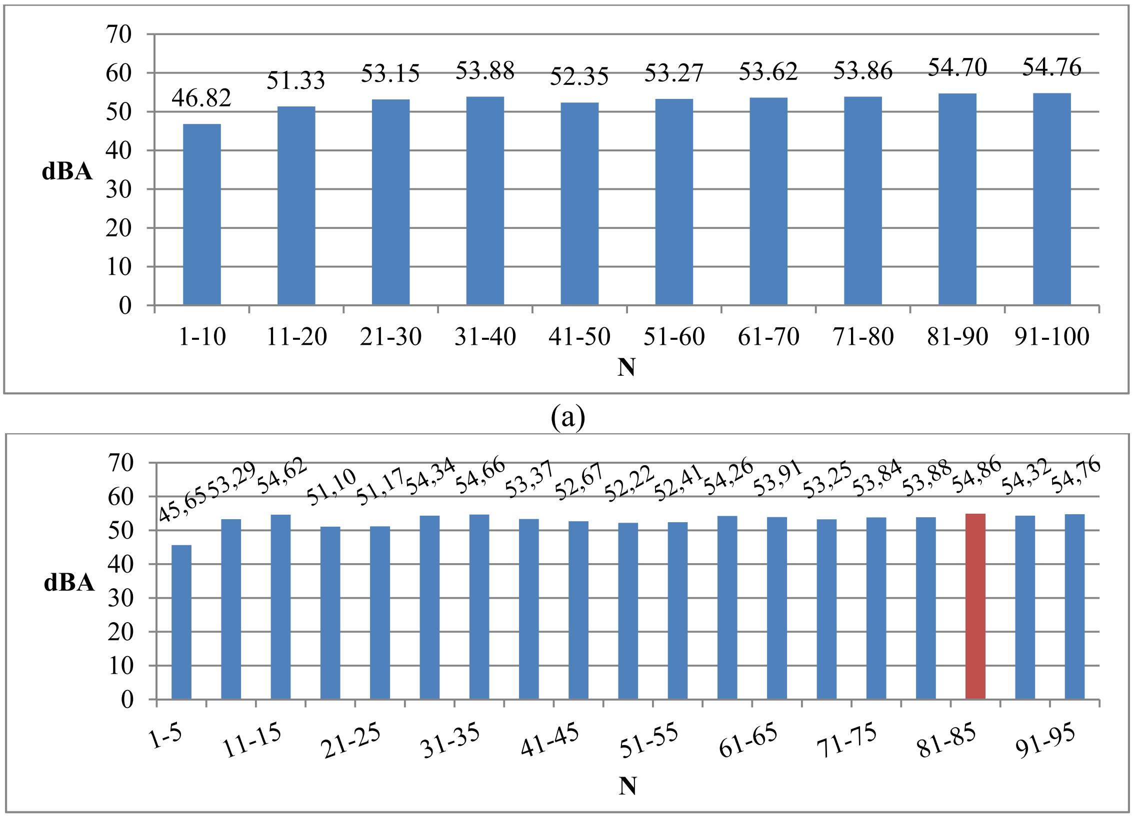


Figure 4.27. Measured Data Log in OPO IV.



(a)

(b)

Figure 4.28. a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

In Figure 4.28 a and b, measurements are categorized in groups of 10 and 5 number of occupants, the maximum number of occupants was 94. Maximum background noise levels were seen for 81-85 occupant category.

According to Table 4.11, min deviation between measured and predicted values is 10.39 dBA (N:20) and maximum is 19.54 dBA (N:90) and the average deviation is 16.01 dBA. RMSE was 16.32 and MAPE was 29.93%.

Table 4.11. Application of Rindel's Model to OPO IV
c:0.5, Ap:0.3, g:3 (V:1760 m^3, RT:1.15).

N	Predicted LA_{eq} (dBA)	Measured LA_{eq} (dBA)	Abs. Deviation (dBA)
20	61.49	51.10	10.39
25	63.38	51.17	12.21
30	64.91	54.34	10.57
35	66.20	54.66	11.54
40	67.30	53.37	13.93
45	68.28	52.67	15.61
50	69.14	52.22	16.92
55	69.92	52.41	17.51
60	70.63	54.26	16.37
65	71.27	53.91	17.36
70	71.87	53.25	18.62
75	72.42	53.84	18.58
80	72.93	53.88	19.05
85	73.41	54.86	18.55
90	73.86	54.32	19.54
95	74.28	54.76	19.52
		Average Dev.:	**16.01**
		RMSE:	**16.32**
		MAPE:	**29.93 %**

In Figure 4.29 the difference between measured and predicted LA_{eq} is shown graphically. As the number of occupants increases, predicted LA_{eq} increases, but measured LA_{eq} does not increase as rapidly.

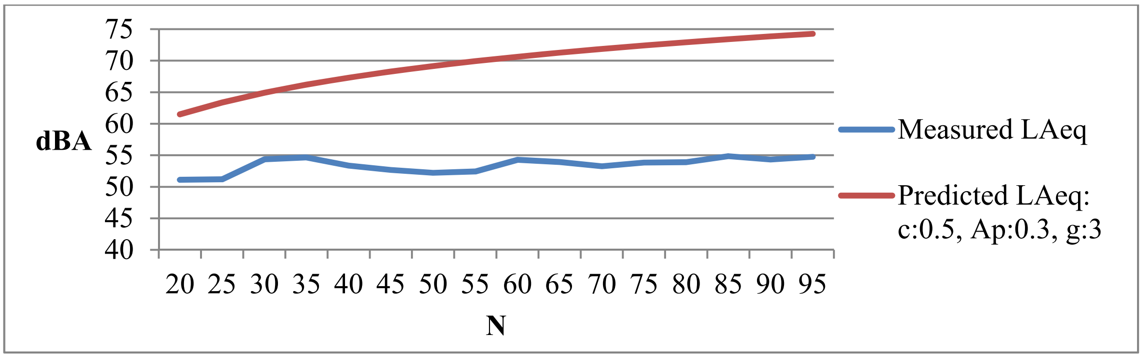


Figure 4.29. OPO IV Predicted and Measured LA_{eq}.

4.4.5. Open Plan Office V

Another studied open plan office is open plan office V, which is located in the same building with open plan office IV. As mentioned before, open plan office V is on the upper floor of open plan office IV. They have the same floor plan scheme (Figure 4.30). The two offices belong to different companies, but they were similar in working principle. The capacity of open plan office V was 70 occupants with a 1573 m^3 volume. During measurements maximum number of occupants reached up to 74. In open plan office V employees and managers were working together in the same place (Figure 4.31).

Noise source on the floor was mainly occupant-based noises. Reverberation time of the office was 0.71 s, detailed reverberation time measurement results can be found in Appendix B.

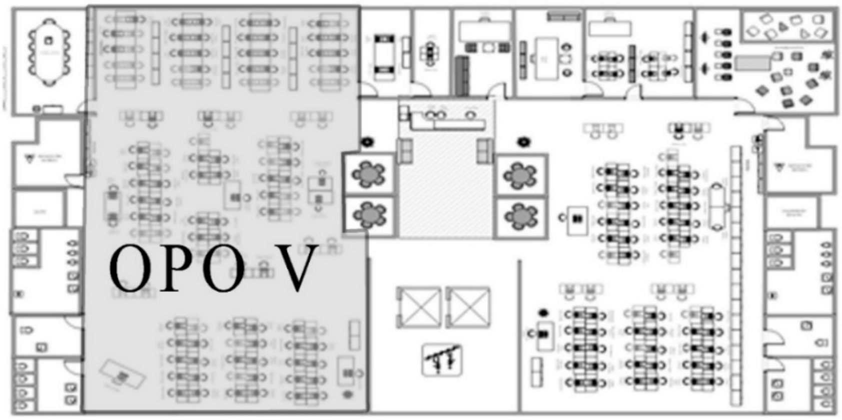


Figure 4.30. OPO V Plan Layout.

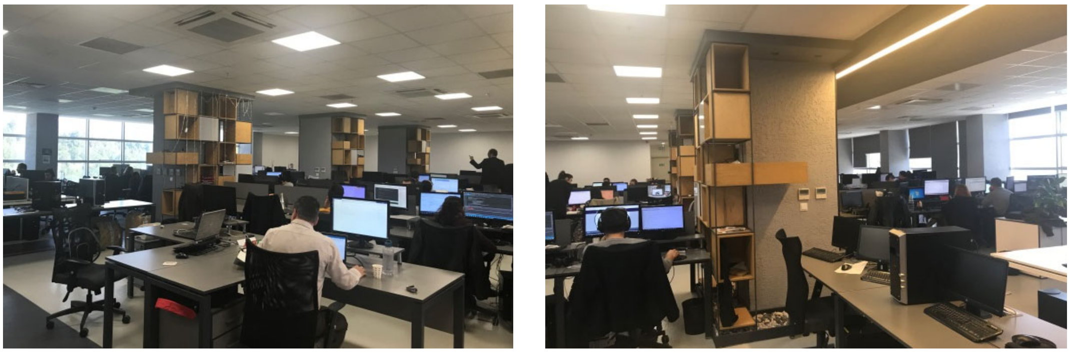


Figure 4.31. Interior of OPO V.

In Figure 4.32 measured minutes are shown, and the density was seen around 40-75 occupants on the floor. It was observed that during measurements the office was fully occupied and maximum N reaches up to 74 with visiting coworkers from other floors.

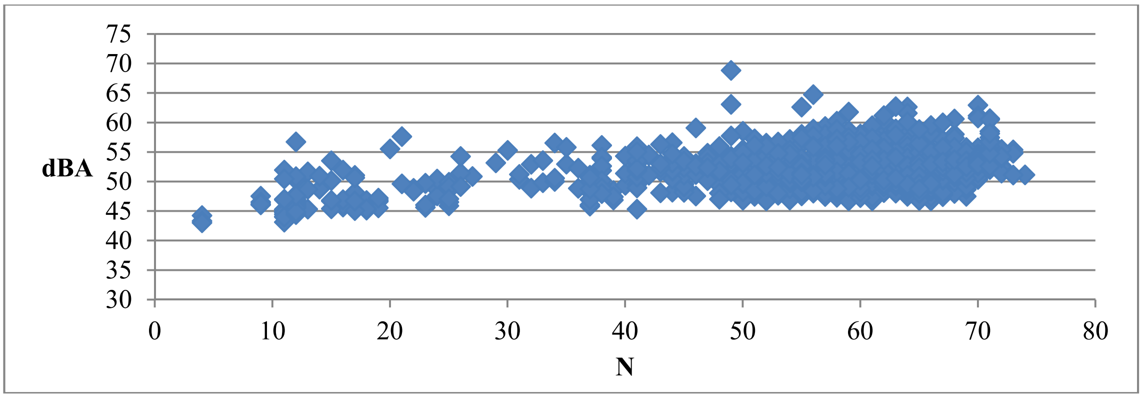
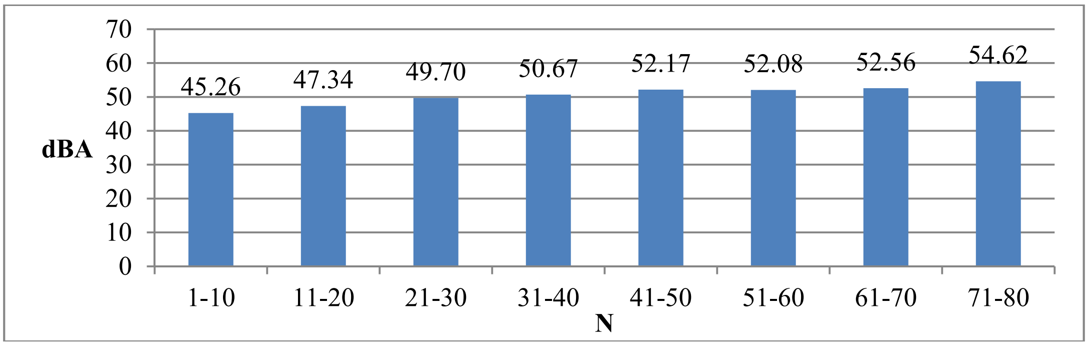
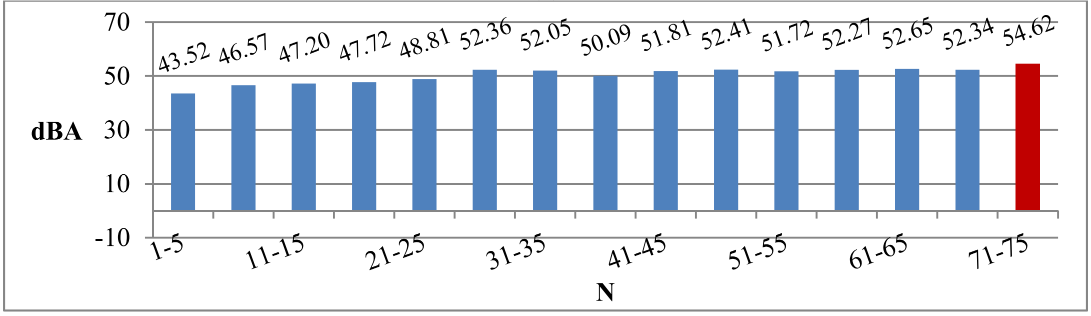


Figure 4.32. Measured Data Log in OPO V.

In Figure 4.33 a and b, when gathered data is grouped, in groups of 5, maximum LA_{eq} is seen within 71-75 occupants with 54.62 dBA.



(a)



(b)

Figure 4.33 a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

In Table 4.12. deviation between measured and predicted values, RMSE and MAPE results are shown. Minimum deviation between measured and predicted LA_{eq} is 9.43 dBA (N:30) and maximum deviation is 16.54 dBA (N:70) the average results is 13.44 dBA. RMSE of the variables is 13.61 and MAPE is 26.02 %.

Table 4.12. Application of Rindel's Model to OPO V
c:0.5, Ap:0.3, g:3 (V:1573 m^3, RT:0.71).

N	**Predicted LA_{eq} (dBA)**	**Measured LA_{eq} (dBA)**	**Abs. Deviation (dBA)**
20	58.34	47.71	10.63
25	60.24	48.81	11.43
30	61.79	52.36	9.43
35	63.09	52.04	11.05
40	64.22	50.09	14.13
45	65.21	51.80	13.41
50	66.09	52.40	13.69
55	66.88	51.70	15.18
60	67.60	52.26	15.34
65	68.26	52.65	15.61
70	68.87	52.33	16.54
75	69.43	54.61	14.82
		Average Dev.:	**13.44**
		RMSE:	**13.61**
		MAPE:	**26.02%**

In Figure 4.34 measured and predicted results of OPO V is shown. According to the prediction model LA_{eq} increases as the number of people increases. However, the noise measured in the office does not increase as rapidly, the actual increase was observed to be much less.

