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**Acoustic assessment of outdoor soundscapes through
parametric facade design: Insights from Batna 1
university**

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Dedication

*To my Parents,
my Sons and Wife,
my Brother and Sisters,
my Friends,
and my Extended Family...*

Acknowledgements

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Abstract

Serene outdoor environments promote well-being, offering reduced anxiety, better cognitive function, and therapeutic benefits. However, noise pollution from urbanization, construction, and transportation often disrupts this tranquility, affecting health, sleep, attention, and communication. The morphology of surrounding buildings significantly influences noise propagation in these spaces. This research investigates the impact of architectural morphology on acoustic characteristics in urban outdoor spaces of Batna city. Focusing on case studies at Batna 1 University, as a representative urban site, the study examines how façade design, building layouts, shapes, and configurations influence sound propagation and acoustic behavior. Additionally, it explores the effect of courtyard shape as a variable, assessing how different courtyard geometries impact acoustic parameters. The study is motivated by the lack of research in Algeria on the acoustic effects of building morphology in outdoor environments. Field measurements were conducted. Acoustic data collection involved using a starter clapper as the sound source to measure Reverberation Time (RT20), Early Decay Time (EDT), Speech Transmission Index (RaSTI), and Sound Pressure Level (SPL) attenuation. White noise produced by a directional speaker was used to analyze SPL attenuation across a broad frequency spectrum, with unweighted decibel (dB) values recorded to capture overall sound pressure levels. The findings reveal that building layout, enclosure degree, façade height, and courtyard shape significantly affect acoustic parameters. Higher façades and more enclosed layouts demonstrate longer reverberation times and distinct sound attenuation patterns. The geometry of courtyards further influences sound reflections and decay, highlighting its role in shaping outdoor acoustic environments. This research contributes to the understanding of outdoor sound environments by emphasizing the role of built environment morphology, offering valuable insights for architectural design and urban planning. The conclusions aim to provide generalizable knowledge beyond the specific case study, enriching the broader discourse on sound propagation in outdoor urban spaces.

Key words: Outdoor acoustic environment; Façade design; Building layout; courtyard shape; Noise mitigation; Acoustic comfort.

ملخص

توفر البيانات الخارجية الهادئة فوائد صحية ونفسية، حيث تقلل من القلق، وتعزز الوظائف الإدراكية، وتوفر تأثيرات علاجية. ومع ذلك، فإن التلوث الضوضائي الناتج عن التحضر وأعمال البناء ووسائل النقل غالبًا ما يعطل هذا الهدوء، مما يؤثر على الصحة والنوم والانتباه والتواصل. يؤثر شكل المباني المحيطة بشكل كبير على انتشار الضوضاء في هذه المساحات. يبحث هذا البحث في تأثير الشكل المعماري على الخصائص الصوتية في المساحات الخارجية الحضرية في مدينة باتنة. من خلال دراسة حالات في جامعة باتنة 1 كموقع حضري تمثيلي، يفحص البحث كيف تؤثر تصميمات الواجهات وتخطيطات المباني وأشكالها وتكويناتها على انتشار الصوت والسلوك الصوتي. بالإضافة إلى ذلك، يستكشف البحث تأثير شكل الفناء كمتغير، حيث يتم تقييم كيفية تأثير الأشكال الهندسية المختلفة للفناء على المعايير الصوتية. تأتي هذه الدراسة استجابةً لنقص الأبحاث في الجزائر حول تأثير شكل المباني على البيئة الصوتية الخارجية. تم إجراء قياسات ميدانية لجمع البيانات الصوتية، حيث تم استخدام "المصفق المبدئي" كمصدر صوتي لقياس زمن الارتداد (RT20) وزمن الاضمحلال المبكر (EDT) ومؤشر نقل الكلام (RaSTI) وتخفيف مستوى ضغط الصوت (SPL). كما تم استخدام ضوضاء بيضاء صادرة عن مكبر صوت اتجاهي لتحليل تخفيف مستوى ضغط الصوت عبر طيف تردد واسع، حيث تم تسجيل القيم بوحدة الديسيبل غير الموزون لالتقاط مستويات الضغط الصوتي الإجمالية. تكشف النتائج أن تخطيط المباني ودرجة الانغلاق وارتفاع الواجهات وشكل الفناء تؤثر بشكل كبير على المعايير الصوتية. إذ تؤدي الواجهات الأعلى والتخطيطات الأكثر انغلاقًا إلى أزمنة ارتداد أطول وأنماط مميزة لتخفيف الصوت. كما أن الهندسة المعمارية للفناء تؤثر على انعكاسات الصوت واندثاره، مما يبرز دورها في تشكيل البيئة الصوتية الخارجية. يساهم هذا البحث في فهم البيانات الصوتية الخارجية من خلال التركيز على دور الشكل المعماري للبيئة المبنية، حيث يوفر رؤى قيمة لتصميم المباني والتخطيط الحضري. تهدف الاستنتاجات إلى تقديم معرفة قابلة للتعميم تتجاوز الحالة الدراسية المحددة، مما يعزز النقاش الأوسع حول انتشار الصوت في المساحات الحضرية الخارجية.

الكلمات المفتاحية

البيئة الصوتية الخارجية؛ تصميم الواجهة؛ تخطيط المبنى؛ شكل الفناء؛ التخفيف من الضوضاء؛ الراحة الصوتية.

Résumé

Les environnements extérieurs sereins favorisent le bien-être en réduisant l'anxiété, en améliorant les fonctions cognitives et en offrant des effets thérapeutiques. Cependant, la pollution sonore due à l'urbanisation, aux chantiers de construction et aux transports perturbe souvent cette tranquillité, affectant la santé, le sommeil, l'attention et la communication. La morphologie des bâtiments environnants influence de manière significative la propagation du bruit dans ces espaces. Cette recherche examine l'impact de la morphologie architecturale sur les caractéristiques acoustiques des espaces extérieurs urbains de la ville de Batna. En se concentrant sur des études de cas à l'Université de Batna 1, un site urbain représentatif, elle analyse comment la conception des façades, l'aménagement des bâtiments, leurs formes et leurs configurations influencent la propagation du son et le comportement acoustique. De plus, cette étude explore l'effet de la forme de la cour comme variable, en évaluant comment différentes géométries de cour influencent les paramètres acoustiques. Cette étude est motivée par le manque de recherches en Algérie sur les effets acoustiques de la morphologie des bâtiments dans les environnements extérieurs. Des mesures de terrain ont été réalisées. La collecte des données acoustiques a impliqué l'utilisation d'un claquoir de départ comme source sonore pour mesurer le Temps de Réverbération (RT20), le Temps de Décroissance Précoce (EDT), l'Indice de Transmission de la Parole (RaSTI) et l'atténuation du Niveau de Pression Acoustique (SPL). Un bruit blanc généré par un haut-parleur directionnel a été utilisé pour analyser l'atténuation du SPL sur un large spectre de fréquences, avec des valeurs enregistrées en décibels non pondérés pour capturer les niveaux globaux de pression sonore. Les résultats révèlent que la disposition des bâtiments, le degré d'encloussement, la hauteur des façades et la forme de la cour influencent de manière significative les paramètres acoustiques. Des façades plus hautes et des agencements plus fermés entraînent des temps de réverbération plus longs et des schémas distincts d'atténuation du son. La géométrie des cours influence également les réflexions et la décroissance du son, mettant en évidence son rôle dans la formation des environnements acoustiques extérieurs. Cette recherche contribue à la compréhension des environnements sonores extérieurs en mettant en avant le rôle de la morphologie de l'environnement bâti, offrant des perspectives précieuses pour la conception architecturale et la planification urbaine. Les conclusions visent à fournir des connaissances généralisables au-delà de l'étude de cas spécifique, enrichissant ainsi le débat plus large sur la propagation du son dans les espaces urbains extérieurs.

Mots-clés : Environnement acoustique extérieur ; Conception de façade ; Disposition du bâti ; Forme de la cour ; Atténuation du bruit ; Confort acoustique.

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List of Abbreviations

RT20	Reverberation Time measured over the 20 dB decay range
SPL	Sound Pressure Level
S/N	Signal-to-Noise Ratio
RaSTI	Rapid Speech Transmission Index
INR	Impulse-to-Noise Ratio
EDT	Early Decay Time
D50	Definition Index (Clarity)
UEN	Urban Environment Noise
RNs	Registered nurses
TN	Traffic noise
RN/TN	Regional traffic noise levels
RN	Regional noise

General introduction

General introduction

1. General context and problem statement

Serene outdoor environments significantly influence people's feelings of tranquility and composure, mostly determined by the visual appeal of spaciousness and natural beauty (Yan et al., 2024). Research indicates many advantages, such as less anxiety, enhanced cognition, and increased engagement (Aspinall et al., 2015; Bratman et al., 2015). These environments also provide therapeutic experiences (Kaplan, 1995). Nevertheless, serenity may be interrupted by disruptive or unpleasant noises, resulting in adverse feelings (Yan et al., 2024). Noise pollution has emerged as the second most significant contributor to environmental degradation, primarily due to the rapid expansion of the construction and transportation sectors, along with urbanization-related social activities (World Health Organization, 2018). In a period of fast urbanization, the growing reliance on mechanization has resulted in a gradual acceptance of noise as an inevitable aspect of life (L. K. Wang et al., 2005). Noise pollution has become a significant environmental issue, with both immediate and prolonged adverse effects on human health and the ecosystem. It disrupts sleep, attention, communication, and leisure activities, resulting in both actual and perceived consequences (*Environmental Noise Guidelines for the European Region*, n.d.; Goines & Hagler, n.d.).

Universities, serving as microcosms of urban environments, have difficulties in preserving serene outdoor areas vital for students' academic success and well-being. University settings, specifically, embody an urban intricacy pertinent to this issue. The acoustic environment in cognitive performance settings, particularly on university campuses, has garnered considerable focus in the last ten years (Çolakkadioğlu et al., 2018; Goswami et al., 2011; Su et al., 2013; Xie et al., 2011; Zannin et al., 2013; Zannin & Zwirte, 2009). This phenomenon poses a threat to urban areas, particularly university campuses, adversely affecting students' behavior and comprehension. Noisy environments hinder learning, complicate instruction, and induce frustration and difficulty in concentration (Çolakkadioğlu et al., 2018; Goswami et al., 2011; Su et al., 2013; Xie et al., 2011; Zannin et al., 2013; Zannin & Ferraz, 2016; Zannin & Zwirte, 2009).

University outdoor areas are primarily aimed to preserve the restorative and relaxing experiences of students (Gulwadi et al., 2019). Nonetheless, outdoor spaces surrounded by structures are the first regions to be subjected to and affected by noise sources. Structures produce several intricate acoustic phenomena when sound propagates through the atmosphere, influencing both the transient sound levels related to Reverberation Time (RT) and the persistent noise levels, such as Sound Pressure Level (SPL), often produced by vehicular activity (Yang et al., 2013). The prevalence of reflections, diffractions, and diffusions depends on parameters like the size, irregularity, material properties, architectural configuration, and ground surfaces of the building. They may influence aural comfort for both recreation and relaxation in outdoor settings. They may also affect inside facilities, such as schools, libraries, and labs, which may be subjected to elevated background noise from such outside areas. Consequently, designing outdoor spaces with favorable acoustics may improve the overall quality of life for educational, instructional, and recreational activities.

The configuration of the built environment significantly affects the acoustic characteristics of outdoor spaces (Bouzir & Zemmouri, 2017; Guedes et al., 2011; Oliveira & Silva, 2011; Silva et al., 2014; B. Wang & Kang, 2011). Its many attributes possess the capability to alter noise levels. The configuration and organization of a building's layout, as a crucial factor, may influence the acoustic characteristics of the sound environment.