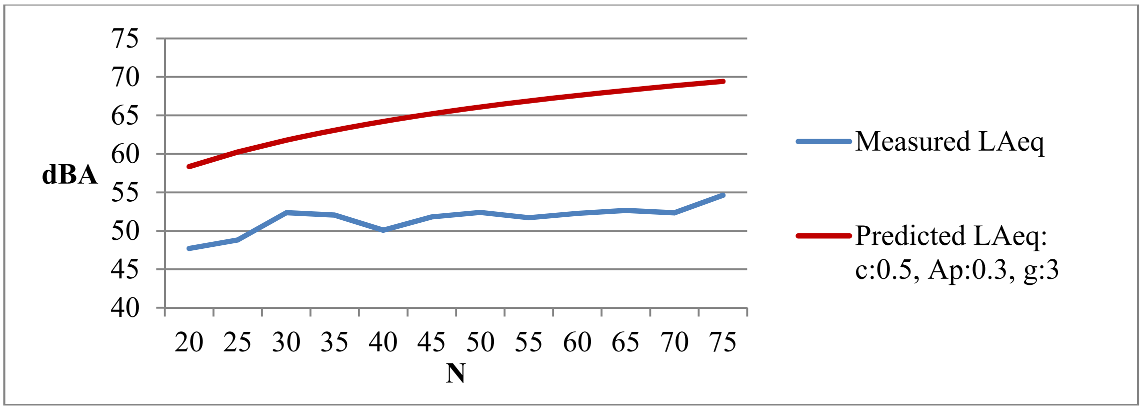


Figure 4.34. OPO V Predicted and Measured LA_{eq}.

4.4.6. Open Plan Office VI

Open plan office VI and V were open plan offices of the same company and were located on the same floor. Two offices were next to each other and separated with an entrance hall of the floor (Figure 4.35). The whole floor belongs to same company, so, employees had a lot in common to work on, they were frequently moving to the other office during the day. Open plan office VI was designed for 46 occupants with 1105 m^3 volume, and maximum number of occupants reached up to 50 (Figure 4.36).

As finishing materials, floor was covered with vinyl sheets, walls and columns were painted with white and gray colored paint and suspended ceiling was covered with acoustic tiles. Noise sources were mainly occupant-based noises. Reverberation time of the office was 0.72 s. Detailed reverberation time measurements are available in Appendix B.

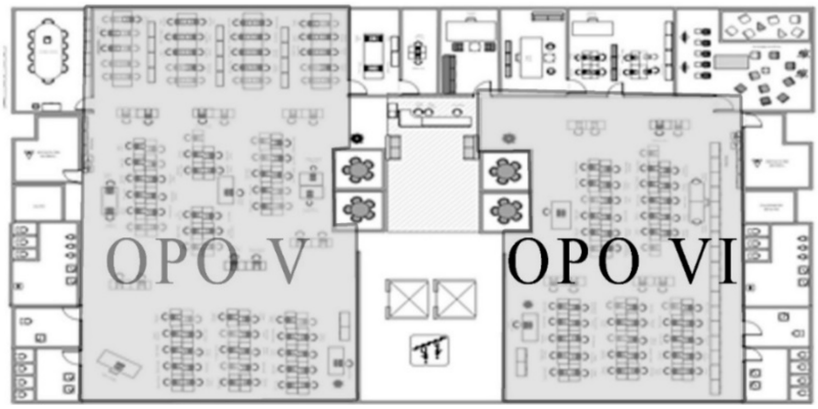


Figure 4.35. OPO VI Plan Layout.

Figure 4.36. Interior of OPO VI.

There were screen panels between working stations to provide privacy, yet the screens were low enough to enable collaboration. According to the Figure 4.37 the density of collected data was between 25-50 occupants with 50 dBA - 60 dBA noise levels. Maximum number of occupants on the floor reached 51.

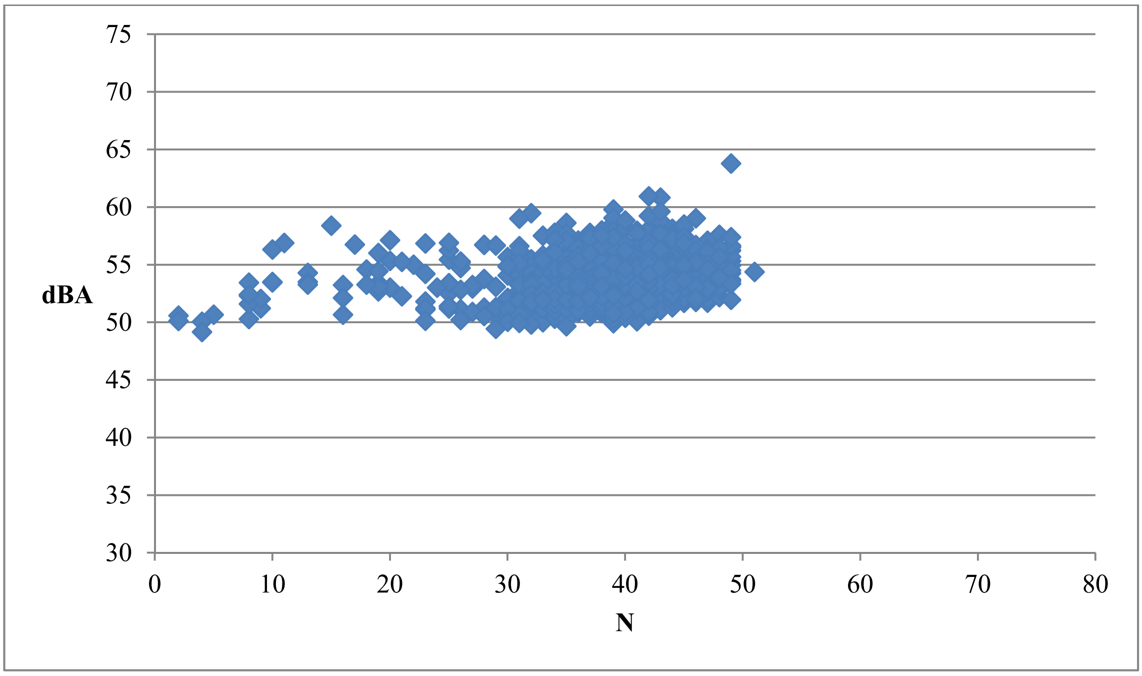
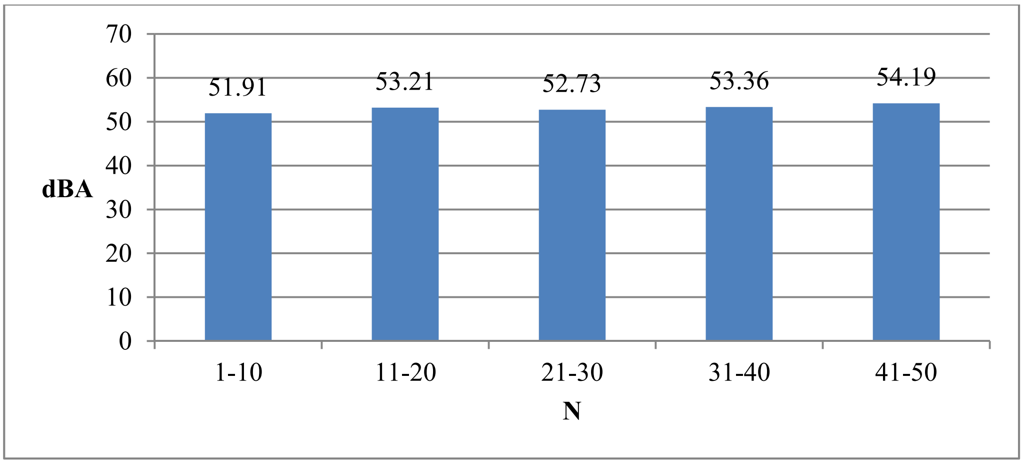
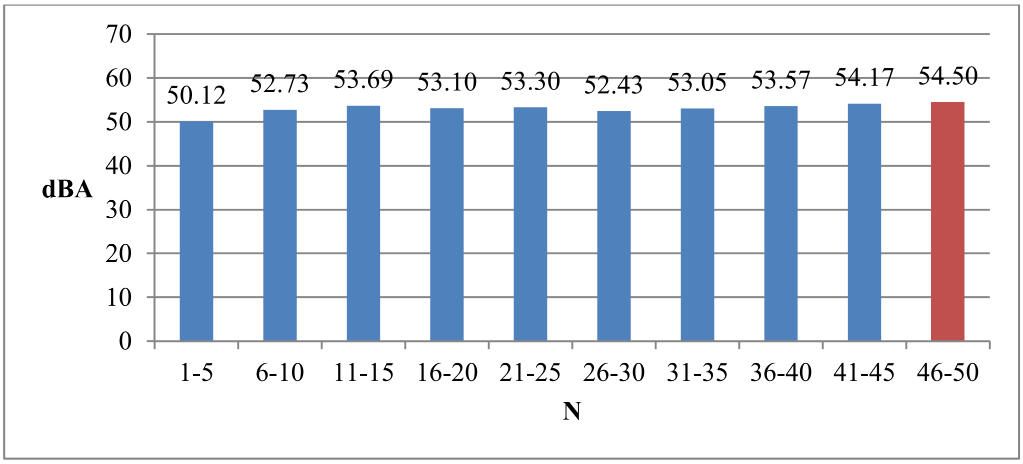


Figure 4.37. Measured Data Log of OPO VI.



(a)



(b)

Figure 4.38 a, b. Average Noise Levels; (a) in Groups of Ten, (b) Five Occupants.

In Figure 4.38 a and b, maximum LA_{eq} was observed within 46-50 occupants with 54.50 dBA. In this office it was seen that the average noise level does not increase as expected as depending on the number of occupants.

In Table 4.13 when predicted and measured LA_{eq} levels are listed, minimum deviation was 8.37 dBA (N:20) and maximum was 14.62 dBA (N:50), and average absolute deviation was 12.34 dBA. When error rates are studied, RMSE was 12.53 and MAPE was 23.07%.

Table 4.13. Application of Rindel’s Model to OPO VI c:0.5, Ap:0.3, g:3 (V:1105 m^3, RT:0.72).

N	Predicted LA$_{eq}$ (dBA)	Measured LA$_{eq}$ (dBA)	Abs. Deviation (dBA)
20	61.47	53.1	8.37
25	63.35	53.3	10.05
30	64.88	52.43	12.45
35	66.17	53.05	13.12
40	67.28	53.57	13.71
45	68.25	54.17	14.08
50	69.12	54.50	14.62
		Average Dev.:	**12.34**
		RMSE:	**12.53**
		MAPE:	**23.07 %**

In Figure 4.39 predicted and measured values of open plan office VI are shown. When the figure is examined, predicted value increases as N increases as expected, yet increase in measured LA$_{eq}$ is very slight.

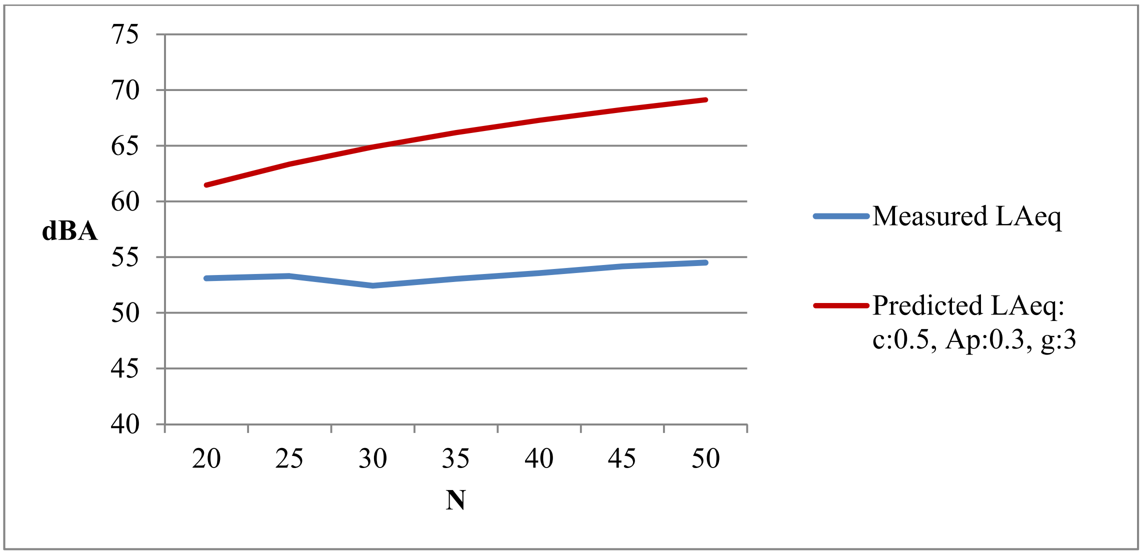


Figure 4.39. OPO VI Predicted and Measured LA$_{eq}$.

4.5. Model Development

When open plan office and eating establishment results are compared, predicted LA_{eq} values for open plan offices were not as successful as eating establishments. By using suggested parameters from previous studies (c: 0.5, g:3 and Ap:0.3), average LA_{eq} deviation and error rates of open plan offices are given in Table 4.14.

Table 4.14. Suggested Model's Findings.

	Avg. Deviation	RMSE	MAPE
OPO I	6.76 dBA	6.96	11%
OPO II	8.97 dBA	9.04	15.83 %
OPO III	9.29 dBA	9.74	17.56 %
OPO IV	16.01 dBA	16.32	29.93 %
OPO V	13.44 dBA	13.61	26.02 %
OPO VI	12.34 dBA	12.53	23.07 %

These high error rates indicate that the model, as it is, is not appropriate for use in the context of open plan offices. Instead of using the accepted values for the Lombard slope and group size in eating establishments, would other values for these parameters be able to explain the noise levels in open plan offices? In order to achieve a better fit with lower error rates and smaller deviations, the best combination of values for the model's parameters are explored through optimization using MS Excel's Solver add-in. For all optimizations in this study the absorption per person parameter – A_p – is fixed to 0.3 based on the fact that the clothing worn by occupants during measurements is already known. For A_p, in previous studies minimum value was 0.15 (Pinho et al., 2018) and maximum was 0.5 (Jens Holger Rindel, 2010). Values for the Lombard slope (c) and group size (g) are optimized with varying constraints.

For Lombard slope, according to the studies, suggested minimum and maximum values for eating establishments was between 0.22 to 0.7 (Lazarus 1986, Dodd and Whitlock 2004), in order to fit and foresee a new slope value for open plan offices current range was expanded to minimum 0 and maximum 1. For group size, based on observations, maximum value was set to 10 and minimum to 5 in offices where public was allowed to access and to 7 in private offices.

4.6. Parameter Optimization Results

First, an overall optimization using all six office measurements was carried out. Based on the observations over all measurements the minimum value for group size was taken as 5, maximum was 10. Lombard slope value was constrained to the range 0.0 – 1.0. The optimized values for c, and g were 0.15, and 5, respectively. Table 4.15 lists the error rates obtained using these optimized values along with error rates obtained using parameter values appropriate for eating establishments for comparison.

Table 4.15. Suggested Model's and Overall Optimization's Values and Findings.

	Suggested Model (c:0.5, Ap:0.3, g:3)			Overall Optimization (c:0.15, Ap:0.3, g:5)		
	Absolute Av.	RMSE	MAPE	Absolute Av.	RMSE	MAPE
OPO I	6.76 dBA	6.96	11 %	5.27 dBA	5.32	8.6%
OPO II	8.97 dBA	9.04	15.83 %	2.09 dBA	2.2	3.66%
OPO III	9.29 dBA	9.74	17.56 %	1.5 dBA	2.4	2.82%
OPO IV	16.01 dBA	16.32	29.93 %	3.39 dBA	3.78	6.34%
OPO V	13.44 dBA	13.61	26.02 %	2.63 dBA	2.85	5.11%
OPO VI	12.34 dBA	12.53	23.07 %	1.51 dBA	1.65	2.82%

While these error rates based on optimized parameter values show a good level of improvement over error rates obtained using parameter values suggested for eating establishments, the variance in the improvement and the suggested lack of the Lombard effect in working spaces, necessitated further investigation.

For this, the best fit for each individual office was investigated, again through optimizations using Excel Solver. The goal was to identify and underline the differences across offices, in terms of model parameters. The investigated ranges for the variables during individual optimizations are given in Table 4.16.

Table 4.16. Minimum and Maximum Values for Individual Optimizations.

	Max.	**Min.**
c:	1	0
Ap:	0.3	0.3
g:	10	5

In the following part, optimized parameters with their minimum error rates will be explained individually for each open plan office (Table 4.17).

Table 4.17. Suggested Model's and Individual Optimization's Values and Findings.

	Suggested Model's findings (c:0.5, Ap:0.3, g:3)			Optimized Values			Individual Optimization Findings		
	Absolute Av.	RMSE	MAPE	c	Ap	g	Absolute Av.	RMSE	MAPE
OPO I	6.76 dBA	6.96	11%	**0.42**	**0.3**	**5**	1.07 dBA	1.25	1.75%
OPO II	8.97 dBA	9.04	15.83%	**0.31**	**0.3**	**5**	0.5 dBA	0.61	0.89%
OPO III	9.29 dBA	9.74	17.56%	**0.2**	**0.3**	**5**	1.4 dBA	2.36	2.67%
OPO IV	16.01 dBA	16.32	29.93 %	**0.0**	**0.3**	**8.8**	1.18 dBA	1.71	2.2%
OPO V	13.44 dBA	13.61	26.02%	**0.0**	**0.3**	**7**	0.81 dBA	1.07	1.55%
OPO VI	12.34 dBA	12.53	23.07%	**0.13**	**0.3**	**7**	0.76 dBA	1.31	1.42%

Estimating noise levels for open plan office I with suggested values for eating establishments (c:0.5, g:3 and Ap:0.3), average absolute deviation between measured and predicted values is 6.76 dBA. RMSE is 6.96 and MAPE is 11%. After optimization for open plan office I, Lombard slope was found as 0.42. and group size was found as 5. Using these parameters, average absolute deviation drops to 1.07 dBA, RMSE to 1.25, and MAPE to 1.75%. For open plan office II, individual optimization found a Lombard slope of 0.31 and a group size of 5, decreasing average absolute deviation from 8.97 dBA to 0.5 dBA, RMSE from 9.04 to 0.61, and MAPE from 15.83% to 0.89%.

For open plan office III, as a result of the optimization, groups size was again found to be 5, but Lombard slope found was lower at 0.2. The average absolute deviation was decreased to 1.4 dBA from 9.29 dBA; RMSE to 2.36 from 9.74, and MAPE to 2.67% from 17.56%. Both for open plan office IV, and V optimization found best fit when Lombard slope is 0.0, with group sizes 8.8 and 7, respectively. In open offices IV and V, improvements were; in average absolute deviations from 16.01dBA to 1.18 dBA, and from 13.44 dBA to 0.81 dBA, respectively. Similarly, RMSE improved from 16.32 to 1.71, and from 13.61 to 1.07, in offices IV, and V, respectively. MAPE improvements were from 29.93% to 2.2%, and from 26.02% to 1.55% in offices IV and V, again, respectively. Lastly, for open plan office VI, Lombard slope found was 0.13 with a group size of 7. Average absolute deviation decreased from 12.34 dBA to 0.76 dBA. RMSE dropped from 12.53 to 1.31, and MAPE was reduced from 23.07% to 1.42%.

The graphs comparing optimized predictions with actual measurements, and initial predictions based on eating establishment parameters, are presented individually for each office in Figure 4.40.

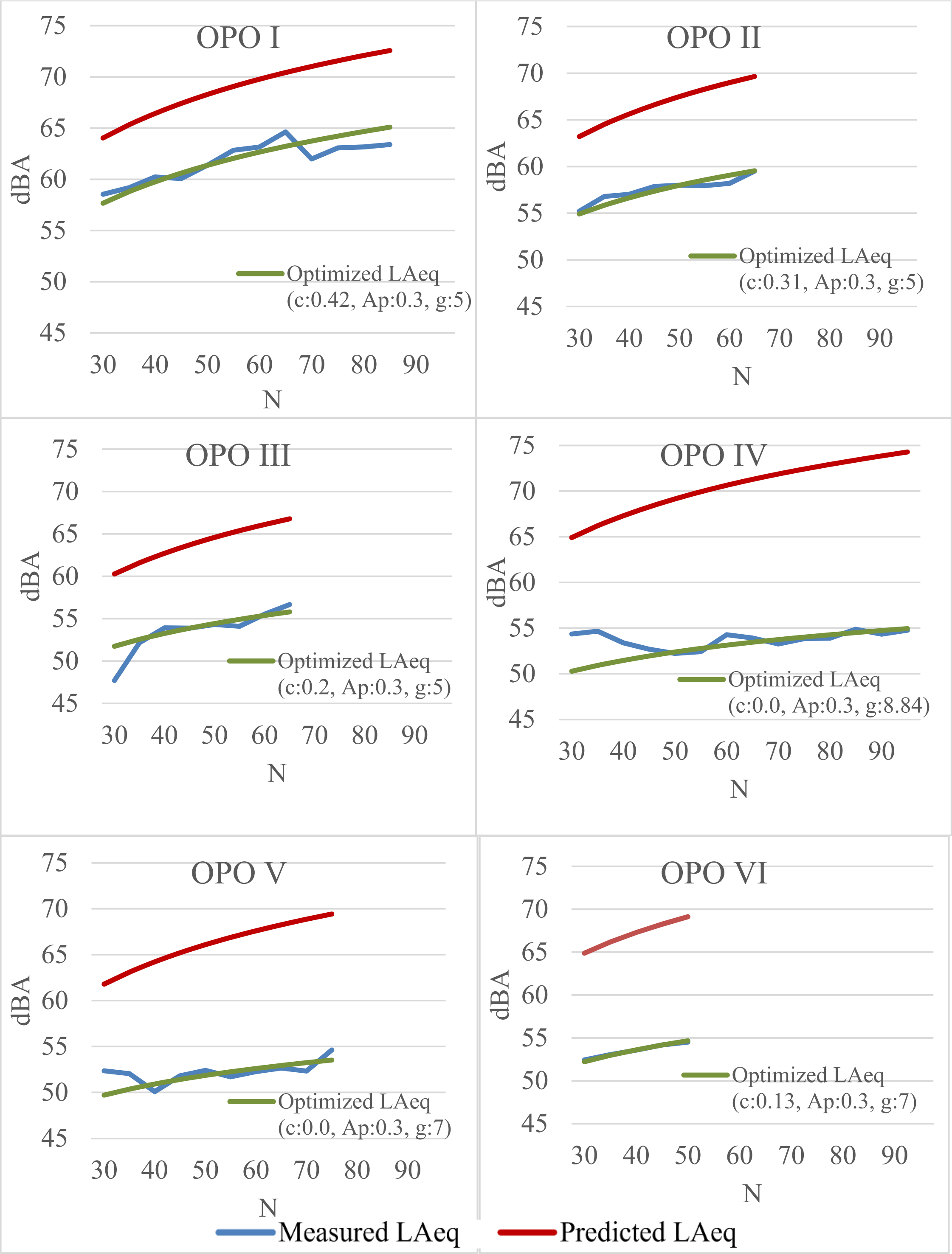


Figure 4.40. Measured, Predicted and Optimized LA_{eq}.

Significant decrease in error metrics is observed pointing to the potential for using this model for noise prediction in open plan offices. However, when results are considered together, the variance in especially Lombard slope parameter indicates that the model needs to be adapted before it can be used for open plan offices.

In order to adapt the model including the Lombard effect to open plan offices, the reason for variance in the required Lombard slope was investigated. When the results are reviewed, the suggested Lombard slopes range between 0.0 and 0.42. Especially in offices where creative work is carried out and concentration is required (OPO IV, V, and VI), best results are obtained when the Lombard slope is taken as 0. However, in offices that are open to outside visitors (or publicly accessible) the suggested Lombard slope is close to suggested values in eating establishments (0.4 - 0.5). These are OPO I and II requiring Lombard slopes of 0.42 and 0.31, respectively.

In OPO IV, V, and IV, besides the fact that mostly software development that takes place mostly requires concentration and focus, managers share the workspace and have their own workstations, resulting in a more formal and calm atmosphere where occupants act relatively more reserved. In contrast, OPO I and II offers public services and the conversations among external visitors as well as between visitors and employees results in a more relaxed atmosphere. This difference in interaction levels that is tied to the nature of work that is carried out in offices is assumed to cause the variance in the Lombard slopes. Depending on the atmosphere of the office, formal or informal; occupants tend to be more reserved or relaxed in controlling their voice levels. In spaces where people can behave more relaxed the interaction level would be higher due to increased interpersonal communication, sharing and co-working. Controlling one's own sound level determines the interaction coefficient of the space.

To confirm this observation further investigation through parameter optimization by grouping the offices according to their public accessibility was carried out. Publicly accessible offices (OPO I and II), and private offices (OPO III-IV-V-VI) formed the two groups. For these optimizations constraints on group size were set differently for each group based on observations. For offices with public accessibility, minimum group size was set as 5, for offices without public accessibility it was set as 7. For both groups Lombard slope limits was maximum 1 and minimum 0, and Ap was fixed as 0.3 (Table 4.18).

Table 4.18. Parameter Constraints for Grouped Optimizations.

		Maximum	Minimum
Offices with Public Accessibility (OPO I and II)	c:	1	0
	Ap:	0.3	0.3
	g:	**10**	**5**
Offices without Public Accessibility (OPO III, IV, V, VI)	c:	1	0
	Ap:	0.3	0.3
	g:	**10**	**7**

By using the constraints in Table 4.18, optimization results are shown with error rates in Table 4.19. Optimization results show that for open plan office I and II Lombard slope is determined as 0.43 and for open plan office III, IV, V and VI it was 0.12. As for the value of group size, for public accessible offices it was gathered as 6.3 and for not accessible offices it was 7.

Table 4.19. Findings of Grouped Optimizations.

	Parameter Values			Grouped Optimization Findings			Overall Optimization (c:0.15, Ap:0.3, g:5)		
	c	Ap	g	Abs. Avg.	RMSE	MAPE	Abs. Avg.	RMSE	MAPE
OPO I	**0.43**	**0.3**	**6.3**	1.76 dBA	2.13	2.92%	5.27 dBA	5.32	8.6%
OPO II				0.89 dBA	1.13	1.56%	2.09 dBA	2.2	3.66%
OPO III	**0.12**	**0.3**	**7**	2.87 dBA	3.42	5.31%	1.5 dBA	2.4	2.82%
OPO IV				1.89 dBA	2.09	3.52%	3.39 dBA	3.78	6.34%
OPO V				1.11 dBA	1.24	1.92%	2.63 dBA	2.85	5.11%
OPO VI				0.82 dBA	1.36	1.54%	1.51 dBA	1.65	2.82%

When grouped optimization results are compared with overall optimization results of all six offices together, it can be seen that by grouped optimization, in publicly accessible offices MAPE decreased to 2.92% from 8.6%, OPO II from 3.66% to 1.56%. Only in OPO III MAPE increases to 5.31% from 2.82%. OPO III was an engineering office with more collaboration compared to OPO IV, V, and VI and individual optimizations had indicated that there is a Lombard slope of 0.2 in this space. However, in other offices, the decrease in MAPE value continues, in OPO IV MAPE decreases to

3.52%, from 6.34%, in OPO V decrease is from 5.11% to 1.92% and in OPO VI from 2.82% to 1.54% (Figure 4.41,Figure 4.42).

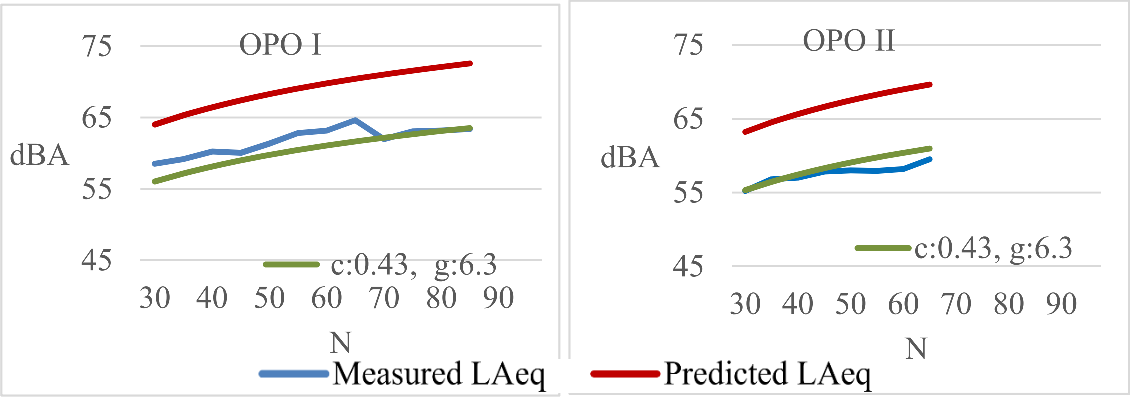


Figure 4.41. Grouped Optimization Results of OPO I and II.