Prior study has explored the influence of architectural plan characteristics on the acoustic environment of outdoor areas. Ariza-Villaverde et al. (2014), Lee and Kang (2015), and Thomas et al. (2013) examined the influence of roadway width on building height. The results demonstrate that the H/W ratio influenced the variability of acoustic properties. Echevarria Sanchez et al. (2016) investigated the influence of building form on noise exposure in the context of the street canyon effect. The findings suggested that flat vertical, flat upwardly inclined, flat downwardly inclined, upwardly stepped convex, downwardly stepped, and concave surfaces may substantially affect people's noise exposure. The research by Eggenschwiler et al. (2022) investigated the influence of building rotation, particularly wall orientation (parallel vs nonparallel), on the feeling of noise discomfort. The rotation of the structure, resulting in non-parallel walls, was shown to correlate with less noise disturbance relative to the original orientation with parallel walls. While

the reduction in sound intensity influenced this result, the positive effect remained even when the sound levels were same for both rotating and parallel structures.

Further study has shown that several morphological components of building designs may influence the acoustic environment. The research Yang *et al.* (2013), Flores *et al.* (2017) and Yang *et al.* (2017) examine the impact of building design and arrangement on acoustic parameters like RT, EDT, D50, and RASTI, along with the reduction of sound pressure levels in outdoor environments. The layout and arrangement of the structure, including linear, square, U-shaped, and parallel forms, significantly influence the acoustic environment. Han *et al.* (2018) seeks to investigate the influence of geographical landscape characteristics on Urban Environment Noise (UEN) and traffic noise in the Shenzhen metropolitan region of China. The research demonstrated significant associations between urban form and regional traffic noise levels (RN/TN). The design and architecture of buildings significantly correlate with registered nurses (RNs). The configuration of buildings correlates with traffic noise (TN), and continuous, interconnected structures next to highways are more effective in mitigating the effects of traffic noise (TN). The dispersed arrangement and irregular shapes of structures contribute to the mitigation of regional noise (RN). Buildings are more effective in noise mitigation when distributed around urban regions, rather than being clustered in a single location.

The impact of building facade height on the sound environment has been a subject of interest in various research studies. Can *et al.* (2015) explored the influence of geometrical and acoustical parameters on sound levels, emphasizing the role of height to width (H/W) ratios in sound attenuation. Ariza-Villaverde *et al.* (2014) utilized multifractal analysis to examine the relationship between street width to building height ratio and noise pollution in urban areas. (Ismail, 2013) investigated the sound propagation characteristics of vertical greenery systems on street facades, highlighting the benefits of installing greenery for sound attenuation. F. Liu and Kang (2018) studied the effects of different facade configurations on acoustic comfort in urban settings. Thomas *et al.* (2013) and Magrini and Lisot, (2016) also contributed insights on the relationship between building facade height and sound levels. Furthermore, Dragna *et al.* (2022) and Xu & Xu (2018) explored the impact of building height on noise reflection and aeroacoustic performance, respectively. Naish *et al.* (2013) developed a regression model to predict speech

interference levels on residential balconies exposed to road traffic noise. These studies collectively contribute valuable insights into understanding the complex relationship between building facade height and the sound environment.

Courtyards are highly effective in shielding outdoor spaces from background noise, particularly from external sources like traffic (Yang et al., 2017). Their enclosed or semi-enclosed geometry helps block noise intrusion and create a controlled acoustic environment. This design significantly reduces external noise levels, often by 4–9 dB(A), depending on the building layout and facade height (Bakker et al., 2023). However, while reducing background noise improves comfort, it also increases the signal-to-noise ratio (S/N) for internal sounds such as human conversation and pedestrian noise. This heightened sensitivity to internal sounds necessitates the use of acoustic materials to maintain a balanced acoustic environment (Yang et al., 2017).

Several architectural factors influence the acoustic performance of courtyards. The height of surrounding buildings affects noise shielding, as taller façades can effectively block external noise but may also lead to prolonged reverberation if not properly treated (Hamouta et al., 2024). The material properties of courtyard surfaces play a crucial role, with highly reflective materials amplifying sound reflections and increasing reverberation time (RT), whereas absorptive materials help control reflections (Crippa et al., 2019; Eggenschwiler et al., 2024). Additionally, façade articulation impacts sound diffusion—smooth, flat surfaces promote strong reflections, while textured façades scatter sound, improving acoustic comfort (Badino et al., 2021). Integrating green walls and vegetation further enhances courtyard acoustics, as greenery acts as a natural sound absorber, reducing reflections and mitigating high-frequency noise. By carefully considering these factors, courtyards can be optimized to function as effective noise barriers while maintaining a comfortable and balanced outdoor acoustic environment (Bakker et al., 2023).

Research on urban spatial arrangement and environmental soundscapes in Algerian settings underscores the influence of urban form on acoustic environments. Benameur et al. (2021) established a robust correlation between recorded sound levels and Space Syntax indices in Pisa, Italy, and Biskra, Algeria. Subsequent study in Biskra highlighted the deficiency of acoustic data for Saharan urban design and shown a favorable association between spatial metrics and noise

patterns (Benameur, 2023). Research conducted on an oasis university campus (Berkouk et al., 2022) shown that building design may obscure mechanical noise and improve natural soundscapes, highlighting significant connections between luminous and auditory environments. Subsequent research in Biskra highlighted the influence of urban morphology on the distribution of road noise (Bouzir & Zemmouri, 2017) and categorized soundscapes into Hi-Fi and Lo-Fi depending on traffic noise levels (Bouzir et al., 2020). Further examinations revealed significant noise pollution in the historic urban zones of Biskra, with more than 90% of measures above international noise standards (Bouzir & Zemmouri, 2018). Research on public places correlated elevated mechanical flow with heightened loudness and discomfort, emphasizing the impact of urban design on acoustic settings (Benameur et al., 2022).

The study of outdoor acoustic environments in university campuses has gained increasing attention due to their impact on the quality of life and the acoustic comfort of users. While outdoor spaces in universities may share similarities with urban streets, squares, and other built-up regions, they exhibit distinct characteristics shaped by their diverse layouts, building types, and spatial configurations. These variations influence sound propagation patterns in unique ways, driven by differences in building arrangements, materials used, and façade designs. Understanding these specific environments requires a focused approach, as their architectural and spatial characteristics contribute uniquely to the acoustic properties of outdoor areas.

Despite valuable research on the relationship between building façade height and sound environments, existing studies often focus on general urban settings, such as streets and open squares. These studies, while informative, may not fully capture the complexities of sound propagation in more enclosed spaces like university courtyards. Factors such as surrounding landscape, urban layout, and the enclosed nature of courtyard settings play a significant role in shaping acoustic behavior, requiring further investigation to understand their specific influence.

Moreover, a notable gap remains in exploring the acoustic impacts of building morphologies and spatial configurations on university campuses in Algeria. Most existing research tends to overlook the detailed analysis of enclosed courtyard environments and their unique contribution to sound propagation characteristics. Addressing these gaps calls for dedicated studies that focus on the

specific architectural and environmental context of Algerian university campuses, providing a more nuanced and comprehensive understanding of their outdoor acoustic environments.

Despite growing interest in outdoor acoustics, existing studies primarily focus on noise control strategies without adequately considering the spatial and morphological characteristics of built environments. Research on the impact of façade configurations, building heights, building layouts and courtyard shape on outdoor sound environments remains limited, particularly in Algerian urban settings. Understanding these interactions is essential for improving acoustic comfort in dense urban areas, yet comprehensive empirical studies and predictive models addressing this issue are scarce. This research aims to fill this gap by analyzing how architectural elements influence sound propagation and noise attenuation in enclosed urban courtyards.

The University of Batna 1 serves as a key case study for this research, not only due to its role as an academic institution but also because of its urban setting and architectural composition. The campus is situated within a dense metropolitan environment, surrounded by a mix of academic, residential, and commercial areas. Its layout features multiple outdoor spaces and courtyards enclosed by varying building arrangements and multi-story structures with diverse façade designs, making it an ideal model for studying the acoustic impact of built morphology. These configurations effectively shield noise from external sources, such as traffic; however, they can also amplify internal noise due to sound reflections, leading to acoustic discomfort in outdoor spaces. Additionally, this noise buildup can extend into indoor spaces and facilities, such as schools, libraries, and laboratories, which can experience increased background noise from external environments, particularly when windows are open due to the increasingly hot climate in Batna city in recent years.

The presence of a high student population, road networks, and open spaces contributes to a complex sound environment, offering a rich context for investigating outdoor noise propagation and control strategies. Understanding the interaction between university structures and their surrounding urban fabric is crucial for developing guidelines that enhance acoustic comfort in similar educational and institutional settings.

Our research focuses on 'Toward Better Outdoor Acoustics in Algerian Universities,' specifically looking at the campus of Batna 1 University. It aims to explore how architectural configuration influences the quality of the outdoor acoustic environment. Therefore, The main concerns of the present research are:

In this context, the study is guided by the following questions:

- How does the current façade configuration influence the nearby outdoor acoustic environment within Batna 1 University?
- What is the impact of façades shaped by the building layout on the behavior of sound characteristics?
- What role do façade heights play in defining the soundscape of these outdoor spaces?
- How does the form of the courtyard affect sound propagation in the outdoor environments of Batna 1 University?

Together, these questions aim to provide a comprehensive understanding of how architectural morphology—through façade design, height, and courtyard form—affects the acoustic performance of semi-enclosed and enclosed outdoor spaces in university settings.

Based on the research questions, the following hypotheses are proposed to guide the study:

- The current façade configuration at Batna 1 University significantly influences the outdoor acoustic environment by altering sound reflection, diffusion, and attenuation patterns.
- Façades shaped by the building layout affect the behavior of sound characteristics, leading to variations in reverberation time, speech intelligibility, and sound pressure levels.
- The height of façades contributes to the overall soundscape quality by modifying reflection paths and increasing the persistence of reverberation in semi-enclosed areas.

- The geometric form of courtyards influences sound propagation, with more elongated layouts allowing faster sound decay than compact, square-shaped spaces.

2. Research Aims and Objectives

This thesis seeks to explore the effects of urban building layouts on outdoor sound environments, with a particular focus on façade configurations, courtyard geometries, and sound propagation mechanisms. The main objectives of the study are:

- To investigate how building layout and urban morphology influence outdoor acoustic environments, focusing on their effects on sound propagation and spatial acoustic characteristics.
- To evaluate the role of building façades and urban morphology in shaping outdoor acoustic environments, considering their impact on sound reflections, absorption, and diffusion.
- To examine the influence of courtyard shapes and urban morphology on outdoor acoustic environments, analyzing their effects on sound propagation, reflection patterns, and overall acoustic performance.
- To analyze sound propagation and attenuation in enclosed and semi-enclosed urban courtyards through in situ field measurements, identifying key acoustic trends and spatial variations.
- To assess the effects of reverberation time (RT), speech intelligibility indices (RaSTI, D50), and sound pressure level (SPL) across different outdoor space configurations, establishing their role in acoustic comfort.
- To develop architectural guidelines for optimizing outdoor soundscapes in urban settings, integrating insights from façade design, courtyard geometry, and urban morphology.

3. Thesis Outlines

In order to address the proposed objectives, this research will be developed across 04 chapters, constructing a comprehensive understanding of how building layout and façade design influences the outdoor sound environment, defined as follows:

We begin with Chapter 1, which sets the stage by offering a critical analysis of existing research on outdoor acoustic environments. It explores sound propagation theories and examines the role of architectural morphology in noise control. Through a review of various methodologies and assessment techniques, this chapter highlights their strengths, limitations, and applicability across different urban contexts.

Chapter 2 takes us deeper into the urban soundscape, focusing on the sources of noise that shape outdoor environments. It investigates the impact of traffic, mechanical noise, and human activity on acoustic quality and well-being, while also evaluating strategies for noise mitigation and control.