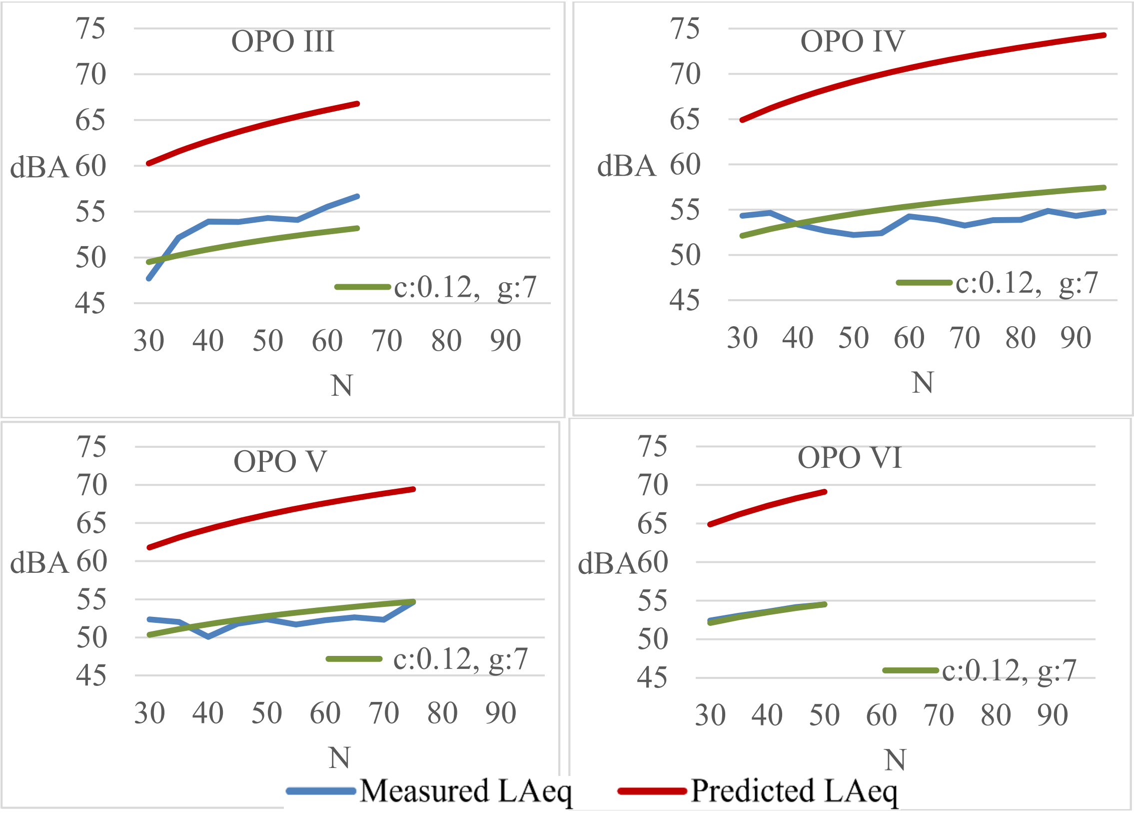


Figure 4.42. Grouped Optimization Results of OPO III, IV, V and VI.

4.7. Proposed Model Adaptation

After analyzing open plan office measurements and optimizations individually and grouped, overall data is gathered and studied. Results show that, for adapting the model to open plan offices, the variables in the model needs to be modified. It was determined that Lombard slope for open plan offices varies between 0.43 to 0.12 and proposed group size varies between 5 to 8. The interaction level in the workspace that is related to the nature of work and the public accessibility of the space, is attributed for the attitudes – reserved or relaxed - of occupants towards the rise in background noise levels and thus the variance in Lombard slopes.

The variance in group size, on the other hand, is of course related to the number of simultaneously speaking occupants. In eating establishments table sizes can reflect group sizes among occupants that allows the model to predict the number of simultaneous talkers. However, in open plan offices predicting simultaneous talkers is not as straight forward. While many factors have an effect on the number of speaking occupants at any given moment, the nature of work and distance between occupants are two major ones. The nature of work is about the ratio of conversations either over the phone or with other employees that is required during a workday. While a marketing department might be expected to have a high number of employees speaking to customers, a software development firm might be expected to have most employees carrying out individual tasks at their workstations. The second major factor - average distance between employees – determines how easy it is for an employee to interact with others. Close proximity encourages interaction. Both these factors are connected to and manifest themselves on the architectural plan layout. The density of the workstations in the office design reflects how the firm will encourage co-working, as well as if a high level of interaction or a calmer environment is preferred.

Therefore, in adapting the eating establishment model to open plan offices, two modifications are proposed: 1) Introduce an Interaction Level coefficient that will adjust the Lombard slope that is constant as 0.5 and reflect workspace atmosphere. 2) Determine the number of simultaneous speakers based on spatial density. Modified equation for open plan offices is given in equation 6.

$$\mathrm{LNA} = \frac{1}{1-c\cdot k_{IL}}\cdot\left(69 - \mathrm{c}\cdot \mathrm{k}_{IL}\cdot 45 - 10\mathrm{Log}\left(\frac{g(0.16\cdot \mathrm{V})}{\mathrm{T0}\cdot \mathrm{N}} + \mathrm{Ap}\right)\right)\ (\mathrm{dB}) \qquad \text{Eq. 6}$$

where,

k_{IL} is the interaction level coefficient

The interaction level is a design variable and needs to be evaluated based on observation or design intent. It is a value between 0 and 1. 1 representing an office where everyone is engaged in various interactions and participate in conversations. 0 representing an office where everyone is focused on work and no interaction takes place. In reserved spaces the interaction level is assumed to be lower, since occupants would behave more self-controlled. In lively spaces since the occupants would behave more relaxed the interaction level would be higher. As a design tool it can be classified as being low, medium or high, and the range can be divided into three at 0.35 and 0.65.

Determining the group size is done using a lookup table, (Table 4.20) and is based on the spatial density or the area per seat in the office. The value for g needs to be corrected for the interaction level of the office. If the interaction level is high, 0.5 should be subtracted and if the interaction level is low, 0.5 should be added to the value of g.

Table 4.20. Group Size Determination Table.

	Spatial Density - area/seat					
	< 4 m^2	< 5 m^2	< 6 m^2	< 7 m^2	< 8 m^2	≥ 8 m^2
g	3	4	5	6	7	8
Correction factors	if k_{IL} is low (0 – 0.35), +0.5; if k_{IL} is high (0.65 – 1.00), -0.5					

For verification, the modified model is applied to all six open plan offices measured. Determination of interaction level and group size values for all studied open plan offices are shown in Table 4.21. OPO I which is open to public access has a high interaction level. However, about half of the offices cater to the public, the other half is restricted.

Thus, for OPO I the interaction level coefficient was determined to be 0.8. Total area per seating capacity ratio was 5.45 m^2. By using Table 4.20, g for OPO I is found to be 5 but needs to be corrected for the high interaction level and becomes 4.5. In OPO II, g is 6 and corrected to 5.5 due to high interaction level. In OPO 3 since interaction level is 0.4, it does not need a correction factor and g is gathered as 6. In OPO IV and V, g is found as 7 and due to low interaction level, it becomes 7.5. Lastly, in OPO VI since g is 8 and with correction factor it is corrected as 8.5 (Table 4.21).

Table 4.21. Interaction Level and Group Sizes for OPO I-VI.

	OPO I	OPO II	OPO III	OPO IV	OPO V	OPO VI
k_{IL}	0.8	0.7	0.4	0.2	0.2	0.2
area/seat [m^2]	5.45	6.67	6.8	7.4	7.4	8
g	**4.5**	**5.5**	**6**	**7.5**	**7.5**	**8.5**

Based on the determined values of interaction level and g, the configuration matrix for the open plan offices is given in Table 4.22

Table 4.22. Configuration Matrix for Open Plan Offices.

			Spatial Density (m^2/seat)					
			Hi				Lo	
			<5 m^2	<6 m^2	<7m^2	<8m^2	>=8m^2	
k_{IL}	IL	g	4	5	6	7	8	Correction:
0.00-0.35	Low					OPO IV, V	OPO VI	g = g + 0.5
0.35-0.65	Medium				OPO III			no correction
0.65-1.00	High			OPO I	OPO II			g = g - 0.5

Using the determined interaction level and group sizes, the error rates of the proposed adapted model predictions are compared with the error rates from individual and overall optimizations in Table 4.23.

Table 4.23. Proposed Adapted Model Error Rates.

	Individual Optimization			Overall Optimization (c:0.15, Ap:0.3, g:5)			Proposed Adapted Model Predictions		
	Abs. Avg.	RMSE	MAPE	Abs. Avg.	RMSE	MAPE	Abs. Avg.	RMSE	MAPE
OPO I	1.07 dBA	1.25	1.75%	5.27 dBA	5.32	8.6%	1 dBA	1.2	1.6%
OPO II	0.5 dBA	0.61	0.89%	2.09 dBA	2.2	3.66%	0.6 dBA	0.7	1%
OPO III	1.4 dBA	2.36	2.67%	1.5 dBA	2.4	2.82%	1.7 dBA	2.59	3.18%
OPO IV	1.18 dBA	1.71	2.2%	3.39 dBA	3.78	6.34%	1.6 dBA	1.77	3.01%
OPO V	0.81 dBA	1.07	1.55%	2.63 dBA	2.85	5.11%	0.9 dBA	1.1	1.66%
OPO VI	0.76 dBA	1.31	1.42%	1.51 dBA	1.65	2.82%	1.9 dBA	2.19	3.6%

The results indicate that the proposed modifications to the noise prediction model is able to adapt to the changing conditions in open plan offices and performs adequately. The offices where overall optimization parameters perform better are OPO III and OPO VI. However, both models come very close to individual optimization results. The graphs comparing adapted model predictions with actual measurements, and initial predictions based on eating establishment parameters, are presented individually for each office in Figure 4.43.

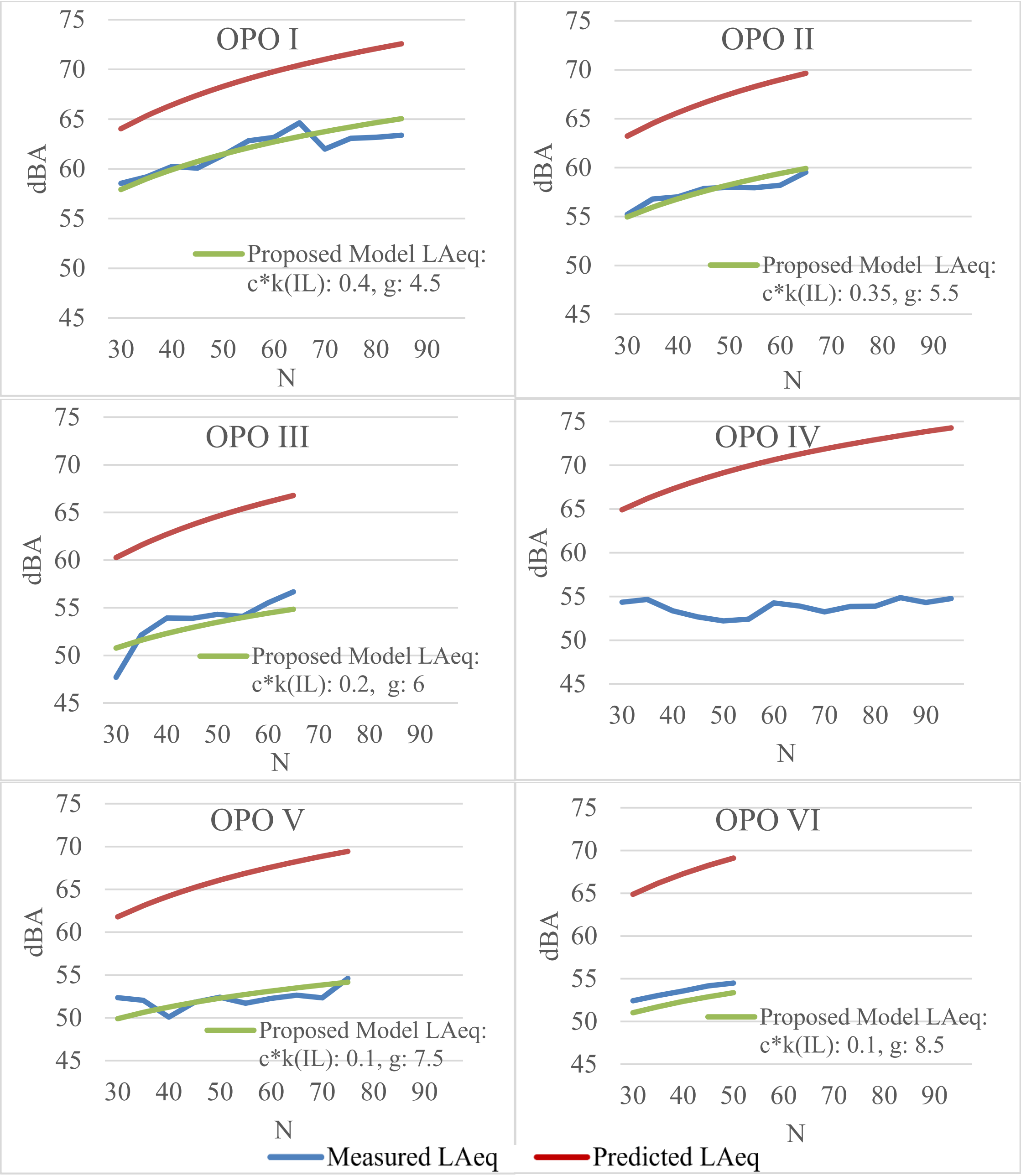


Figure 4.43. Measured, Predicted and Proposed Model’s LA_{eq} Values.

CHAPTER 5

FINDINGS AND DISCUSSION

This chapter presents a summary of the study and provides a discussion of results.

5.1. Results

Due to new life and working styles there is a need for designing larger spaces that can accommodate many people. As the number of people in the space increases, noise level of the space increases. Especially in non-acoustic public spaces where many people gather, communicate and interact noise prediction tools are necessary. In this study, the model that has been developed by Rindel (2010) to foresee noise levels in eating establishments depending on existing number of occupants is studied and adapted for working environments. Following the preliminary measurement studies in two eating establishments, an electronic study room and an architecture studio comparing the performance of the model in eating establishments with its performance in working spaces, the research later tested the model's applicability to open plan offices where a more stable background noise due to occupants themselves is observable compared with library and studio spaces.

Acoustic problems of open plan offices have been the subject of many researches for a very long time. It is mentioned in the studies that these places are very noisy, and the employees do not want to work in such places. Unfortunately, a model that can predict the noise level due to the occupants themselves in open plan offices does not yet exist. In order to analyze noise problems in open offices and characteristics, measurements were conducted in six different open offices. Measured offices are; open plan offices I and II which were different floors in the same building of Izmir Water and Sewage Administration, open plan office III which was an engineering technology firm in the Aegean Free Zone, and open plan offices IV, V and VI which were software companies in a university technopark in Izmir.

During selection of open plan offices, the most important factors were; capacity, density of occupants, working style and plan scheme of the spaces. Principally, offices with at least 45 employees were selected. Secondly, as working style; offices where each employee has an assigned workstation of their own was preferred. Each firm had a different character with regard to the level of interactions that took place in the workplace. Furthermore, plan scheme was also important. Balanced layouts where occupants are spread over the layout homogenously are preferred for measurement purposes. Lastly, in order to keep a count of number of occupants, location and number of gates were also a criterion and offices with one or at most two gates were preferred.

General information about the studied offices are given in Table 5.1. In the table, reverberation time, seating capacity, volume, area and some design features of offices such as the presence of acoustic ceiling or partitions between desks are listed.

Table 5.1. Overall Information of Open Plan Office's.