The Chapter 3, the study's methodology, details the research design, data collection techniques, and analysis methods used in the study. It describes the selection of case study sites, the use of in situ measurements, and the application of advanced acoustic analysis software. Special attention is given to weather conditions, measurement standardization, and equipment calibration to ensure the reliability of results.

Chapter 4 presents the findings from measurements conducted at Batna 1 University. This chapter brings together the data on key acoustic parameters such as reverberation time (RT20), early decay time (EDT), sound pressure level (SPL) attenuation, and speech intelligibility indices like RaSTI. Through thoughtful discussion, these results are interpreted in relation to architectural design strategies and their broader urban planning implications.

Finally, the Conclusion and Future Work part synthesizes the research findings and translates them into practical recommendations for urban planners and architects. By summarizing key insights and proposing directions for future research, this chapter underscores the study's contribution to

the field and its potential to shape more acoustically comfortable and environmentally responsive urban spaces.

4. Methodology Overview

To achieve these objectives, this research employs an in situ measurement approach, focusing on real-world data collection within the University of Batna 1's outdoor spaces. In situ measurements are conducted to capture real-time acoustic data under natural environmental conditions, ensuring high reliability and contextual accuracy. This approach allows for the direct assessment of how sound propagates and attenuates in enclosed courtyards.

Key elements of the in-situ measurement methodology include:

- **Measurement Equipment:** Using specialized and omnidirectional measurement microphones, impulse sound sources to accurately capture acoustic parameters such as RT, , RaSTI, and D50 and directional speaker for SPL.
- **Measurement Locations:** Selecting multiple courtyard configurations with varying façade heights and layouts to compare sound behavior across different architectural settings.
- **Measurement Conditions:** Conducting tests under controlled environmental conditions (e.g., low wind speeds, minimal background noise) to ensure consistency and reliability.
- **Data Analysis:** Processing measurement results using specialized acoustic analysis software to evaluate sound decay, reflection patterns, and intelligibility indices.

By relying solely on **in situ field measurements**, this research provides a **realistic and empirical** understanding of the acoustic performance of urban courtyards.

Chapter 1

State of the art of Approaches and Methods for Outdoor
Acoustic Assessment in the Built Environment

Chapter 1: State of the art of Approaches and Methods for Outdoor Acoustic Assessment in the Built Environment

1. Introduction

The acoustic environment of urban outdoor spaces has become an increasingly critical area of study, driven by growing urbanization, rising noise pollution, and the need for sustainable and livable cities. This chapter provides a comprehensive review of the existing literature, focusing on the evaluation, control, and mitigation of outdoor noise, as well as the methodologies employed to assess these environments. It sets the foundation for understanding how sound behaves in complex urban settings and identifies key strategies to improve acoustic comfort, particularly in contexts relevant to this research.

The chapter begins with an exploration of evaluation approaches for outdoor acoustic environments, emphasizing the two primary frameworks: the soundscape approach, which focuses on subjective human perception, and the noise control approach, which targets objective acoustic measurements and mitigation techniques. These approaches provide a dual perspective for assessing and managing urban acoustic environments.

To understand the methodologies used in acoustic research, the chapter examines assessment techniques, including field measurements (in situ), scale-model experiments, and computer simulations. Each method's advantages and limitations are analyzed, offering insights into their applicability for different research contexts.

Figure 1-1 presents the conceptual framework of this study. It illustrates the relationship between building morphology, assessment methods, noise parameters, and sound sources, all within the broader context of the urban outdoor sound environment and university settings. By providing a detailed and structured overview, this chapter serves as a foundation for the research, linking theoretical knowledge with practical applications to advance understanding and management of outdoor acoustic environments.

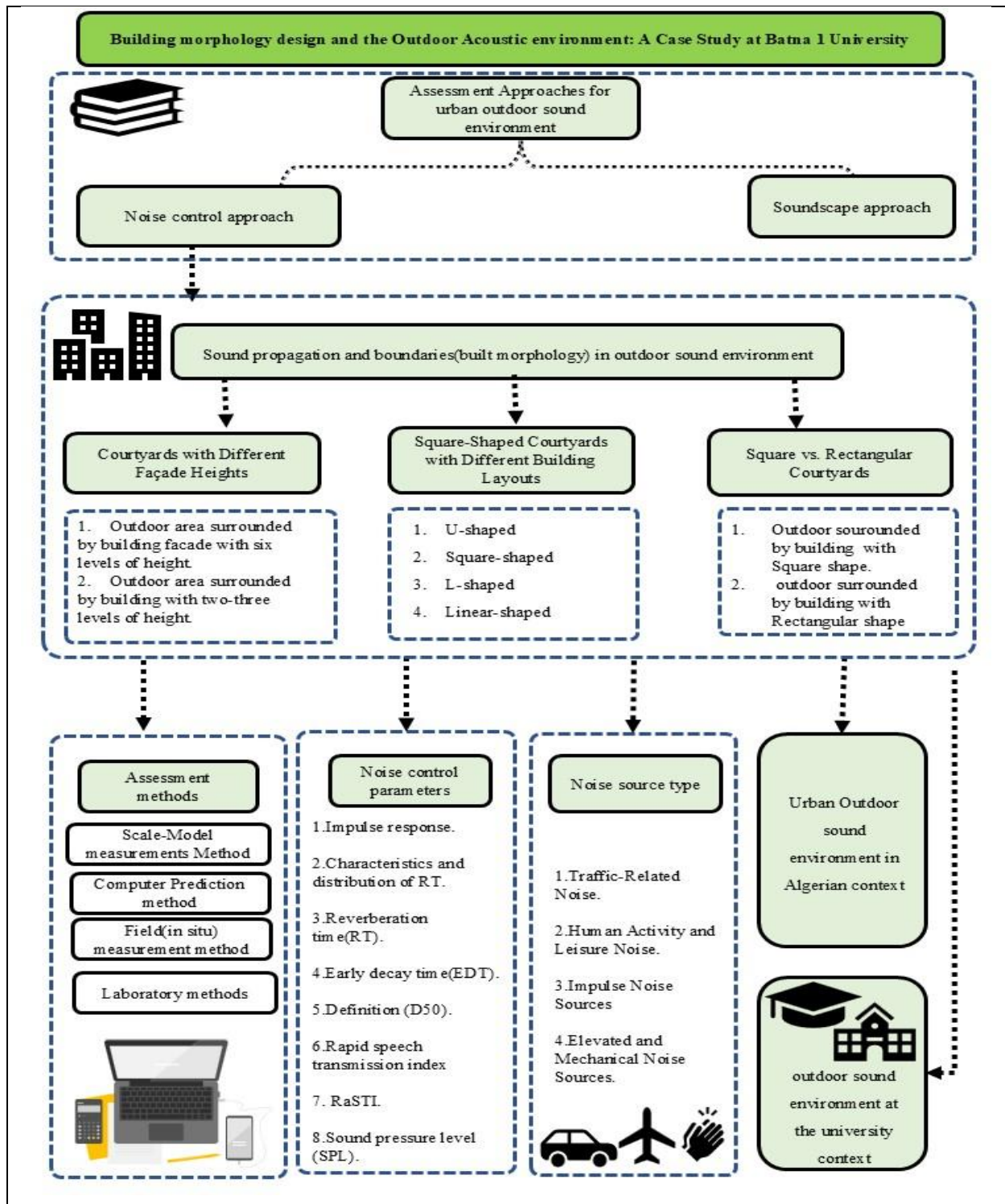


Figure 1-1:Conceptual frame work. Source: (author).

2. Evaluation approach for urban outdoor acoustic environments

Soundscape and noise control approaches offer complementary perspectives for managing urban noise. While soundscape approaches prioritize the subjective experience of sound environments, noise control emphasizes objective noise reduction. This section reviews these theoretical frameworks and discusses their implications for outdoor sound management, providing a basis for integrating these approaches into façade design and urban planning. Table 1-1 presents an overview of research studies related to the evaluation approaches for urban outdoor acoustic environments and have a relevance to this research, highlighting their relevance to this study. These studies encompass various methodologies and perspectives, including noise control strategies and soundscape assessments. Many focus on the role of building façades, vegetation, shading systems, and urban morphology in shaping acoustic environments. The research spans multiple journals and databases, demonstrating a broad and interdisciplinary approach to understanding urban acoustics. By synthesizing these studies, this research builds upon existing knowledge to further explore the relationship between architectural design and outdoor sound environments.

Table 1-1

Overview of evaluation approaches for urban outdoor acoustic environment.

Author	Research Title	Journal Title	Database	Research approach
(Van Renterghem et al., 2013)	The potential of building envelope greening to achieve quietness	Building and Environment	Science Direct	Soundscape/noise control
(Sakamoto & Aoki, 2015)	Numerical and experimental study on noise shielding effect of eaves/louvers attached on building façade	Building and Environment	Science Direct	Noise control
(Jang, Kim, et al., 2015)	Scale-model method for measuring noise reduction in residential buildings by vegetation	Building and Environment	Science Direct	Noise control

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(Jang, Lee, et al., 2015)	Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model	The Journal of the Acoustical Society of America	Silverchair	Noise control
(Zuccherini Martello et al., 2015)	The Use of Sound Absorbing Shading Systems for the Attenuation of Noise on Building Façades. An Experimental Investigation	Buildings	www.mdpi.com	Noise control
(Lee & Kang, 2015)	Effect of Height-To-Width Ratio on the Sound Propagation in Urban Streets	Acta Acustica United With Acustica	discovery.ucl.ac.uk	Noise control
(X. Wang et al., 2015)	Acoustic performance of balconies having inhomogeneous ceiling surfaces on a roadside building facade	Building and Environment	Science Direct	Noise control
(Zuccherini Martello et al., 2016)	A Psychoacoustic Investigation on the Effect of External Shading Devices on Building Facades	Applied Sciences	www.mdpi.com	Noise control
(Magrini & Lisot, 2016)	A simplified model to evaluate noise reduction interventions in the urban environment	Building Acoustics	SAGE Journals	Noise control
(X. Wang et al., 2017)	Effects of ceiling phase gradients on the acoustic environment on roadside balconies	The Journal of the Acoustical Society of America	Silverchair	Noise control
(Calleri et al., 2018)	Evaluation of the influence of building façade design on the acoustic characteristics and auditory perception of urban spaces	Building Acoustics	SAGE Journals	Noise control/sound scape
(F. Liu & Kang, 2018)	Relationship between street scale and subjective assessment of audio-visual environment comfort based on 3D virtual reality and dual-channel acoustic tests	Building and Environment	Science Direct	Soundscape
(Fausti et al., 2019)	The use of façade sun shading systems for the reduction of indoor and outdoor sound pressure levels	Building Acoustics	SAGE Publication s Inc.	Noise control

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(Tang et al., 2019)	Insertion loss of asymmetrical balconies on a building façade	The Journal of the Acoustical Society of America	Silverchair	Noise control
(Badino et al., 2019)	Effect of façade shape and acoustic cladding on reduction of leisure noise levels in a street canyon	Building and Environment	Science Direct	Noise control
(Taghipour et al., 2019)	Acoustic Comfort in Virtual Inner Yards with Various Building Facades	International Journal of Environmental Research and Public Health	www.mdpi.com	Soundscape
(Crippa et al., 2019)	Façade Engineering and Soundscape			soundscape
(Bouzir et al., 2020)	Evaluation and Analysis of the Algerian Oases Soundscape: Case of El Kantara and Sidi Okba	Acoustics Australia	Springer Link	Soundscape
(Eggenschwiler et al., 2022)	Urban design of inner courtyards and road traffic noise: Influence of façade characteristics and building orientation on perceived noise annoyance	Building and Environment	Science Direct	Soundscape

2.1. Soundscape approach

As highlighted in Table 1-1, some studies adopt the soundscape approach to evaluate urban outdoor acoustic environments. The soundscape approach is a vital aspect of understanding outdoor acoustic environments. Therefore, the soundscape approach for evaluating outdoor sound environments emphasizes the subjective experience of individuals in relation to their acoustic surroundings. This method contrasts with traditional noise control approaches, which often focus solely on quantifying sound levels and minimizing noise pollution.