	OPO I	**OPO II**	**OPO III**	**OPO IV**	**OPO V**	**OPO VI**
RT (s)	0.45 s	0.55 s	0.5 s	1.15 s	0.71 s	0.72 s
Seating Capacity	50	55	64	74	70	46
Max. Num. of Occupant.	85	62	65	94	74	50
Volume (m^3)	765 m^3	1029 m^3	1325 m^3	1760 m^3	1573 m^3	1105 m^3
Volume/Seating Capacity (m^3)	15.3 m^3	18.7 m^3	20.7 m^3	23.7 m^3	22.4 m^3	24.0 m^3
Area (m^2)	273	367	441	550	524	368
Area/Seating Capacity	5.45 m^2	6.67 m^2	6.8 m^2	7.4 m^2	7.4 m^2	8 m^2
Out Coming Visitors	✓	✓	-	-	-	-
Employees and Managers are in the same office	-	-	-	✓	✓	✓
Acoustic Ceiling	✓	✓	✓	-	✓	✓
Screen Panels	-	-	✓	✓	✓	✓
Max dBA	68.23	70.73	56.67	54.86	54.62	54.50
Noise Level (dBA)	34.96	34.5	41.9	34.47	43.1	42.7

The reverberation time of open plan office I has the shortest and open plan office IV has the longest with 1.15 s. Only in open plan office IV there is no acoustic ceiling application. It was an exposed ceiling where structural and mechanical systems were visible so, having the longest reverberation time in this office is not surprising. Despite the long reverberation time in open plan office IV, it is the only office within the range of suggested reverberation time values of 0.75 – 1.25 s. (Eguez 2017).

Seating capacities of each open plan office varies according to the needs of the firm; it changes between 46 to 74 occupants. Maximum number of occupants during measurement reaches up to 94 in open plan office IV, the capacity of the office was 74, and visitors were coming from other offices for co-working. When area and seating capacity ratio is analyzed minimum value is 5.45 m^2 per person in open plan office I and maximum is 8 m^2 per person in open plan office VI. Interaction level in offices is based on the nature of the work done. While creativity and concentration requires quiet spaces, public services are more tolerant towards higher levels of background noise. Open plan offices I and II are offices with public accessibility and their occupant density is higher than other offices. Seating capacity to total area ratio is utilized in the adapted model in determining number of simultaneous speakers.

Interaction level is another concept used in the adapted model. In open plan offices III, IV, V and VI only co-workers in the same building were allowed in the office space, and loudness level in those offices were lower than other offices. In open plan offices IV & V and VI employees and managers were working in the same environment. This relatively more formal environment may be one of the factors behind the fact that lowest LA_{eq} levels were observed in those offices. In contrast, open plan offices I and II offer public services and thus more conversations takes place. It can be inferred that the purpose of visitors to the office affects loudness level, whether it is for co-working purpose or for receiving public services.

In order to test and see the eating establishment model's performance with open plan offices, it was applied with suggested parameters (c:0.5, Ap:0.3, g:3) for eating establishments and the results are summarized in Table 5.2. It can be seen that the model can predict noise levels in the two eating establishments from the preliminary stage with low error rates. Especially in YM MAPE is 0.35%. However, in open plan offices, the model does not provide accurate results. For open plan office IV, absolute average deviation is 16.01 dBA, RMSE is 16.32 and MAPE is 29.93%. When the results are analyzed, it was seen that the model cannot accurately predict noise level in these offices and requires modifications.

Table 5.2. Suggested Model’s Values and Findings.

	Suggested Values			Findings		
	c	Ap	g	Absolute Ave. Deviation	RMSE	MAPE
YM	0.5	0.3	3	2.92 dBA	1.01	0.35 %
MD				4.48 dBA	5.03	6.72 %
OPO I				6.76 dBA	6.96	11 %
OPO II				8.97 dBA	9.04	15.83 %
OPO III				9.29 dBA	9.74	17.56 %
OPO IV				16.01 dBA	16.32	29.93 %
OPO V				13.44 dBA	13.61	26.02 %
OPO VI				12.34 dBA	12.53	23.07 %

The model development consisted of 2 stages, parameter optimization and proposed model adaptation. To investigate and better understand the effect of each parameter on the model, parameters were optimized within constraints to match predictions with actual measurements. In all optimizations, Ap – the absorption per person – is constrained to 0.3 since the amount of clothing worn is known. Parameter optimization starts with overall and individual optimizations and follows with grouped optimizations.

Starting with an overall optimization of model parameters where c is unconstrained and g is constrained between 10-5 the results are given in Table 5.3.

Table 5.3.Overall Optimization Results.

	Findings of Overall Optimization (c:0.15, Ap:0.3, g:5)		
	Absolute Av.	RMSE	MAPE
OPO I	5.27 dBA	5.32	8.6%
OPO II	2.09 dBA	2.2	3.66%
OPO III	1.5 dBA	2.4	2.82%
OPO IV	3.39 dBA	3.78	6.34%
OPO V	2.63 dBA	2.85	5.11%
OPO VI	1.51 dBA	1.65	2.82%

While the error rates show a good level of improvement, the variance in the improvement and the suggested lack of the Lombard effect or any working space, necessitated further investigation into how model parameters should be for the best fit in each individual office. Results of parameter optimizations for individual offices are shown in Table 5.4. The limit for g was minimum 5 and for Lombard slope the range was 1 to 0.0.

Table 5.4. Individual Optimization Values and Findings.

	Optimization Values			Individual Optimization Findings		
	c	Ap	g	Absolute Av. Deviation	RMSE	MAPE
OPO I	0.42	0.3	5	1.07 dBA	1.25	1.75 %
OPO II	0.31	0.3	5	0.5 dBA	0.61	0.89 %
OPO III	0.2	0.3	5	1.4 dBA	2.36	2.67 %
OPO IV	0.0	0.3	8.8	1.18 dBA	1.71	2.2 %
OPO V	0.0	0.3	7	0.81 dBA	1.07	1.55 %
OPO VI	0.13	0.3	7	0.76 dBA	1.31	1.42 %

The individual optimization results show that significant decrease in absolute deviation, RMSE and MAPE values are possible with the model. However, especially the Lombard slope parameter requires a wide range of values including 0 maybe indicating the absence of the Lombard effect in some working environments.

In open plan office I, II and III Lombard slope values are 0.42, 0.31 and 0.2 which means that there is a slope, yet the slope is not as defined as it is in eating establishments. In open plan office I and II external visitors (public) were allowed to the floors, so more conversations took place at a natural level probably resulting in a more pronounced Lombard slope.

On the other hand, in open plan office IV, V and VI optimized Lombard slope value is 0 and 0.13. In these three offices managers were in the same space with employees. As a result, a more formal atmosphere is maintained in these offices leading to comparatively lower noise levels. This low, controlled interaction level compared to open plan offices I and II where with public access there is a higher interaction level, can be attributed to the reluctance of the occupants to raise their vocal efforts as background noise levels increase.

The clear separation between required values of the Lombard slope among these two groups of offices motivated an investigation of parameter optimization within these two groups as well. The grouping was based on whether an office is publicly accessible or not. Based on observations during measurements, group size – g – was constrained between 5 and 10 for the publicly accessible offices and between 7 and 10 for the other offices. Lombard slope, c when optimized for publicly accessible offices was 0.43 and when optimized for publicly non-accessible offices was 0.12. The results are shown in Table 5.5.

Table 5.5. Grouped Optimization Results.

	Optimized Parameters			Error Rates After Parameter Optimization in Two groups		
	c	Ap	g	Absolute Av. Dev.	RMSE	MAPE
OPO I	**0.43**	**0.3**	**6.3**	1.76 dBA	2.13	2.92 %
OPO II				0.89 dBA	1.13	1.56 %
OPO III	**0.12**	**0.3**	**7**	2.87 dBA	3.42	5.31 %
OPO IV				1.89 dBA	2.09	3.52 %
OPO V				1.11 dBA	1.24	1.92 %
OPO VI				0.82 dBA	1.36	1.54 %

In Table 5.6, the comparison of error rates and absolute average deviation results are shown for predicted, individually optimized and proposed model values. The proposed model is quite successful in adapting to open plan office environments.

Table 5.6. Comparison of Predicted, Individual Optimization and Proposed Model's Results.

Predicted Values			Individual Optimization			Proposed Model		
Ave. Dev.	RMSE	MAPE	Ave. Dev.	RMSE	MAPE	Av. Dev.	RMSE	MAPE
6.76 dBA	6.96	11 %	1.07 dBA	1.25	1.75 %	1 dBA	1.2	1.6%
8.97 dBA	9.04	15.83 %	0.5 dBA	0.61	0.89 %	0.6 dBA	0.7	1%
9.29 dBA	9.74	17.56 %	1.40 dBA	2.36	2.67 %	1.7 dBA	2.59	3.18%
16.01 dBA	16.32	29.93 %	1.18 dBA	1.71	2.20 %	1.6 dBA	1.77	3.01%
13.44 dBA	13.61	26.02 %	0.81 dBA	1.07	1.55 %	0.9 dBA	1.1	1.66%
12.34 dBA	12.53	23.07 %	0.76 dBA	1.31	1.42 %	1.9 dBA	2.19	3.6%

CHAPTER 6

CONCLUSION

In this chapter conclusion and contributions of the research to the field will be elaborated with possible future studies that may follow this study.

6.1. Conclusion

In this study, the aim was to study the relationship between number of occupants and noise levels, considering the Lombard effect in open plan offices. The preliminary studies showed that an existing model was accurate in eating establishments, and a Lombard slope was clearly observed in dining areas. However, it was found that the model predictions showed considerable deviation from measurements in working environments. Furthermore, the results suggested that the Lombard effect did not exist in working environments. Following preliminary measurements, open plan offices were investigated and it was observed that that the existing model was also not applicable for open plan offices using the suggested parameter values for eating establishments. As number of occupants increased, noise level does not increase as expected by the model in open plan offices. In order to estimate noise levels in open plan offices based on number of occupants, several optimizations were performed to better understand the effect of parameters. The results suggested that the strength of the Lombard effect varies from office to office, depending on the character of the working environment. Two modifications to the model were found to be effective in reflecting the differences among offices and adapting the model to open plan offices.

The scope of our study includes four research questions stated in previous chapters. First of all, existence of Lombard effect in spaces other than eating establishments was examined. It was shown that the model was able to successfully explain the relationship between noise levels and number of occupants and the expected Lombard slope was between 0.4 and 0.5 in dining areas. However, the model that considers the Lombard effect failed to predict noise levels reliably in working environments. The results of open plan measurements suggest that the Lombard slope varies from office to office. In some offices where occupants are more relaxed about having a conversation, Lombard slopes similar to eating establishments (0.4 - 0.5) are observed. In other offices where the environment is more formal, occupants are careful about the noise they generate and the Lombard slope approaches 0.0 suggesting that there is no Lombard effect.

The second question that was explored was whether it was possible to estimate noise levels in open plan offices depending on the number of occupants. Based on measurement results several parameter optimizations were performed to achieve better fit for the model. It was seen that the model required modifications in order to be adapted to open plan offices. The modifications were needed for accounting for the variance in the Lombard slope as well as the group size that determined the number of simultaneously speaking occupants.

The third research question focused on the search for the relationship between number of occupants and noise levels in open plan offices. The two modifications were required to reliably reflect this relationship in the model. The first modification was introducing an interaction level coefficient and the second was determining the number of speaking occupants based on spatial density. Those two factors can be defined by the designer, where interaction level is related to the nature of work, public accessibility of the space and distance between occupants. Whether the space is reserved or relaxed and the density of workstations reflects the interaction level. With the proposed modifications, the model better predicts noise levels in open plan offices.

The final research question was interrogating the associated value of the Lombard slope specifically in open plan offices. Based on our results, it can be said that in open plan offices, the strength of the Lombard effect varies between 0.5 and 0.0 and that it depends on the nature of work, the density of occupants and the presence of public. The modifications to the model are proposed reflecting these variables.

6.2. Contributions

This thesis proposing an adaption of an established model for noise level prediction in eating establishments to open plan offices makes the following contributions:

- The measurement results have shown that the Lombard slope varies among spaces. This is attributed to the interaction level that is encouraged by the working environment. Some working spaces are lively and allow occupants to talk more naturally, some are more formal, calling for more self-control.
- The spatial density in open plan offices, in terms of area per seat, has been shown to be a good indicator for predicting the number of simultaneously speaking occupants in these offices and that it can be used to replace table size based estimations in eating establishments.
- Through the adaptation of an existing model for eating establishments, a model has been developed that can be used for the planning and design of open plan offices and allows prediction of occupant based noise levels in these spaces.

6.3. Future Studies

In terms of architectural acoustics, it has been shown that there is a definite need for further investigation of noise prediction models in open plan offices. Yet, for future studies, there are many other interesting research questions. For example, the effect of cultural differences in tolerating noise levels in working and eating establishments can be investigated. Whether or not the magnitude of the Lombard slope changes depending on cultural context should be explored.

Finishing materials and furniture used have high impact on reverberation times. Since throughout the study it was observed that reverberation time is an important variable for the model's performance, research on the effects of absorptivity coefficients of materials used on generated noise levels could take this research a step further.

A noise prediction model for open plan offices needs to be a tool for designers to predict possible noise levels that may be generated by occupants. For this purpose, types of open planed offices can be varied, plan schemes other than rectangular plans can be considered. Surely, more measurements in open plan offices are needed.

Also, other types of spaces beyond open plan offices need to be investigated. The noise prediction model developed by Rindel and intended for eating establishments should be extended beyond open plan.

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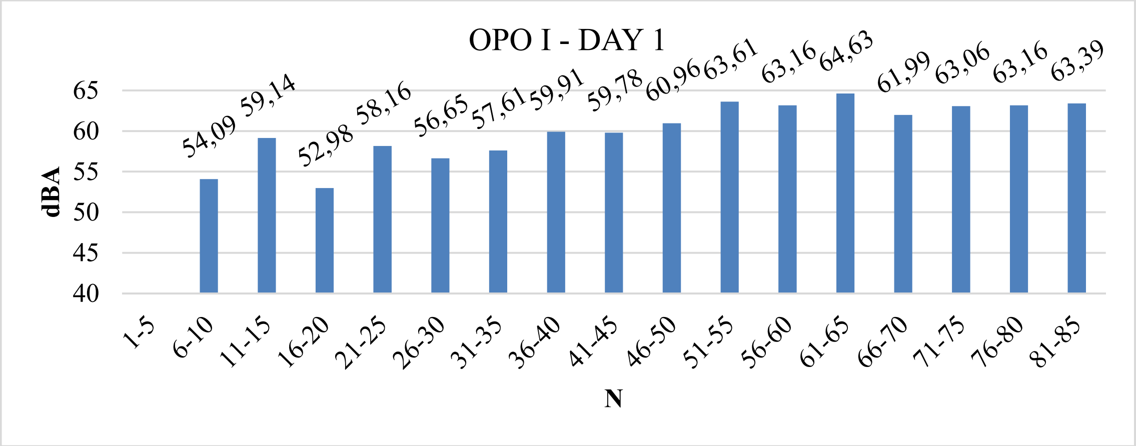
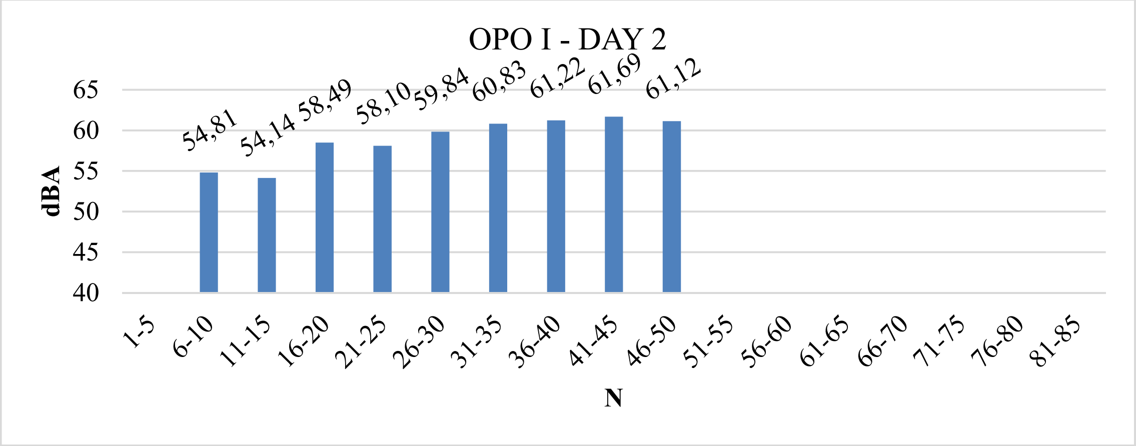
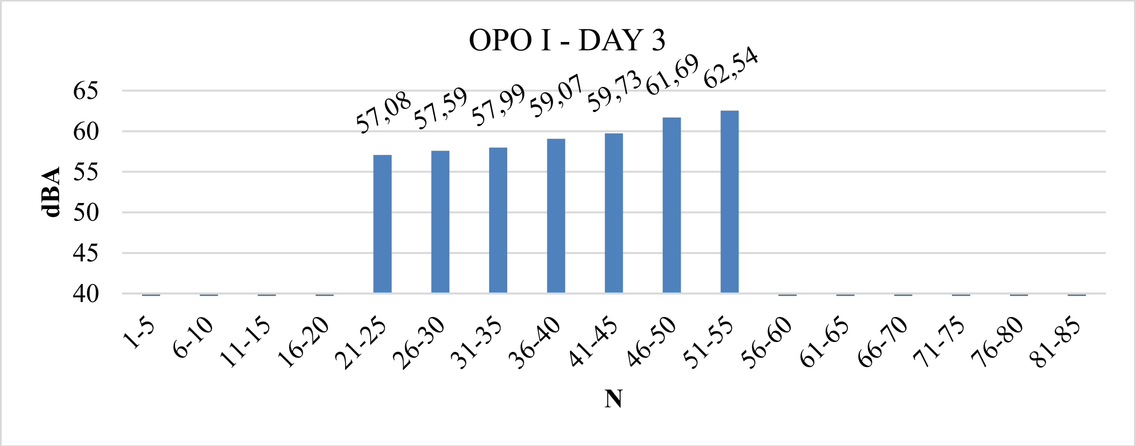
APPENDICES