The word "soundscape" has been extensively embraced in both academic and popular domains outside its initial context of human perception (Mitchell et al., 2024, p. 695). The term "soundscape" refers to the acoustic environment that is experienced by humans inside a particular

setting. Michael Southworth was the one who first came up with the word (Southworth, 1969), but R. Murray Schafer was the one who brought it to widespread use. Schafer highlighted the significance of understanding sound as a component of the environment that influences human experience. According to Schafer, the soundscape is comprised not just of the sounds themselves but also of the manner in which these sounds are structured in space and time. This results in an immersive auditory experience that has an effect on both perception and behavior (Schafer, 1980).

The concept of soundscape includes three primary categories of sound sources (Grinfeder et al., 2022):

- **Biophony:** The sounds produced by non-human organisms, such as animal vocalizations.
- **Geophony:** Natural sounds generated by non-biological elements, including wind, water, and geological activity.
- **Anthrophony:** Sounds created by human activities, which can range from speech and music to industrial noises

Importantly, the soundscape is not merely a collection of sounds; it is influenced by the listener's context and perception. As noted by Truax (1980), the soundscape reflects "*how that environment is understood by those living within it*", highlighting the subjective nature of sound perception. The International Organization for Standardization (ISO) has also standardized definitions related to soundscapes, reinforcing their significance in various fields such as urban design, ecology, and acoustic research. The ISO defines soundscape as "*the acoustic environment as perceived*" and emphasizes its contextual nature (Mitchell et al., 2024). The soundscape approach focuses on how individuals perceive and interpret their acoustic environments, distinguishing it from traditional noise management, which often views sound primarily as a nuisance to be minimized (Brown, 2014).

Therefore, the soundscape approach for evaluating outdoor sound environments emphasizes the subjective experience of individuals in relation to their acoustic surroundings. This method contrasts with traditional noise control approaches, which often focus solely on quantifying sound levels and minimizing noise pollution. The soundscape approach is based on the premise that

sound is not only a pollution, but may be seen as a resource that enhances quality of life. This viewpoint advocates assessing sounds according to their impact on human perception and emotional reactions, rather than only their physical characteristics. The ISO definition states that a soundscape includes the noises a human may conceive, perceive, or comprehend within a certain situation (J. Liu et al., 2024).

2.1.1. Dimensions of Soundscape Assessment

Research has identified several key dimensions that characterize outdoor soundscapes (Figure 1-2), shaping how people perceive and interact with their acoustic environment soundscapes (G. Zhu et al., 2023; P. Zhu et al., 2021). One of these dimensions is relaxation, which reflects the calming and soothing qualities of certain sounds. Natural elements such as birdsong, rustling leaves, or flowing water often enhance this perception, creating a sense of tranquility in outdoor spaces. Another important dimension is communication, which highlights the role of sound in facilitating social interactions. Human voices, laughter, and conversational noise contribute positively to this aspect, reinforcing the social function of public spaces. Lastly, quietness plays a crucial role in shaping soundscape perception. It represents the absence of disruptive or unwanted noise, fostering a more pleasant and comfortable acoustic environment. A quieter setting can enhance overall satisfaction with an outdoor space, making it more conducive to relaxation and social engagement.

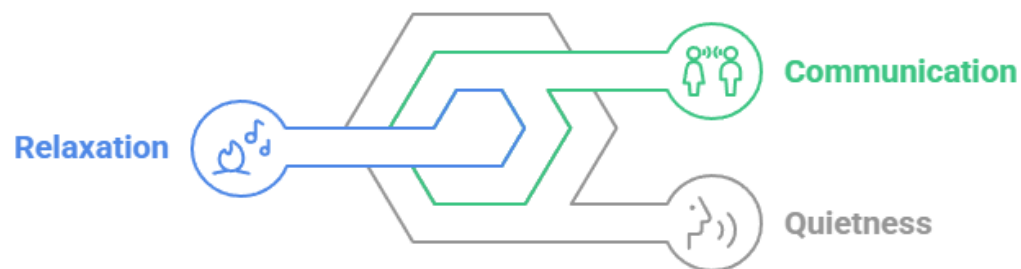


Figure 1-2: *Dimensions of Soundscape Assessment. source:(author)*

Studies show that these dimensions are influenced by various factors, including community layout and the presence of natural versus artificial sounds. For instance, enclosed communities often exhibit lower traffic noise and higher levels of human sounds, leading to increased relaxation and reduced feelings of annoyance.

The insights that are obtained from soundscape evaluations have the potential to have a significant impact on urban planning and design. By understanding the impact of various sounds on human experience, urban planners can create environments that optimize auditory comfort, promote well-being, and enhance the overall sensory experience in public spaces. This may involve increasing the biodiversity of urban surroundings in order to encourage the production of natural sounds or deliberately putting impediments in order to reduce the amount of noise that is not acceptable (Brown, 2012; J. Liu et al., 2024; Tarlao et al., 2019).

2.1.2. Studies applied in urban soundscape

The urban soundscape is a crucial aspect of urban design, with studies examining how to improve perceived acoustic environments using building envelopes and street design. Four studies followed the same approach and method, focusing on improving perceived acoustic environment using building envelopes and street design. However, they differed in terms of the sites they were conducted on (Figure 1-3).

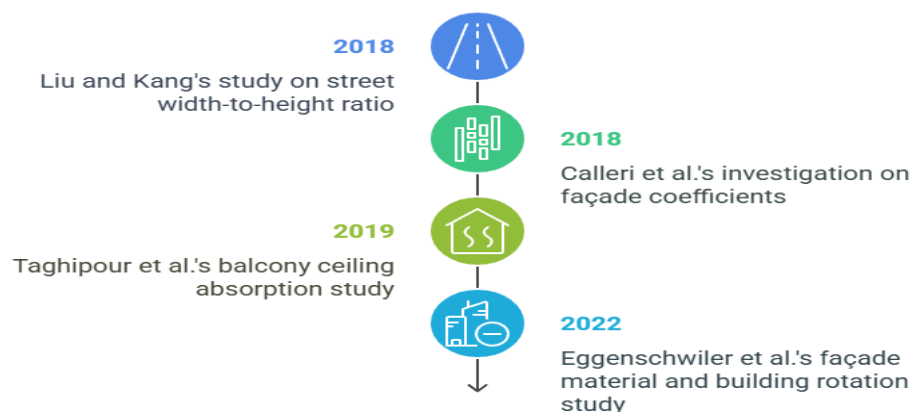


Figure 1-3: Soundscape Approach Applications in Research. Source: (author)

The effect of façade on the soundscape was studied with different variables, such as façade elements, indicators for measuring perception, and the kind of places they were conducted on. Liu and Kang (2018) found a strong positive correlation between audio-visual comfort and the street width-to-height ratio, with respondents finding the audio-visual level most comfortable when the ratio is greater than 1, street width is within 20 m, height of street buildings is less than 26 m, and the sound level is less than 58 dBA.

Calleri et al. (2018) investigated the effect of different absorption and scattering coefficients of façade upholsteries on soundscape, measuring subjective spatial wideness with different physical properties of sound. They found that the absorption coefficient of façades has an influence on the subjective perception of space wideness.

Taghipour et al. (2019) applied another element of façade, the absorption of the ceiling of balcony, to measure perception comfort. The results showed that moderate absorption of the facade increased acoustic comfort, and absorbing balcony ceilings tended to improve acoustic comfort. Significant differences were observed between acoustic comforts at distinct observer positions, which could be exploited when designing inner yards.

Eggenschwiler et al. (2022) conducted a study on the effects of façade surface material (sound reflecting, absorbing or diffusing) and building rotation (parallel vs. nonparallel walls) on perceived noise annoyance in a residential area. The study involved artificially generating moving passenger cars and using loudspeakers to spatially reproduce the stimuli. Results showed that absorbing façades were associated with lower noise annoyance than reflecting or diffusing façades due to reduced sound pressure level. However, these façades were perceived as more annoying, indicating unfavorable acoustical quality. Building rotation, resulting in nonparallel walls, was associated with lower noise annoyance compared to the original parallel-wall building orientation. This was due to reduced sound level, but the positive effect tended to remain even when the level was the same for rotated and parallel buildings. The study highlights the importance of façade surface material and building rotation in optimizing the sound environment of inner courtyards. Building rotation, whether parallel or nonparallel, can be an important architectural feature to consider when designing residential spaces.

2.1.3. Challenges

Despite the advantages of the soundscape approach for evaluating outdoor sound environments, several challenges persist that hinder its broader application and effectiveness:

- **Subjectivity:** Individual perceptions of sound can vary significantly based on personal experiences, cultural backgrounds, and contextual factors. This variability complicates the standardization of assessments and the establishment of universally applicable soundscape descriptors. While subjective experiences are integral to understanding soundscapes, the lack of standardized assessment tools presents challenges in comparing results across studies. This variability complicates the development of universally applicable soundscape metrics (Aletta & Xiao, 2018; Kang, 2021).
- **Dynamic Nature:** Outdoor sound environments are inherently dynamic, changing with time, weather conditions, and human activity. This variability poses challenges for capturing a consistent picture of a soundscape at any given moment. As noted in recent literature, the temporal aspects of soundscapes need to be better understood to accurately assess their impact on human perception and behavior. The fluctuating nature of sounds makes it difficult to establish reliable data that can inform design and planning effectively (Aletta & Xiao, 2018; Chen et al., 2024).

2.2. Noise control approach

As shown in Table 1-1, many studies adopt the noise control approach, which focuses on strategies and methodologies aimed at reducing noise pollution and its impacts on individuals and communities. This approach is particularly relevant in urban settings where noise can significantly affect quality of life, health, and well-being. Below is an overview of the noise control approach, including its principles, methods, and applications.

The noise control approach, also referred to as noise abatement, is characterized by its focus on managing sound as a waste product that needs to be reduced and controlled (Kang, 2007). According to Truax (1984), this approach is traditionally objective and energy-based, emphasizing

the need to mitigate environmental noise through various strategies. This includes managing noise at its source, along its propagation path, or at the receiver level. The aim is to minimize discomfort caused by unwanted sounds, which can lead to adverse effects such as sleep disturbance, annoyance, and physiological issues (Brown, 2010).

In contrast to the soundscape approach, which views sound as a resource to be utilized and enhanced for quality of life, the noise control approach prioritizes the reduction of sounds that are perceived as detrimental. As such, it encompasses various methods and techniques aimed at achieving effective noise reduction and management in both outdoor and indoor environments.

2.2.1. Key Components of Noise Control

Effective noise control relies on a combination of strategies that address different aspects of sound generation and transmission. These strategies can be categorized into three main approaches: controlling noise at its source, managing its transmission path, and protecting the receiver from excessive exposure (Brown & Muhar, 2004). Figure 1-4 summarizes the main strategies for the noise control approach.

One of the most effective ways to mitigate noise is by addressing it directly at its origin. This approach involves reducing or eliminating noise generation before it spreads. A key method is the use of quieter equipment, where machinery is specifically designed to operate at lower noise levels, thereby minimizing disturbances (Noise Management - Noise Control Ordinance, n.d.). Additionally, engineering modifications play a crucial role in noise reduction. By integrating sound-dampening materials and optimizing designs to limit vibration, unwanted noise can be significantly diminished (Government of Canada, 2024).

When noise cannot be eliminated at the source, modifying its transmission path becomes essential. This strategy focuses on disrupting the propagation of sound before it reaches sensitive areas. One common solution is the construction of sound barriers, such as walls or fences, which effectively block or deflect sound waves, reducing their impact on nearby environments (NSW, 2023).

Another technique involves the use of absorptive materials, which help to dissipate sound energy, minimizing reflections and reverberations that could amplify noise levels (Calleri et al., 2018).

Even with source control and path management, some noise inevitably reaches individuals, making receiver protection a crucial aspect of noise control. Personal protective equipment (PPE), such as earplugs or earmuffs, provides a direct means of reducing noise exposure for individuals working in high-noise environments (Noise Management - Noise Control Ordinance, n.d.; World Health Organization, 2018).

Beyond physical protection, administrative measures can also be implemented to minimize exposure. Policies that regulate the duration of noise exposure, such as rotating work shifts or limiting time spent in high-noise areas, help to mitigate the long-term effects of sound-related hazards (Government of Canada, 2024).

By integrating these three strategies—source control, path management, and receiver protection—effective noise control measures can be developed, ensuring safer and more comfortable environments for individuals and communities. To mitigate the noise, the sound treatment can be in many scales and strategies: control at the source, management of the transmission path between source and receiver, and protection of the receiver (Brown & Muhar, 2004).



Figure 1-4: Key Components of Noise Control. Source: (author)

Importance of the Noise Control Approach in Outdoor Sound Environment Assessment

The noise control approach plays a critical role in assessing outdoor sound environments, particularly in urban settings where noise pollution can significantly affect the quality of life for residents, workers, and wildlife. Figure 1-5 presents several key reasons why this approach is essential.

Effective noise control measures help mitigate the health impacts associated with excessive noise exposure, such as stress, sleep disturbances, and cardiovascular issues. Monitoring outdoor noise levels allows for the identification of harmful noise sources and the implementation of strategies to reduce exposure (Acoustics, 2023).

Many regions have established regulations governing acceptable noise levels in outdoor environments. Conducting thorough noise assessments ensures compliance with local regulations and helps avoid potential fines or legal issues (Department of Environment, Climate Change and Water NSW, 2009). Regular monitoring and assessment are crucial for maintaining adherence to these standards.

Noise assessments contribute to enhancing the overall quality of life in communities by identifying and addressing existing noise problems. By understanding the impact of noise on residents, effective management strategies can be developed to create more pleasant living conditions (SOCOTEC, 2024).

Outdoor sound assessments are not only important for human health but also for protecting local wildlife. Excessive noise can disrupt animal behavior, communication, and habitats. By evaluating outdoor sound environments, strategies can be implemented to minimize noise pollution's impact on ecosystems (Papanagiotou, 2020).

Noise assessments provide valuable data that can inform urban planning decisions. Understanding the prevailing noise climate helps planners design spaces that minimize noise exposure for residents and enhance the overall acoustic environment (NSW, 2023). This is particularly important when considering new developments or modifications to existing sites.

The use of predictive modeling in noise assessments allows for better planning and management of future noise impacts from construction projects or changes in land use. By simulating potential noise scenarios, stakeholders can make informed decisions about mitigation measures before issues arise (SOCOTEC, 2024).



Figure 1-5: *Noise control outcomes. Source: (author)*

2.2.2. Studies applied in urban outdoor environment

Research on noise control in urban outdoor environments has demonstrated that sound propagation along city streets is influenced by several factors. These include atmospheric absorption, geometrical divergence, diffraction around buildings, and multiple reflections from both buildings and streets (Aylor et al., 1973). Among these factors, buildings play a critical role as primary reflective surfaces that significantly affect sound levels. Their design can actively contribute to mitigating noise pollution by influencing how sound is absorbed, reflected, or diffused.

In urban outdoor settings, architects and urban planners can particularly engage in optimizing the transmission path of sound. This involves strategic design choices and interventions that aim to reduce noise levels and improve acoustic environments.

In urban outdoor environments, a significant number of studies have focused on noise control, with many researches adopting an objective approach aimed at reducing sound pressure. These studies explored various façade elements to evaluate outdoor sound, leading to distinct findings.

One area of investigation was balconies, where several studies examined their acoustic performance. Wang et al. (2015) utilized computer predictions to assess different balcony types against road traffic noise, concluding that balconies with specific ceiling designs could effectively mitigate exterior noise. Similarly, Magrini and Lisot (2016) found that balconies served as better noise barriers in narrower streets. Wang et al. (2017) further explored the impact of balcony ceiling design on street soundscapes, suggesting that a well-balanced design could enhance noise reduction. Badino et al. (2019) analyzed the influence of balcony shape and arrangement, noting a measurable decrease in sound levels with deeper balconies. Tang et al. (2019) focused on asymmetrical balconies, revealing that the orientation of side-walls significantly affected noise insertion loss.

Vegetated façades were another focal point, with Jang and Kim et al. (2015) and Jang and Lee et al. (2015) employing scale model measurements to assess noise reduction in urban settings. Their findings indicated that vegetated façades could lower noise levels, albeit modestly, with Jang and Lee et al. noting a reduction of less than 2 dB at pedestrian level.

Sun shading techniques were also examined (Zuccherini Martello et al., 2015). Zuccherini Martello et al. (2015) investigated the impact of sound-absorbing louvers on glass surfaces. Their results indicated that while standard shading devices could increase sound pressure levels, sound-absorbing materials effectively mitigated this issue. Sakamoto and Aoki (2015) compared different eave types, finding inclined eaves to be particularly effective in noise reduction. Further research by Zuccherini Martello et al. (2016) highlighted how shading devices influenced psychoacoustic parameters, demonstrating that sound-absorbing systems provided better attenuation than traditional designs. Fausti et al. (2019) confirmed that adding sound-absorbing materials to louvers could reduce sound pressure levels on adjacent façades.

Lastly, the height of façades emerged as a critical variable in urban acoustics. Lee and Kang (2015) studied the height-to-width ratio's effect on sound fields, discovering that this ratio influenced sound pressure levels and reverberation times, particularly in narrow streets.

This study adopts the noise control approach to investigate the impact of architectural design on outdoor acoustic environments. While the soundscape approach provides valuable insights into subjective sound perception, the focus of this research is on objective acoustic parameters such as sound pressure level (SPL) attenuation, reverberation time (RT), and speech intelligibility metrics (RaSTI, D50). These quantitative measures allow for a precise evaluation of how building façades and urban morphology influence outdoor sound propagation.

By utilizing the noise control framework, this research aims to provide data-driven insights that can inform urban planning and façade design strategies to improve acoustic conditions in outdoor spaces. This approach aligns with established methodologies in environmental acoustics and contributes to a more systematic understanding of sound behavior in built environments. Figure 1-6 presents a comparison between the soundscape and noise control approaches, illustrating their distinct perspectives. While both approaches play a role in shaping urban acoustic environments, this study prioritizes measurable noise control strategies to assess and optimize outdoor sound conditions.

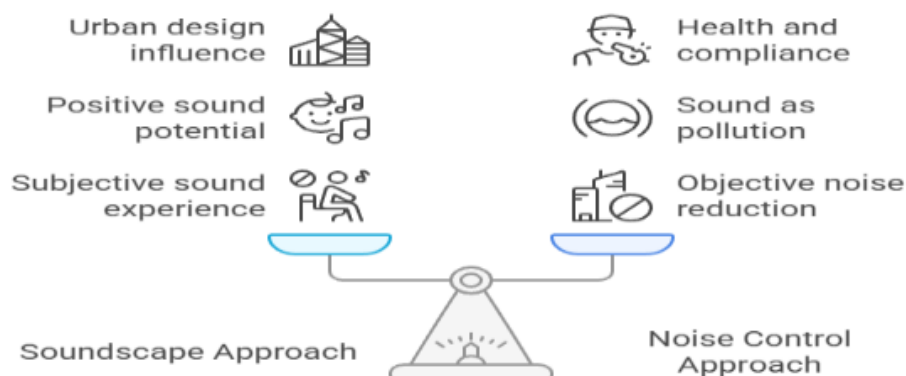


Figure 1-6: Balancing Soundscape and Noise Control in Urban Environments.

Source:(author)

3. Methodologies for assessing outdoor sound environments

Accurate analysis of urban sound environments requires robust methodologies. This section examines three primary methods—field (in situ) measurements, scale-model experiments, and computer prediction techniques—used to investigate acoustic phenomena. The strengths and limitations of each method are discussed, with a focus on their applicability to this study's investigation of Algerian urban settings. A summary of the methods utilized in relevant studies is presented in Table 1-2.

Table 1-2

Methods Used in Studies on Urban Outdoor Acoustic Environment Evaluation

Author	Title	Publication Title	Database	Method
(Hornikx et al., 2018)	The wind effect on sound propagation over urban areas: Predictions for generic urban sections	Building and Environment	Science Direct	computer prediction
(Aylor et al., 1973)	Reverberation in a city street	The Journal of the Acoustical Society of America	Silverchair	Field Measurement (in situ measurement)
(Zuccherini Martello et al., 2016)	A Psychoacoustic Investigation on the Effect of External Shading Devices on Building Facades	Applied Sciences	www.mdpi.com	scale-model Measurement
(Sakamoto & Aoki, 2015)	Numerical and experimental study on noise shielding effect of eaves/louvers attached on building façade	Building and Environment	Science Direct	scale-model Measurement
(Yang et al., 2017)	An experimental study on the acoustic characteristics of outdoor spaces surrounded by multi-residential buildings	Applied Acoustics	Science Direct	computer prediction
(Flores et al., 2017)	A Case Study of the Influence of Urban Morphology on Aircraft Noise	Acoustics Australia	Springer Link	Field Measurement (in situ measurement)

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(Yang et al., 2013)	Acoustic characteristics of outdoor spaces in an apartment complex	Noise Control Engineering Journal	Ingenta Connect	Field Measurement (in situ measurement)
(Jang, Kim, et al., 2015)	Scale-model method for measuring noise reduction in residential buildings by vegetation	Building and Environment	Science Direct	scale-model Measurement
(Jang, Lee, et al., 2015)	Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model	The Journal of the Acoustical Society of America	Silverchair	scale-model Measurement
(Krimm et al., 2017)	Updated urban facade design for quieter outdoor spaces	Journal of Facade Design and Engineering	journals.op en.tudelft.nl	scale-model Measurement
(Zuccherini Martello et al., 2015)	The Use of Sound Absorbing Shading Systems for the Attenuation of Noise on Building Façades. An Experimental Investigation	Buildings	www.mdpi.com	Field Measurement (in situ measurements)
(Lee & Kang, 2015)	Effect of Height-To-Width Ratio on the Sound Propagation in Urban Streets	Acta Acustica United With Acustica	discovery.ucl.ac.uk	computer prediction
(Tang et al., 2019)	Insertion loss of asymmetrical balconies on a building façade	The Journal of the Acoustical Society of America	Silverchair	scale-model Measurement
(Magrini & Lisot, 2016)	A simplified model to evaluate noise reduction interventions in the urban environment	Building Acoustics	SAGE Journals	computer prediction
Yeow, K.W. (Yeow, 1977)	Decay of sound levels with distance from a steady source observed in a built-up area	Journal of Sound and Vibration	Science Direct	Field Measurement (in situ measurement)
(Steenackers et al., 1978)	Reverberation in Town Streets	Acta Acustica united with Acustica	Ingenta Connect	Field Measurement (in situ measurement)

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(Wiener et al., 1965)	Sound Propagation in Urban Areas	The Journal of the Acoustical Society of America	Silverchair	Field Measurement (in situ measurement)
(Thomas et al., 2013)	Reverberation-based urban street sound level prediction	The Journal of the Acoustical Society of America	Silverchair	Field Measurement (in situ measurement)
(Picaut et al., 2005)	Experimental study of sound propagation in a street	Applied Acoustics	Science Direct	Field Measurement (in situ measurement)
(Crippa et al., 2019)	Façade Engineering and Soundscape	n.d	nd	computer prediction

3.1. Field Measurement (In Situ Measurement) Methods in Urban Outdoor Sound Environments

In situ measurement methods are pivotal for understanding acoustic characteristics within urban outdoor environments. These methods directly capture sound propagation and environmental interactions under real-world conditions, making them indispensable for studying urban noise dynamics (Figure 1.7).