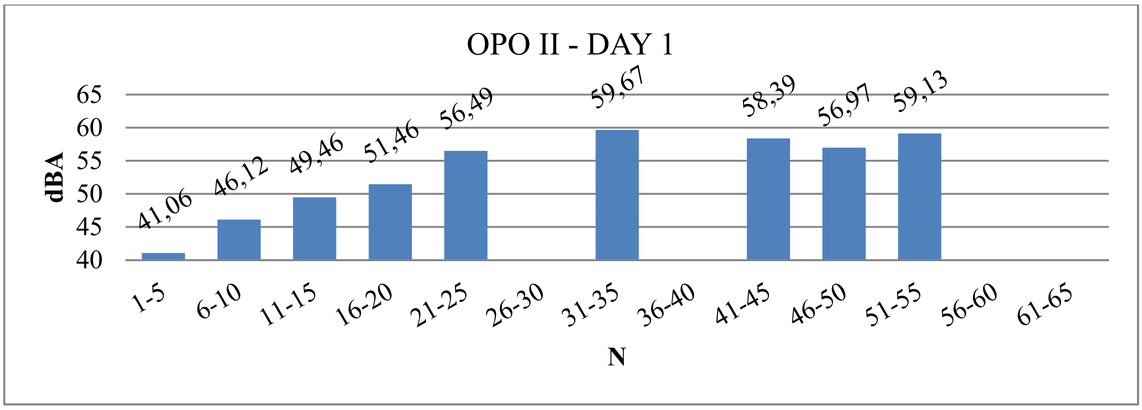
APPENDIX A

MEASUREMENT DAYS AND RESULTS





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56,97
59,13
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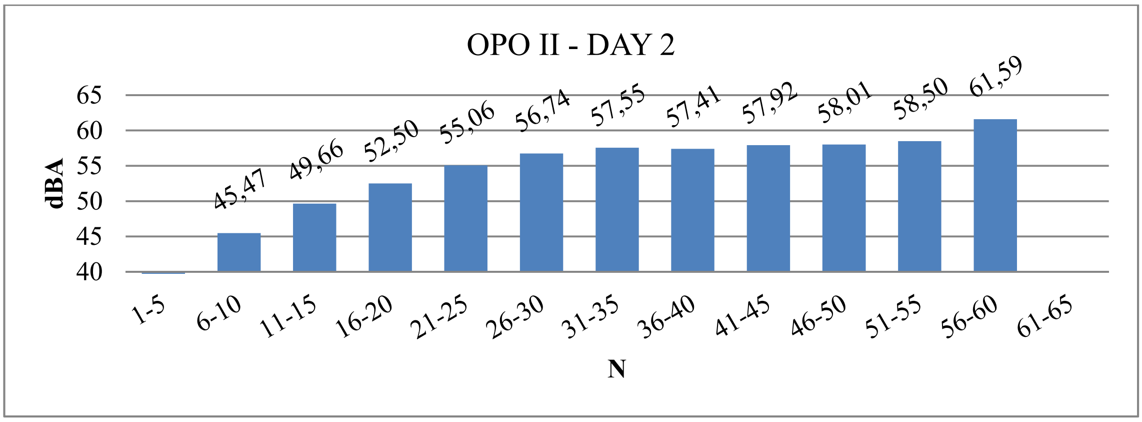
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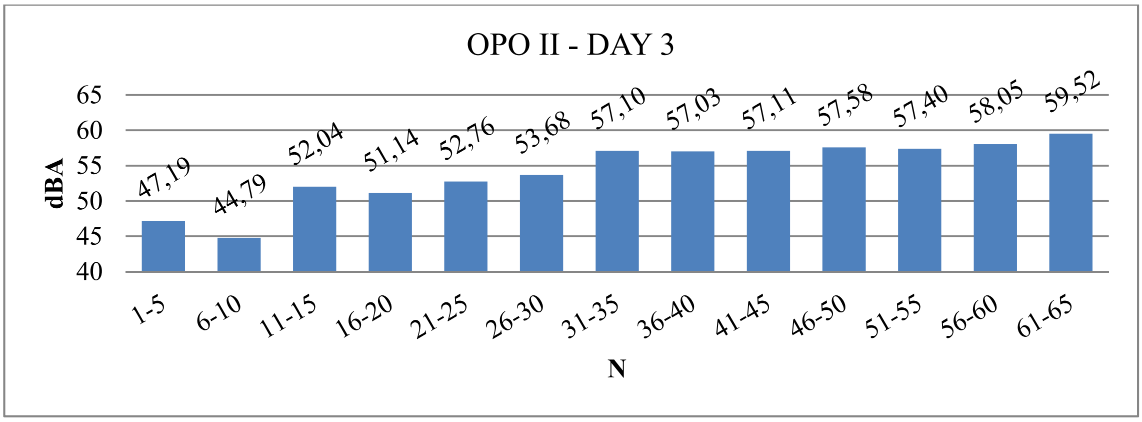
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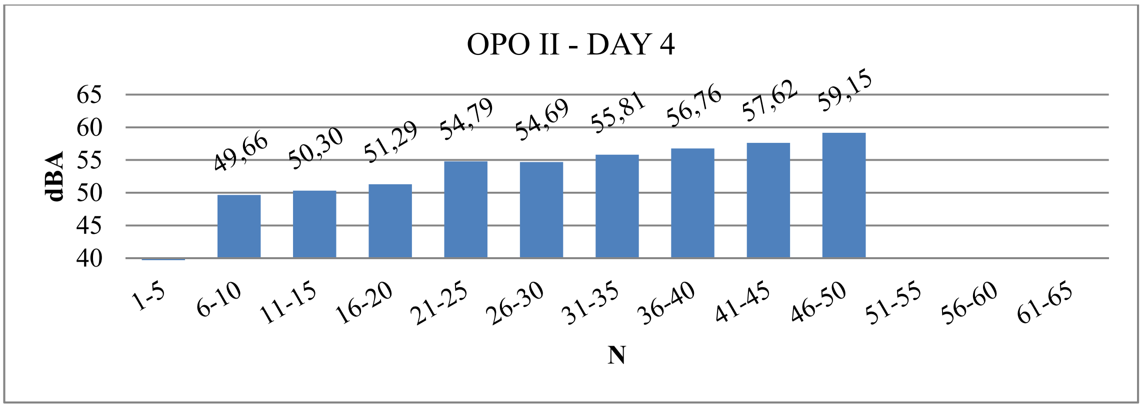
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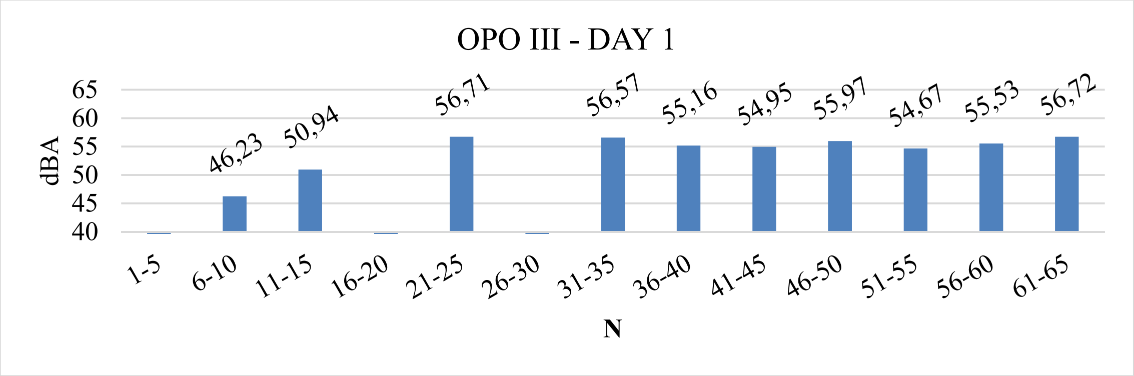
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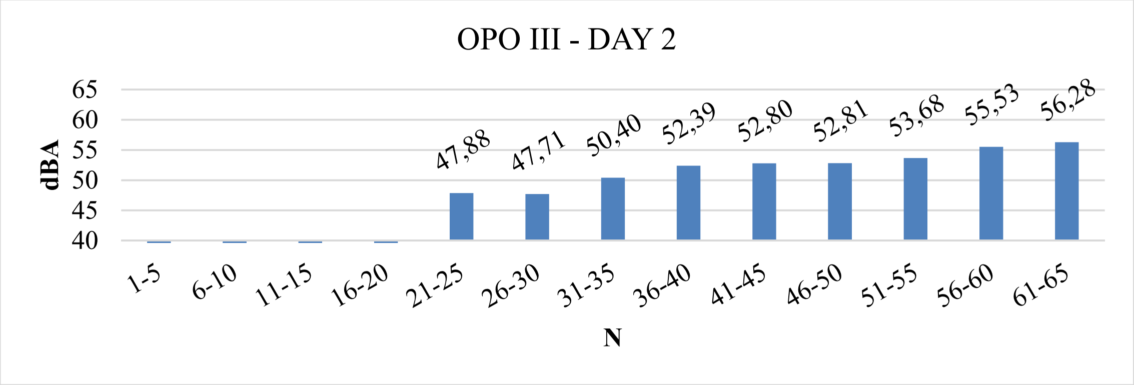
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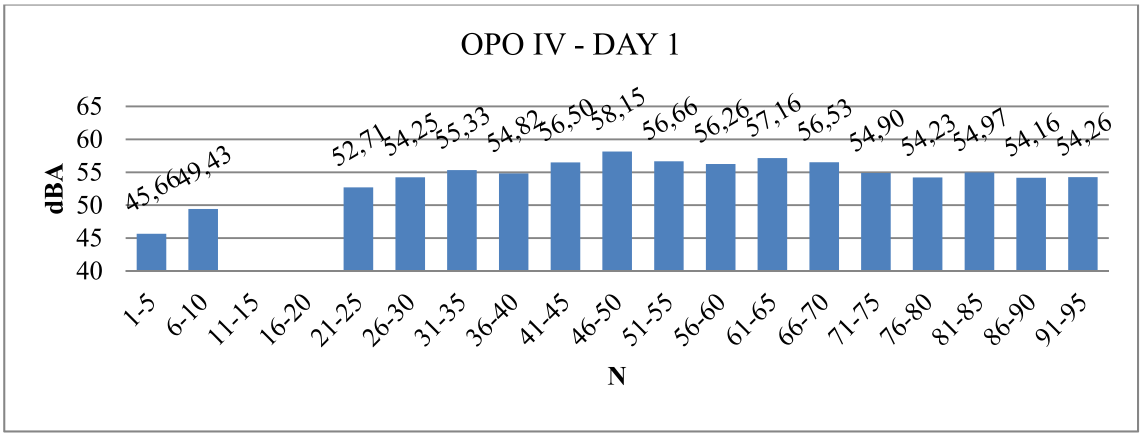
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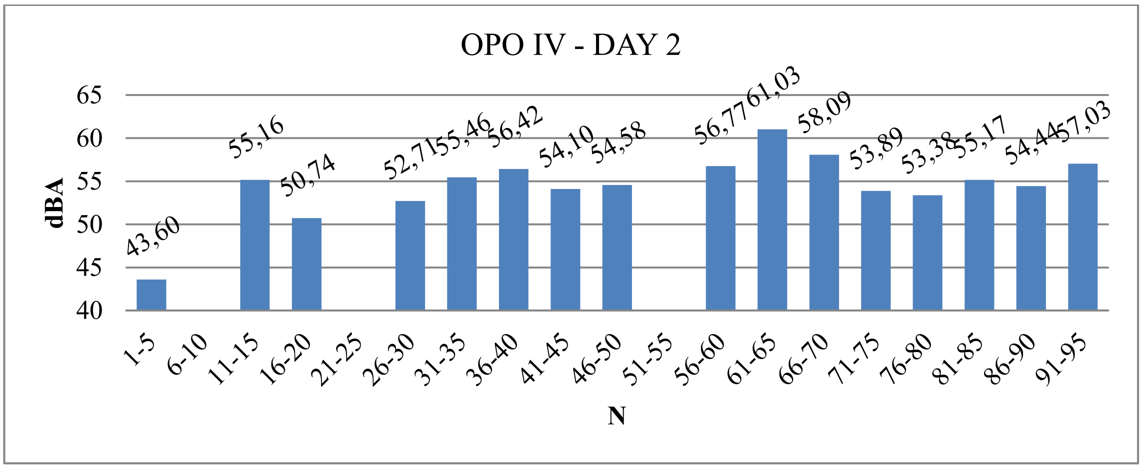
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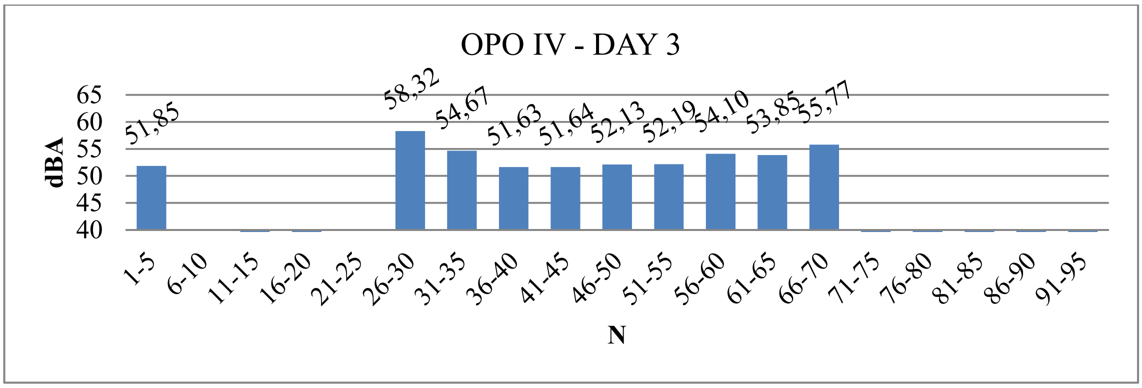
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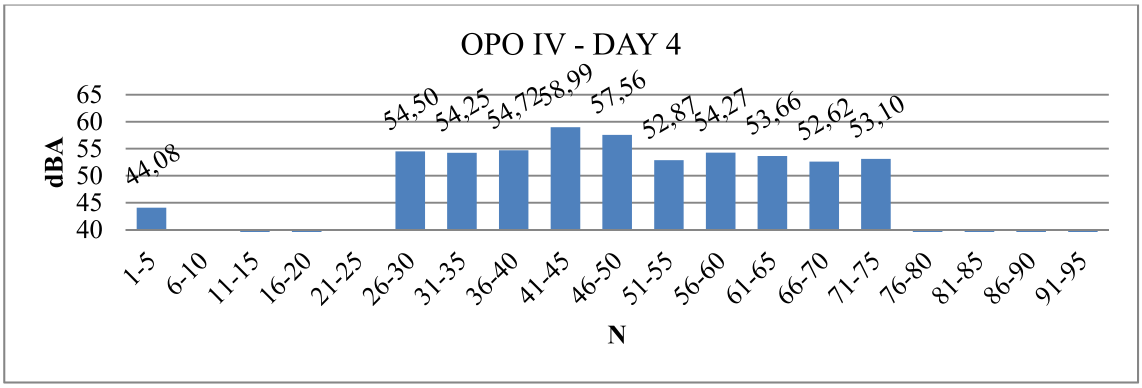
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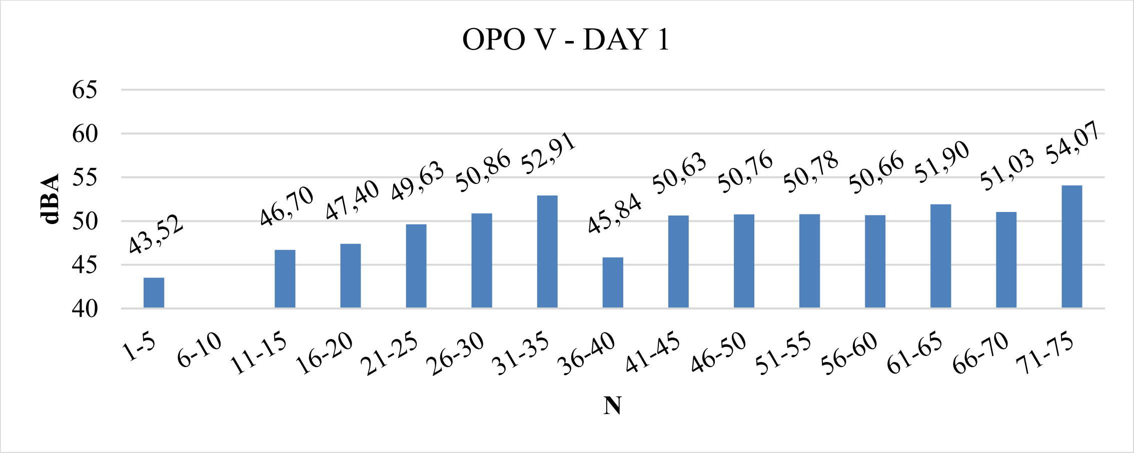
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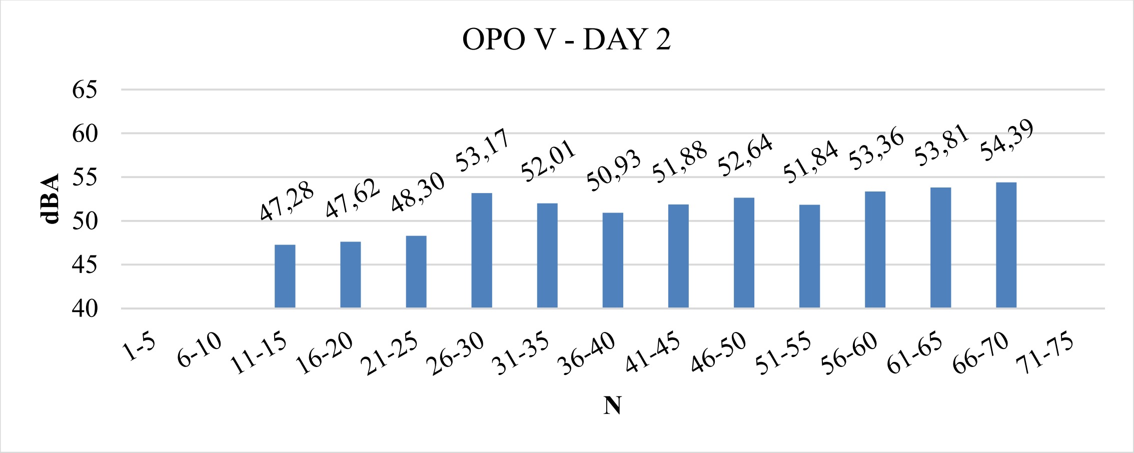
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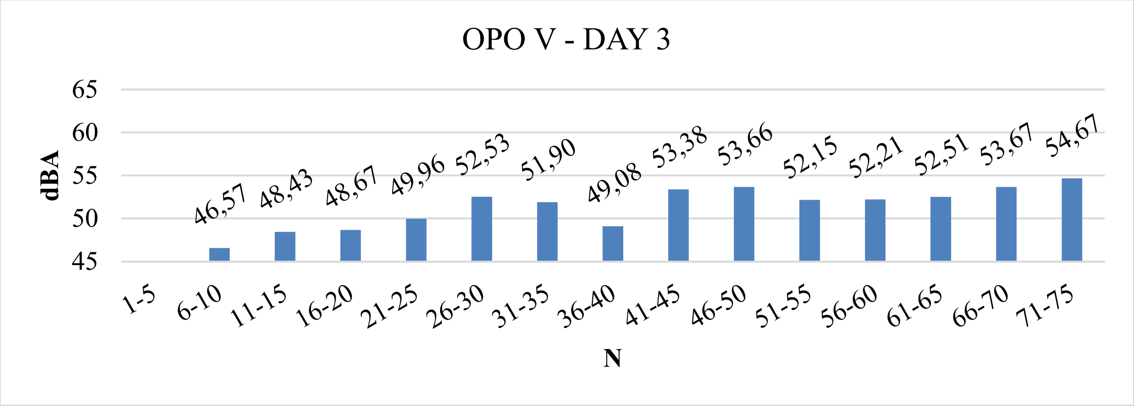
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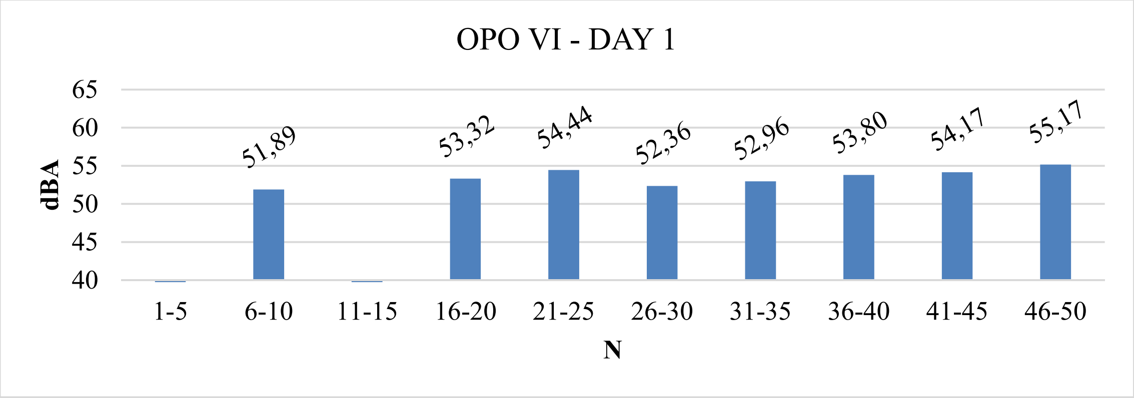
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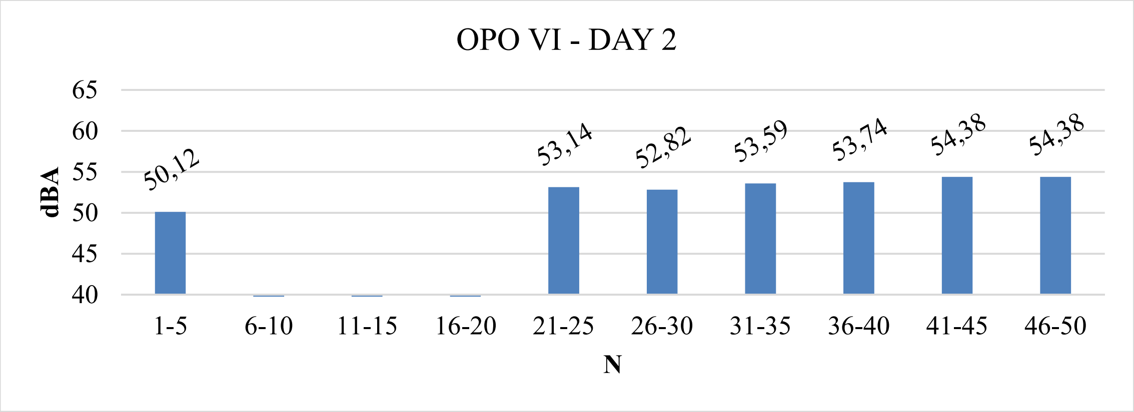
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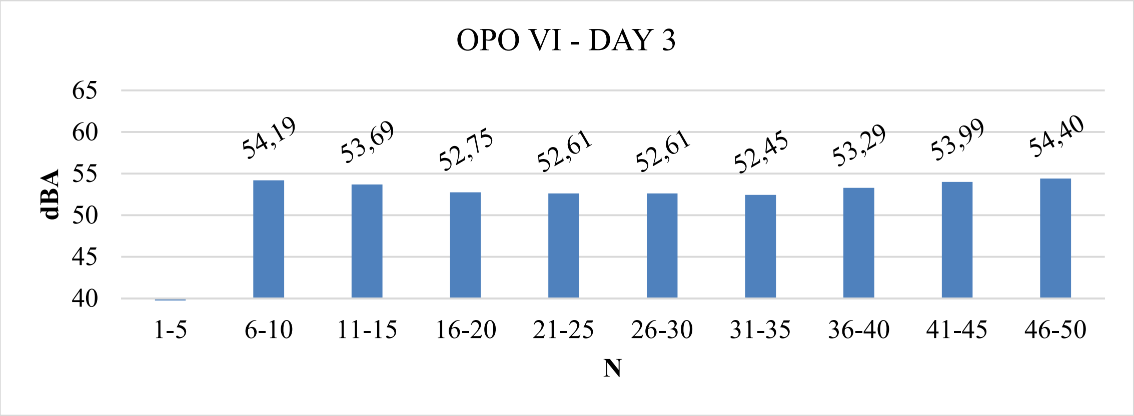
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APPENDIX B

REVERBERATION TIME MEASUREMENTS

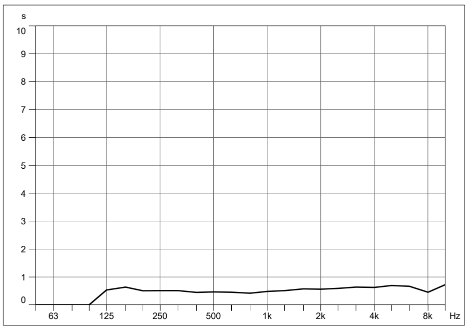

Figure B.1. OPO I Reverberation Time Measurement Graphic.

Table B.1. OPO I Frequency Based RT Measurement Results.