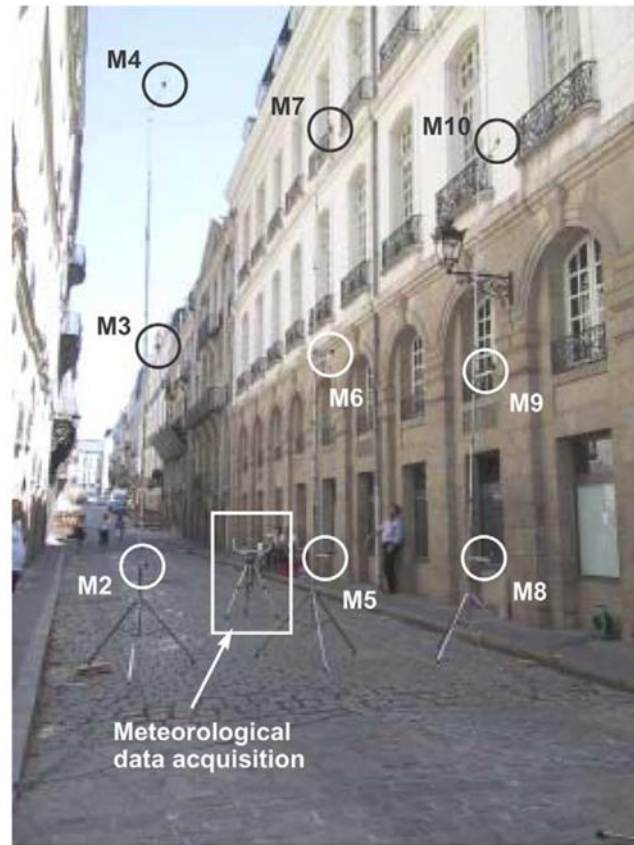


Figure 1-7: Capture sound propagation and environmental interactions under real-world conditions. source: (Picaut et al., 2005)

Thomas et al. (2013) employed in situ measurements across 99 streets in Ghent, Belgium, to investigate urban acoustic features. Using omnidirectional sound sources and microphones placed at specific heights, they minimized interference and ensured accurate sound level readings. The study also included 57 reference measurements in rural areas, reinforcing the method's reliability in urban contexts. Similarly, Flores et al. (2017) conducted in situ measurements in Madrid and Pisa near schools and libraries located close to major airports. They employed strategically placed microphones to analyze noise exposure influenced by street topologies and building façades, emphasizing baseline noise levels' importance for accurate urban noise analysis.

The role of architectural features in urban acoustics has been extensively studied using in situ methods. For instance, Krimm et al. (2017) assessed how façade designs influenced sound reflection at the Henninger Turm in Frankfurt. By analyzing various façade modifications, their

measurements offered valuable insights into urban noise mitigation. Yang et al. (2013, 2017) examined outdoor spaces in Seoul's apartment complexes, employing impulsive sounds like a starter pistol and white noise to capture reverberation time (RT), early decay time (EDT), and rapid speech transmission index (RaSTI) at multiple distances and heights. This comprehensive analysis highlighted the role of façade geometry and materials in sound propagation.

The impact of urban morphology was a focal point for Picaut et al. (2005), who conducted in situ measurements to examine sound propagation in various urban configurations under real atmospheric conditions. Their work underscored the importance of street layouts and urban design in shaping acoustic environments. Similarly, Wiener et al. (1965) studied sound propagation on Boston's Summer Street and Commonwealth Avenue, combining acoustical and meteorological measurements to analyze speech intelligibility and urban sound transmission under different weather conditions.

Specific building elements have also been investigated. Martello et al. (2015) evaluated sound insulation and pressure levels on glazed surfaces of a four-story office building, focusing on variations caused by standard versus sound-absorbing louvers. Their findings align with Aylor et al. (1973) who analyzed the acoustic effects of ivy on urban facades. Measurements conducted before and after ivy foliage development revealed its significant impact on sound absorption and scattering, illustrating how vegetation can influence urban acoustic performance.

In traffic noise studies, Steenackers et al. (1978) utilized decay curves of sound in urban streets to refine absorption and diffusion coefficients for façades. This approach enhanced the accuracy of predictive noise models by reconciling theoretical frameworks with real-world data. Yang et al. (2017) extended the scope of in situ measurements through their work in Korean apartment complexes, where 209 measurement points were used to study parameters such as RT, EDT, and RaSTI. Their methodology provided a detailed analysis of how architectural and urban factors affect sound propagation.

Lastly, Sakamoto and Aoki (2015) conducted field measurements to explore how urban design elements like street width and façade materials influence sound propagation and decay in outdoor

environments. Their findings complement the broader understanding of urban acoustic environments, demonstrating how small design variations can significantly impact noise distribution.

In conclusion, in situ measurement methods are crucial for accurately capturing the complexities of urban sound environments. By addressing variations in urban morphology, building façades, and environmental conditions, these methods enable comprehensive analyses that inform effective noise management strategies and urban planning. However, this study is not exhaustive, as field measurements across diverse physical, natural, and climatic contexts could further enhance the understanding of how different environmental factors influence acoustic performance. Factors such as temperature, humidity, wind patterns, and ground surface materials can significantly alter sound propagation and should be examined in various urban settings. Additionally, incorporating long-term monitoring and comparative studies between different geographical regions would provide deeper insights into the dynamics of outdoor sound environments. Future research should consider these aspects to develop more adaptable and resilient urban acoustic strategies.

3.2. Scale-Model measurements Method in Urban Outdoor Sound Environments

The scale-model method has emerged as an effective approach to investigating urban sound environments, offering controlled experimental conditions and practical insights into noise reduction strategies. This method involves constructing physical models, scaled down from real-life structures, to simulate sound propagation and measure acoustic performance under controlled laboratory conditions.

The scale-model method is based on the premise of maintaining geometric, material, and acoustic fidelity to the real environment, enabling detailed analysis of sound behavior. According to Sakamoto and Aoki (2015), this approach is particularly useful for studying noise reduction effects in complex architectural setups. Their experiments used a 1:20 scale model in a semi-anechoic chamber to minimize unwanted reflections and simulate semi-free field conditions (Figure 1.8).

Key components, such as medium-density fiberboard walls and aluminum eaves, were carefully constructed to replicate real-world material properties.

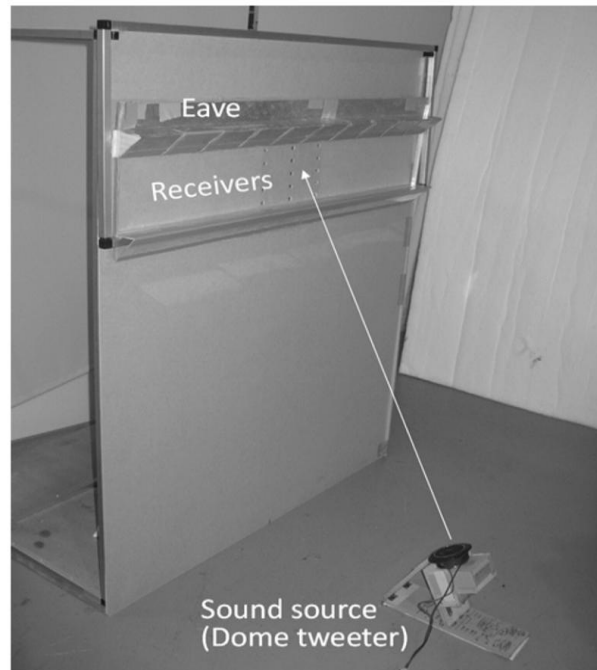


Figure 1-8: Experiments used a 1:20 scale model in a semi-anechoic chamber. Source: (Sakamoto & Aoki, 2015)

Similarly, Tang et al. (2019) applied the method to investigate the acoustical insertion loss of asymmetrical balconies on high-rise buildings. Using a 1:3 scale model in a semi-anechoic chamber, the study examined the effects of balcony orientation and elevation on noise reduction. The model's dimensions and microphone placements were meticulously designed to ensure accurate representation of real-world traffic noise impacts.

The method has also been extended to full-scale (1:1) physical models to evaluate specific architectural elements. Martello et al. (2016) utilized a 1:1 scale model of shading devices to study their acoustic properties in a semi-anechoic chamber. This approach enabled precise measurements of sound pressure levels and impulse responses, which were critical for assessing

psychoacoustic parameters such as loudness and sharpness. Comparing the results against a blank facade provided insights into how shading devices influence acoustic performance.

3.2.1. Applications in Vegetation and Urban Design

The versatility of the scale-model method is evident in studies focused on the acoustic effects of vegetation in urban environments. Jang et al. (2015) constructed 1:10 scale models of street canyons and courtyards to evaluate noise reduction from vegetated façades and green roofs. By incorporating complex material behaviors, such as those of vegetation, the method overcame limitations of numerical modeling. Measurements in semi-anechoic chambers ensured accurate simulation of urban conditions, revealing the effectiveness of vegetation treatments, such as trees and shrubs, in mitigating noise.

The method also includes advanced assessments of material absorption coefficients and ground impedance. As reported by Jang et al. (2015), the results obtained from scale models closely aligned with geometric computer simulations, validating the method's accuracy and cost-efficiency compared to field measurements.

3.2.2. Advantages and Limitations

The scale-model method provides several advantages, including the ability to replicate complex shapes and materials in controlled conditions. It allows researchers to isolate specific variables and conduct repeatable experiments, as noted by Jang et al. (2015) and Tang et al (2019). Additionally, the method is economical and avoids the logistical challenges associated with field measurements. However, maintaining fidelity in material properties and scaling sound frequency to match real-world conditions remains challenging. This difficulty arises because materials in scale models may not exhibit the same acoustic properties (such as absorption and reflection coefficients) as their full-scale counterparts. Additionally, sound waves interact with surfaces differently at reduced scales, requiring frequency adjustments to ensure that wave behavior, including diffraction and interference, corresponds accurately to real-world scenarios. To address these challenges, meticulous calibration is necessary, including selecting appropriate scaling laws,

adjusting material compositions, and validating results against reference data from full-scale measurements.

The scale-model method offers a robust framework for studying noise reduction and sound propagation in urban outdoor environments. Its applications range from analyzing architectural elements like eaves and balconies to evaluating vegetation's role in noise mitigation. By bridging experimental accuracy and practical insights, the method continues to be a valuable tool for urban acoustic research. Additionally, it enables researchers to test different urban configurations under controlled conditions, reducing the uncertainties associated with real-world variability. Advanced measurement techniques, such as laser scanning and 3D printing, further enhance the precision of scale models by replicating complex geometries with high fidelity.

3.3. Computer Prediction Techniques

Urban outdoor sound environments are complex systems influenced by numerous factors, including architectural configurations, material properties, and meteorological conditions. Researchers have increasingly turned to computer prediction methods to model and analyze sound propagation in these environments. These methods utilize various computational approaches, including finite-difference, finite-element, boundary-element, and hybrid techniques, to provide insights into sound behavior and potential noise mitigation strategies.

The literature on computer prediction methods for urban sound environments highlights various approaches and tools used to model and analyze sound propagation in complex urban settings. One prominent method involves the use of computer-aided acoustic prediction software, such as CATT-Acoustic (Figure 1.9), which employs geometrical acoustics to predict octave-band echograms based on 3D CAD models. This method assigns frequency-dependent material properties to model surfaces and source directivities to sound sources, allowing for the estimation of sound pressure levels, speech intelligibility, and reverberation times in urban spaces (Crippa et al., 2019).

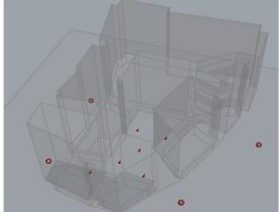
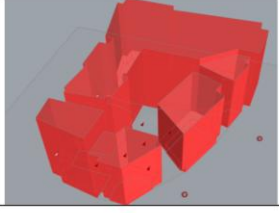
CATT analyses – Baseline options				
Case			Description	Main Result
0			Fully reflective façade Typical real-world scenario. Mixture of glass and concrete throughout.	Source A2 High sound level experienced in the square due to a strong direct and reverberant sound field.
				Source A3 High sound level experienced in the square due to a large build-up in the reverberant sound field.
1			Fully absorptive façade. While unrealistic, Case 1 presents the ultimate limit in SPL reduction achievable by applying acoustic absorption in the square, setting out a benchmark for future scenarios.	Source A2 10-15 dB reduction at receiver 02/03 due to screening. Minimal losses at receiver 01/04 as direct sound is dominant.
				Source A3 15-20 dB reduction at all receivers, as absorption reduces the reverberant sound field.
1.1			Absorptive façade from 7 metres and above.	Source A2 Minimal reductions experienced at all receivers.

Figure 1-9:Computer prediction using CATT analysis software. source: (Crippa et al., 2019)

Similarly, SoundPLAN (Figure 1-10), a three-dimensional simulation model, is used to quantify the influence of architectural configurations and potential intervention solutions on noise propagation in urban environments. This model helps in evaluating the impact of different acoustic and geometric characteristics, such as facade absorption and road width, on noise levels (Magrini & Lisot, 2016).

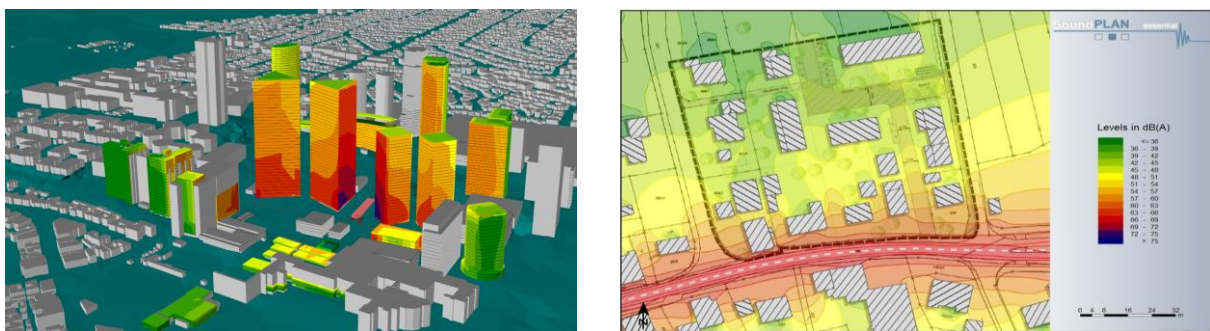


Figure 1-10: Simulation of Urban Noise Propagation Using SoundPLAN. source: (SoundPLAN, 2024)

Another approach involves the use of computational fluid dynamics (CFD) and computational acoustics (CA) methods to predict sound propagation, taking into account meteorological effects and urban morphology. This hybrid approach combines the finite-difference time-domain (FDTD)

method and parabolic equations (PE) to compute sound propagation in urban areas, particularly under varying wind conditions (Hornikx et al., 2018).

Additionally, the use of ray tracing and image source methods in software like ODEON has been validated through comparisons with experimental studies, demonstrating reliable predictions of sound pressure levels and reverberation times in urban street canyons (Lee & Kang, 2015).

These methods collectively underscore the importance of integrating architectural and environmental factors in the prediction of urban soundscapes, providing valuable insights for urban planners and acousticians aiming to enhance acoustic comfort in outdoor urban environments. The empirical models developed for predicting reverberation time (RT) and sound pressure level (SPL) attenuation in outdoor spaces further illustrate the role of building geometry and layout in shaping urban sound environments, emphasizing the need for comprehensive simulation techniques to inform urban design (Yang et al., 2017).

4. Conclusion

In conclusion, Chapter 1 has provided a thorough review of the various approaches and methodologies for assessing outdoor acoustic environments within the built environment. The chapter highlighted the two primary approaches—soundscape and noise control—which offer contrasting but complementary perspectives on managing and understanding urban sound environments.

The soundscape approach is rooted in the idea of shaping sound to enhance the overall acoustic experience, emphasizing the positive aspects of sound in creating a richer urban atmosphere. On the other hand, the noise control approach seeks to mitigate harmful noise, focusing on strategies to reduce or eliminate noise pollution, which can significantly impact health and well-being. Both approaches are essential, as they address different facets of the urban acoustic experience and provide a balanced framework for sound management.

The review of methodologies for assessing outdoor sound environments illustrated the variety of techniques used to measure and evaluate acoustics. Each offer distinct advantages in

understanding how urban environments influence acoustics. Field measurements, conducted under real-world conditions, allow researchers to gather accurate, context-specific data on sound propagation, influenced by factors such as weather, time of day, and local noise sources. This approach provides insight into how sound behaves in actual urban spaces, allowing for the study of environmental factors that impact acoustic comfort.

Scale-model experiments, conducted in controlled settings, enable the isolation and examination of specific variables like architectural elements, vegetation, and layout configurations. These experiments replicate real-world conditions in a smaller, more manageable form, allowing for detailed exploration of how particular design elements—such as facades, building heights, and open spaces—affect sound transmission. Though useful for understanding these factors in depth, scale-model experiments are typically limited by their inability to fully replicate the complexity of large-scale urban environments.

Computer prediction techniques, employing advanced acoustic simulation software, allow for the modeling of sound propagation in virtual urban settings. These techniques can incorporate a wide range of factors, such as meteorological conditions, the geometry of urban spaces, and sound reflections. By simulating various design scenarios, researchers can predict how changes in building layouts or urban morphology will influence sound levels and acoustic comfort. Though computational models provide powerful predictive capabilities, their accuracy is often contingent upon the quality and precision of input data and assumptions.

Emerging technologies, including artificial intelligence (AI), machine learning, and noise mapping, are transforming the study of urban acoustics. AI-driven models and machine learning algorithms offer new possibilities for analyzing large datasets, improving predictive accuracy, and optimizing urban soundscapes. Noise mapping, supported by real-time data collection, enhances noise control strategies by identifying high-exposure areas and assessing the effectiveness of mitigation measures. These advancements present promising opportunities for developing more efficient, data-driven approaches to urban acoustic planning, ultimately contributing to healthier and more sustainable built environments.

Chapter 2

A Review of Noise Sources and Impacts in Urban Outdoor Spaces

Chapter 2: A Review of Noise Sources and Impacts in Urban Outdoor Spaces

1. introduction

Urban outdoor spaces are shaped by a complex interplay of natural and human-made sounds, influencing both the quality of life and the functionality of these environments. As cities continue to grow, concerns over noise pollution have intensified, necessitating a deeper understanding of its sources, propagation, and effects. Noise not only impacts acoustic comfort but also plays a crucial role in shaping social interactions, well-being, and overall urban livability. Addressing these challenges requires a multidisciplinary approach that integrates architectural design, urban planning, and acoustical engineering.

The chapter begins by examining key noise control indices, including reverberation time (RT), early decay time (EDT), definition index (D50), rapid speech transmission index (RaSTI), and sound pressure level (SPL), which serve as critical metrics for evaluating acoustic comfort in outdoor spaces.

The chapter also reviews the influence of noise sources and urban morphologies on acoustic environments. This includes an examination of common noise sources, such as traffic, aircraft, impulse and human activities noise, and their interaction with urban structures like building layouts, façades, and courtyards. The discussion highlights how these architectural elements shape sound propagation and contribute to noise attenuation.

A particular focus is placed on the Algerian noise pollution landscape, with an emphasis on university outdoor environments. These spaces present unique challenges due to their architectural configurations, human activity patterns, and exposure to environmental noise. By contextualizing the discussion within this framework, the chapter highlights the relevance of acoustic studies in shaping healthier and more functional public spaces.

The chapter concludes by identifying gaps in the existing literature, emphasizing the need for further research on noise mitigation in urban outdoor spaces. Through this structured review, the chapter lays the foundation for the subsequent analysis in this thesis, linking theoretical knowledge

with practical applications to enhance the understanding and management of outdoor acoustic environments.

2. Noise control indices in urban outdoor environments

Understanding key acoustic parameters, such as Reverberation Time (RT), Early Decay Time (EDT), and Sound Pressure Level (SPL), is essential for evaluating and managing urban sound environments. This section reviews these parameters and their significance in assessing acoustic performance through multiple journals and databases. Table 2-1 presents an overview of essential acoustic parameters used to evaluate and manage urban sound environments, highlighting their relevance to this study. The discussion establishes their relevance to the study's focus on built morphology acoustics and sound propagation.

Table 2-1:

Summary of key Research Studies on Urban Noise Parameters and Acoustic Characteristics

Author	Research Title	Journal Title	Database	Noise parameter studied
(Flores et al., 2017)	A Case Study of the Influence of Urban Morphology on Aircraft Noise	Acoustics Australia	Springer Link	SPL
(Magrini & Lisot, 2016)	A simplified model to evaluate noise reduction interventions in the urban environment	Building Acoustics	SAGE Journals	SPL
(Yang et al., 2013)	Acoustic characteristics of outdoor spaces in an apartment complex	Noise Control Engineering Journal	Ingenta Connect	RT/EDT/RaSTI/SPL
(Montes González et al., 2018)	Acoustic screening effect on building façades due to parking lines in urban environments. Effects in noise mapping	Applied Acoustics	Science Direct	SPL
(Yang et al., 2017)	An experimental study on the acoustic characteristics of outdoor spaces surrounded by multi-residential buildings	Applied Acoustics	Science Direct	RT/EDT/RASTI/D50/ SPL
(Badino et al., 2019)	Effect of façade shape and acoustic cladding on reduction of leisure noise levels in a street canyon	Building and Environment	Science Direct	SPL

Chapter 2 - A Review of Noise Sources and Impacts in Urban Outdoor Spaces

(Lee & Kang, 2015)	Effect of Height-To-Width Ratio on the Sound Propagation in Urban Streets	Acta Acustica United With Acustica	discovery.uci.ac.uk	RT/EDT/RE SPL
(Qu & Kang, 2017)	Effects of built environment morphology on wind turbine noise exposure at building façades	Renewable Energy	Science Direct	SPL
(Jang, Lee, et al., 2015)	Evaluation of road traffic noise abatement by vegetation treatment in a 1:10 urban scale model	The Journal of the Acoustical Society of America	Silverchair	RT/INSERTION LOSS
(Jang, Lee, et al., 2015)	Evaluation of the influence of building façade design on the acoustic characteristics and auditory perception of urban spaces	Building Acoustics	SAGE Journals	RT/SUBJECTIVE SQUARE WIDENESS
(Crippa et al., 2019)	Façade Engineering and Soundscape	n.d	n.d	RT/SPL
(Kang, 2005)	Numerical modeling of the sound fields in urban squares	The Journal of the Acoustical Society of America	Silverchair	RT/EDT/SPL
(Jang, Kim, et al., 2015)	Scale-model method for measuring noise reduction in residential buildings by vegetation	Building and Environment	Science Direct	RT/INSERTION LOSS
(Kang, 2001)	Sound Propagation in Interconnected Urban Streets: A Parametric Study	Environment and Planning B: Planning and Design	SAGE Journals	RT/EDT/SPL
(Kang, 2000)	Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries	The Journal of the Acoustical Society of America	Silverchair	RT30/EDT/SPL
(Hornikx et al., 2018).	The wind effect on sound propagation over urban areas: Predictions for generic urban sections	Building and Environment	Science Direct	SPL

(Krimm et al., 2017)	Updated urban facade design for quieter outdoor spaces	Journal of Facade Design and Engineering	journals.open.tudelft.nl	SPL
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2.1. Reverberation time in Urban Outdoor Environments

Reverberation time (RT) is a fundamental acoustic parameter that quantifies how long sound persists in a space after the sound source has stopped. This parameter is critical in evaluating sound quality, intelligibility, and auditory perception in various settings, including urban outdoor environments. In such contexts, RT is influenced by factors like building configurations, materials, and natural elements, which create unique challenges compared to enclosed spaces.