[Hz]	01[s]	02[s]	03[s]	04[s]	Avg.[s]	StdDev.
50	N/A	N/A	N/A	N/A	N/A	N/A
63	N/A	N/A	N/A	N/A	N/A	N/A
80	N/A	N/A	N/A	N/A	N/A	N/A
100	N/A	N/A	N/A	N/A	N/A	N/A
125	0.43	0.63	N/A	N/A	0.53	0.10
160	0.46	0.58	0.59	0.88	0.63	0.15
200	0.61	0.44	0.44	0.50	0.50	0.06
250	0.44	0.58	0.40	0.63	0.51	0.09
315	0.50	0.41	0.59	0.54	0.51	0.06
400	0.38	0.42	0.60	0.36	**0.44**	0.09
500	0.43	0.35	0.59	0.46	**0.46**	0.08
630	0.52	0.35	0.47	0.45	**0.45**	0.06
800	0.43	0.38	0.53	0.35	**0.42**	0.06
1 k	0.38	0.44	0.42	0.69	**0.48**	0.12
1.25 k	0.44	0.42	0.62	0.55	**0.51**	0.08
1.6 k	0.46	0.51	0.69	0.60	0.57	0.08
2 k	0.43	0.55	0.71	0.56	0.56	0.09
2.5 k	0.51	0.58	0.64	0.64	0.59	0.05
3.15 k	0.46	0.57	0.74	0.76	0.63	0.12
4 k	0.56	0.49	0.66	0.78	0.62	0.10
5 k	0.52	0.66	0.84	0.73	0.69	0.11
6.3 k	0.60	0.62	0.74	0.69	0.66	0.05
8 k	0.39	0.50	N/A	N/A	0.45	0.05
10 k	0.40	1.03	N/A	N/A	0.72	0.31

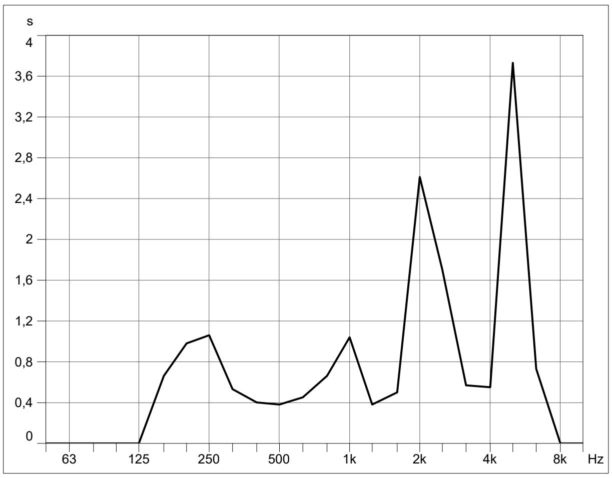

Figure B.2. OPO II Reverberation Time Measurement Graphic.

Table B.2. OPO II Frequency Based RT Measurement Results.

[Hz]	**01[s]**	**02[s]**	**03[s]**	**04[s]**	**05[s]**	**06[s]**	**Avg.[s]**	**StdDev.**
50	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
63	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
80	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
100	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
125	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
160	N/A	N/A	N/A	N/A	N/A	0.66	0.66	0.00
200	N/A	N/A	N/A	1.20	1.32	0.43	0.98	0.39
250	2.25	N/A	N/A	N/A	0.51	0.41	1.06	0.84
315	N/A	N/A	N/A	N/A	0.53	0.52	0.53	0.00
400	0.45	N/A	0.39	0.35	0.45	0.35	**0.40**	0.04
500	0.38	N/A	0.33	0.41	0.47	0.29	**0.38**	0.06
630	0.39	N/A	0.62	0.30	0.65	0.27	**0.45**	0.15
800	0.77	N/A	N/A	N/A	N/A	0.55	**0.66**	0.11
1 k	0.50	N/A	N/A	N/A	2.08	0.54	**1.04**	0.73
1.25 k	0.30	N/A	N/A	0.39	0.43	0.40	**0.38**	0.04
1.6 k	0.38	N/A	0.61	0.55	0.59	0.37	0.50	0.10
2 k	0.52	N/A	N/A	8.94	0.58	0.39	2.61	3.65
2.5 k	0.55	N/A	6.37	0.64	0.51	0.42	1.70	2.33
3.15 k	0.50	N/A	0.69	0.57	0.53	N/A	0.57	0.07
4 k	0.57	N/A	N/A	0.65	0.56	0.42	0.55	0.08
5 k	9.92	N/A	N/A	N/A	0.74	0.52	3.73	4.38
6.3 k	1.29	N/A	N/A	0.61	0.54	0.47	0.73	0.32
8 k	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
10 k	NA	N/A	N/A	N/A	N/A	N/A	N/A	N/A

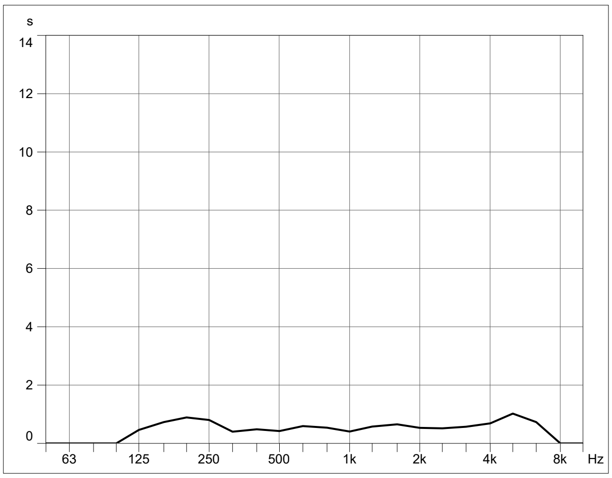

Figure B.3. OPO III Reverberation Time Measurement Graphic.

Table B.3. OPO III Frequency Based RT Measurement Results.

[Hz]	**01[s]**	**02[s]**	**Avg.[s]**	**StdDev.**
50	N/A	N/A	N/A	N/A
63	N/A	N/A	N/A	N/A
80	N/A	N/A	N/A	N/A
100	N/A	N/A	N/A	N/A
125	0.30	0.62	0.46	0.16
160	0.77	0.69	0.73	0.04
200	1.04	0.74	0.89	0.15
250	0.75	0.84	0.80	0.04
315	0.44	0.36	0.40	0.04
400	0.57	0.38	**0.48**	0.09
500	0.37	0.47	**0.42**	0.05
630	0.85	0.33	**0.59**	0.26
800	0.69	0.38	**0.54**	0.15
1 k	0.45	0.36	**0.41**	0.04
1.25 k	0.74	0.42	**0.58**	0.16
1.6 k	0.86	0.44	0.65	0.21
2 k	0.56	0.50	0.53	0.03
2.5 k	0.65	0.39	0.52	0.13
3.15 k	0.63	0.50	0.57	0.06
4 k	0.79	0.58	0.69	0.10
5 k	1.29	0.75	1.02	0.27
6.3 k	0.78	0.68	0.73	0.05
8 k	0.00	N/A	0.00	0.00
10 k	N/A	N/A	N/A	N/A

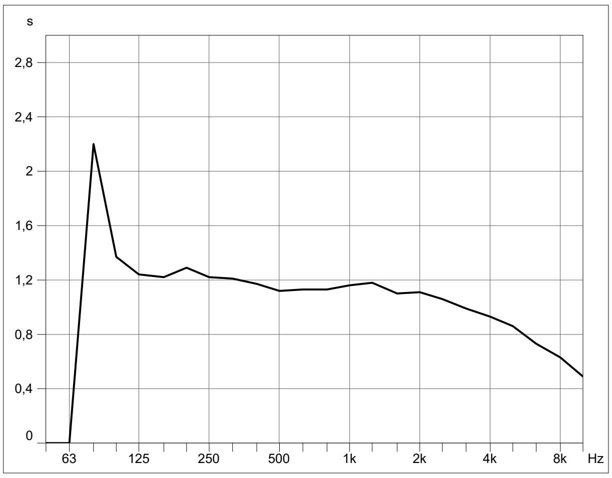

Figure B.4. OPO IV Reverberation Time Measurement Graphic.

Table B.4. OPO IV Frequency Based RT Measurement Results.

[Hz]	**01[s]**	**02[s]**	**03[s]**	**04[s]**	**Avg.[s]**	**StdDev.**
50	N/A	N/A	N/A	N/A	N/A	N/A
63	N/A	N/A	N/A	N/A	N/A	N/A
80	5.20	1.18	1.21	1.22	2.20	1.73
100	0.92	1.54	1.35	1.68	1.37	0.28
125	0.91	1.50	1.41	1.12	1.24	0.23
160	1.22	1.14	1.38	1.13	1.22	0.10
200	1.19	1.22	1.32	1.41	1.29	0.08
250	1.21	1.18	1.25	1.23	1.22	0.02
315	1.17	1.17	1.25	1.23	1.21	0.03
400	1.30	1.12	1.10	1.14	**1.17**	0.07
500	1.09	1.07	1.17	1.15	**1.12**	0.04
630	1.08	1.16	1.16	1.12	**1.13**	0.03
800	1.13	1.17	1.07	1.14	**1.13**	0.03
1 k	1.15	1.17	1.17	1.15	**1.16**	0.01
1.25 k	1.18	1.12	1.15	1.26	**1.18**	0.05
1.6 k	1.07	1.10	1.11	1.11	1.10	0.01
2 k	1.12	1.06	1.10	1.14	1.11	0.02
2.5 k	1.06	1.05	1.05	1.08	1.06	0.01
3.15 k	0.99	0.98	1.00	1.00	0.99	0.00
4 k	0.91	0.93	0.94	0.93	0.93	0.01
5 k	0.85	0.84	0.88	0.86	0.86	0.01
6.3 k	0.70	0.73	0.71	0.76	0.73	0.02
8 k	0.62	0.63	0.62	0.66	0.63	0.01
10 k	0.49	0.48	0.48	0.49	0.49	0.00

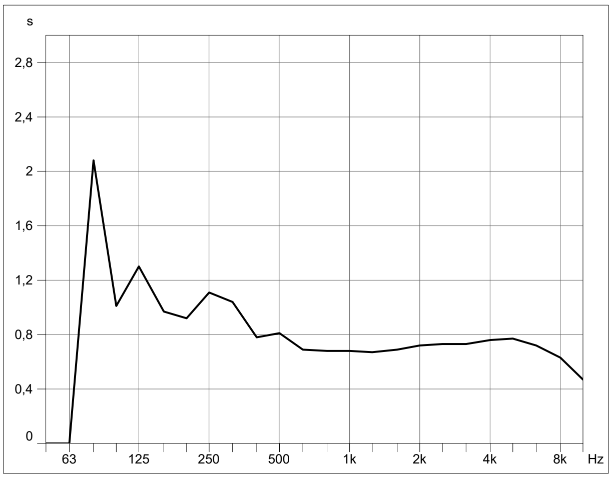

Figure B.5. OPO V Reverberation Time Measurement Graphic.

Table B.5. OPO V Frequency Based RT Measurement Results.

[Hz]	**01[s]**	**02[s]**	**03[s]**	**04[s]**	**Avg.[s]**	**StdDev.**
50	N/A	N/A	N/A	N/A	N/A	N/A
63	N/A	N/A	N/A	N/A	N/A	N/A
80	1.30	1.67	0.91	4.45	2.08	1.39
100	1.27	N/A	0.78	0.98	1.01	0.20
125	1.18	1.30	1.43	N/A	1.30	0.10
160	0.79	0.97	1.06	1.04	0.97	0.10
200	0.85	0.79	0.90	1.13	0.92	0.12
250	1.64	0.94	0.94	0.92	1.11	0.30
315	0.89	0.83	0.83	1.60	1.04	0.32
400	0.77	0.55	0.62	1.19	**0.78**	0.24
500	0.77	0.70	0.70	1.05	**0.81**	0.14
630	0.66	0.56	0.58	0.96	**0.69**	0.16
800	0.70	0.64	0.59	0.77	**0.68**	0.06
1 k	0.64	0.60	0.62	0.85	**0.68**	0.10
1.25 k	0.66	0.62	0.61	0.77	**0.67**	0.06
1.6 k	0.69	0.67	0.66	0.75	0.69	0.03
2 k	0.70	0.66	0.69	0.84	0.72	0.06
2.5 k	0.74	0.74	0.66	0.79	0.73	0.04
3.15 k	0.70	0.75	0.66	0.80	0.73	0.05
4 k	0.71	0.78	0.74	0.81	0.76	0.03
5 k	0.70	0.79	0.79	0.80	0.77	0.04
6.3 k	0.67	0.70	0.72	0.77	0.72	0.03
8 k	0.60	0.65	0.63	0.64	0.63	0.01
10 k	0.46	0.48	0.46	0.48	0.47	0.01

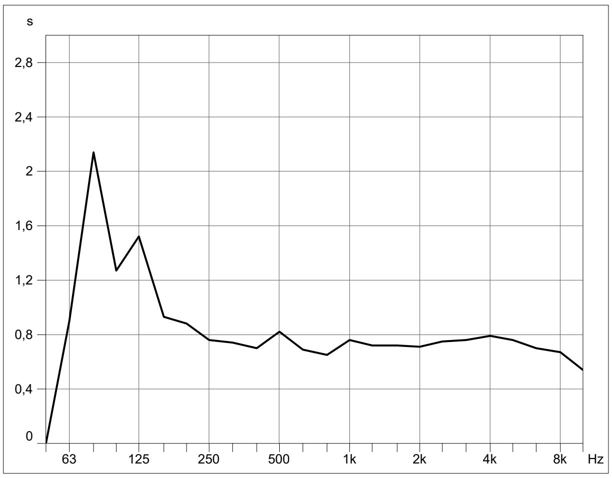

Figure B.6. OPO VI Reverberation Time Measurement Graphic.

Table B.6. OPO VI Frequency Based RT Measurement Results.

[Hz]	01[s]	02[s]	03[s]	04[s]	Avg.[s]	StdDev.
50	N/A	N/A	N/A	N/A	N/A	N/A
63	N/A	0.84	0.96	N/A	0.90	0.06
80	4.45	0.94	1.45	1.70	2.14	1.36
100	0.69	1.04	1.73	1.62	1.27	0.42
125	3.49	0.89	1.07	0.61	1.52	1.15
160	1.12	0.84	0.83	0.92	0.93	0.11
200	0.94	0.90	0.97	0.72	0.88	0.09
250	0.71	0.69	0.90	0.75	0.76	0.08
315	0.75	0.57	0.72	0.91	0.74	0.12
400	0.49	0.77	0.80	0.75	**0.70**	0.12
500	0.96	0.84	0.72	0.74	**0.82**	0.09
630	0.47	0.63	0.88	0.79	**0.69**	0.15
800	0.64	0.56	0.75	0.66	**0.65**	0.06
1 k	0.62	0.83	0.84	0.74	**0.76**	0.08
1.25 k	0.63	0.70	0.81	0.73	**0.72**	0.06
1.6 k	0.63	0.70	0.79	0.77	0.72	0.06
2 k	0.63	0.70	0.77	0.72	0.71	0.05
2.5 k	0.70	0.76	0.81	0.73	0.75	0.04
3.15 k	0.70	0.75	0.85	0.72	0.76	0.05
4 k	0.73	0.78	0.86	0.79	0.79	0.04
5 k	0.71	0.77	0.84	0.72	0.76	0.05
6.3 k	0.66	0.70	0.75	0.70	0.70	0.03
8 k	0.67	0.67	0.69	0.65	0.67	0.01
10 k	0.55	0.55	0.53	0.53	0.54	0.01

VITA

Zeynep Sevinç Karcı was born in Izmir, in 1985. She studied Interior Architecture and Environmental Designer in Ihsan Doğramacı Bilkent University and graduated in 2008. She completed her MSc degree in Interior Architecture in Yaşar University. She graduated from Izmir Institute of Technology with a PhD degree in Architecture in 2020.

Zeynep has worked as an interior architect in several design companies including in USA and in Turkey. Besides an academic background, having field experience has provided an opportunity to examine the interior design discipline from different perspectives.

Her current areas of interest include building physics, interior construction methods, and interior architecture education. Furthermore, has several publications including; SCI indexed, peer-reviewed journals, book chapter and several studies presented in national and international conferences.