2.1.1. Vegetation and Building Configurations

Urban outdoor environments are characterized by their non-diffuse fields, where sound propagation is shaped by multiple reflections, diffraction, and absorption. Studies have shown that in outdoor spaces surrounded by buildings, RT values can be relatively high due to reflective surfaces. For instance, Yang et al. (2013) reported RT values exceeding 4 seconds at 500 Hz and 1000 Hz in areas enclosed by two-sided facades, a phenomenon attributed to multiple reflections between the facades.

In contrast, single-sided facades result in shorter RTs, with reductions of approximately 1.8 seconds at 500 Hz compared to two-sided configurations. Additionally, the increase in RT with source-receiver distance above 500 Hz highlights the influence of geometry and material properties on sound decay. At lower frequencies, such as 125 Hz, RT values tend to be shorter, reflecting the lesser impact of reflections at these frequencies.

Vegetation has been shown to play a significant role in modulating RT in urban outdoor environments. Studies by Jang et al. (2015) reveal that vegetated facades and the strategic placement of trees can reduce RT across frequency bands. Vegetation decreases flutter echoes and enhances sound absorption, particularly at lower frequencies, though it may increase noise levels

above 1 kHz due to scattered reflections. These findings underscore the importance of vegetation in urban design to improve acoustic comfort.

Building configurations also significantly affect RT. Research by lee and Kang (2015) demonstrated that the height-to-width (HW) ratio of street canyons influences RT (T30), with increases of 150-300 ms observed for higher HW ratios. Wider streets tend to exhibit constant or slightly increasing RTs with distance, while narrower streets amplify sound persistence.

RT not only affects objective acoustic metrics but also influences subjective auditory perception. Studies by Calleri et al. (2018) highlight the correlation between RT values at specific frequency bands (e.g., 0.5-1 kHz) and listeners' perception of space wideness. Variations in RT can lead to differing spatial and auditory experiences, emphasizing the importance of tailored acoustic designs for outdoor urban areas.

2.1.2. Methodologies for Measuring RT

Advancements in RT measurement techniques have significantly deepened our understanding of outdoor acoustics. One notable example is the work of Jang et al. (2015), who used scale models in line with ISO 354 standards to measure impulse responses and assess the absorption coefficients of various materials. Their approach provided valuable insights into how different surfaces interact with sound in controlled environments.

Meanwhile, Calleri et al. (2018) took a different approach by using balloons as sound sources for in-situ measurements, adhering to the ISO 3382-1:2009 standard. They assigned accurate absorption and scattering coefficients to materials, ensuring that the simulated results closely reflected real-world scenarios. This not only enhanced the reliability of their findings but also utilized ODEON software for advanced simulations, bridging the gap between theory and practice.

In another study, Crippa et al. (2019) employed CATT-Acoustic software to predict octave-band echograms from a detailed 3D CAD model. They carefully assigned frequency-dependent material properties to both surfaces and sound sources, simulating various conditions with different types

of absorptive materials. The results, which included estimates of SPL and RT, were validated through rigorous on-site testing, further solidifying the accuracy of their simulations.

Together, these methods shed light on how building materials and configurations can mimic real-world acoustic environments, offering crucial insights for the design and analysis of outdoor spaces. The findings from these studies have significant implications for urban planning. Effective management of RT can enhance speech intelligibility, reduce noise pollution, and improve the overall auditory experience. Urban planners and architects must consider factors such as facade design, vegetation placement, and street geometry to create acoustically favorable environments.

Reverberation time remains a critical metric for understanding and improving the acoustic quality of urban outdoor environments. The interplay of building geometry, material properties, vegetation, and subjective perception underscores the complexity of designing spaces with optimal acoustic characteristics. Future research should focus on integrating advanced modeling techniques and exploring innovative design solutions to address the challenges of urban acoustics.

2.2. Early decay time (EDT) in Urban Outdoor Environments

Early Decay Time (EDT) is a vital acoustic parameter used to assess how quickly sound levels decay in an environment after the cessation of a sound source. In urban outdoor environments, EDT plays a significant role in understanding sound propagation, speech intelligibility, and the overall acoustic quality of spaces such as streets, squares, and residential complexes. This review synthesizes key findings and explores the factors influencing EDT in urban settings.

The definition and measurement of EDT provide a foundation for its relevance in outdoor acoustic studies. Derived from the sound decay curve using reverse-time integration, EDT measures the time it takes for sound to decay by 10 dB after the initial sound stops (Kang, 2001). Unlike traditional reverberation time (RT), EDT is particularly sensitive to the early reflections of sound, making it an essential tool for analyzing acoustic behavior in spaces with non-diffuse sound fields. Its strong correlation with speech intelligibility underscores its importance in urban environments where clear communication is crucial (Kang, 2001). Figure 2-1 illustrates the concept of EDT in

urban outdoor environments, highlighting its measurement process and significance in evaluating sound reflections and decay.

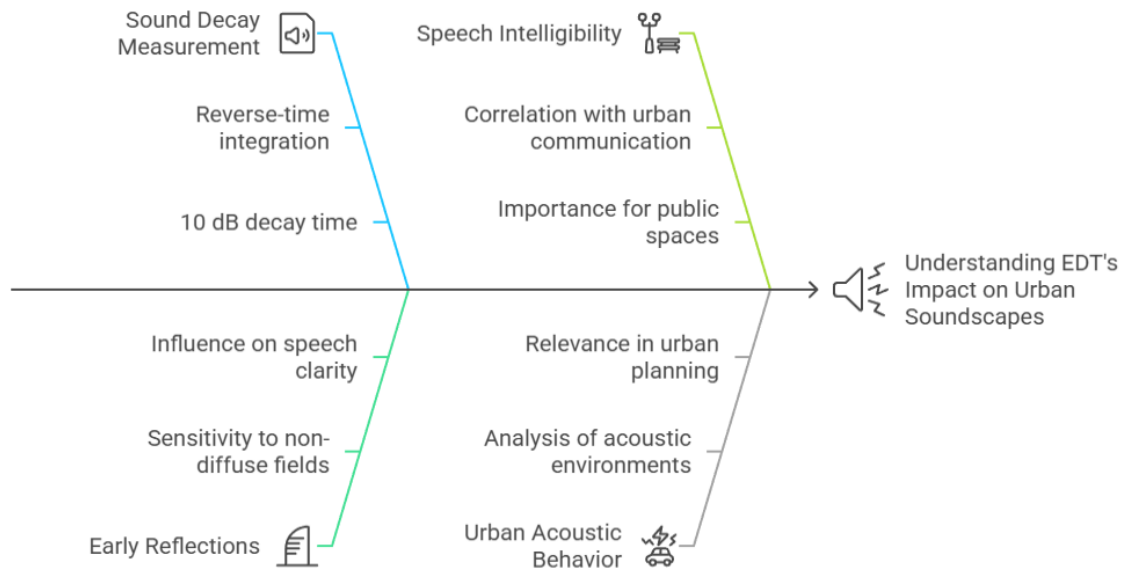


Figure 2-1: Analyzing EDT concept in urban outdoor acoustics. Source: (author)

A variety of factors influence EDT in urban outdoor spaces. The type of boundary surfaces, such as geometrically or diffusely reflecting facades, significantly affects sound decay. Geometrically reflecting boundaries typically result in longer EDT values, as they conserve sound energy by reflecting it more directly, while diffusely reflecting boundaries promote sound scattering and reduce EDT (Kang, 2000). Studies have shown that in urban squares, geometrically reflecting boundaries can produce EDT values as long as 8 to 10 seconds, whereas diffusely reflecting boundaries yield much shorter decay times (Kang, 2005).

The height-to-width ratio (H/W) of street canyons is another critical factor. Research indicates that higher H/W ratios lead to longer EDT values, particularly in narrow streets. For instance, in streets with a width of 6 meters, EDT values remain below 2 seconds, while in wider streets of 27 meters, they exceed 5 seconds (Lee & Kang, 2015). These variations highlight the interplay between street geometry and acoustic behavior.

Receiver height and source-to-receiver distance also contribute to variations in EDT. As the receiver height increases, so does EDT, reflecting the influence of vertical sound propagation. For example, studies have observed an increase in EDT values from 1.4 to 3.2 seconds at 500 Hz as the receiver height rises (Yang et al., 2013). Additionally, EDT tends to increase logarithmically with greater distances from the sound source, stabilizing at longer distances where the sound decay becomes more linear (Yang et al., 2017).

Urban outdoor environments present unique challenges and opportunities for acoustic optimization. In street canyons, the distinct geometrical configurations often result in varied EDT values, which can inform strategies for noise mitigation and sound enhancement. Similarly, in urban squares, balancing sound energy from reflections can enhance the clarity of speech or the enjoyment of music, while longer EDT values may increase noise annoyance (Kang, 2000). Residential complexes, with their diverse architectural designs, demonstrate the importance of building configurations in shaping acoustic environments. Studies have found that EDT variations in these spaces are linked to the arrangement of buildings and the inclusion of sound-absorbing materials (Yang et al., 2017).

Comparisons between EDT and other acoustic parameters, such as RT, further emphasize its distinct role. EDT is generally longer than RT beyond certain source-to-receiver distances, as it captures the effects of early reflections more effectively (Yang et al., 2017). This characteristic makes EDT an essential parameter for understanding sound quality in open-air environments where traditional reverberation measures may fall short.

Despite the progress in understanding EDT in urban contexts, research gaps remain. Limited studies have explored the combined impact of building materials, facade designs, and vegetation on EDT. Additionally, the influence of climatic conditions, such as wind and temperature, on sound decay has yet to be fully understood. Future research should focus on developing predictive models to simulate EDT behavior in complex urban settings, enabling architects and urban planners to design acoustically optimized spaces.

In conclusion, EDT is a critical parameter in urban acoustic studies, offering valuable insights into sound behavior in outdoor environments. Its sensitivity to early reflections and its correlation with acoustic quality make it indispensable for designing functional and comfortable urban spaces. By addressing existing research gaps and exploring new avenues, future studies can further enhance our understanding of EDT and its applications in urban environments.

2.3. D50 in Urban Outdoor Environments

D50, a critical parameter in assessing speech clarity, is defined as the ratio of early arriving sound energy (within the first 50 milliseconds) to the total arriving sound energy, expressed as a percentage (Yang et al., 2017). This index is particularly relevant in outdoor urban environments, where architectural design and spatial configuration significantly influence speech intelligibility. Understanding D50 helps evaluate how effectively sound propagates in urban settings, especially in areas surrounded by buildings.

Research conducted by Yang et al. (2017) analyzed D50 across varying source-to-receiver distances in urban environments characterized by different building layouts. The findings indicated that D50 generally decreases logarithmically as the distance between the sound source and receiver increases. This trend suggests that clarity diminishes with greater distances, highlighting the challenges of maintaining speech intelligibility in outdoor spaces, particularly in densely built areas where sound may reflect off multiple surfaces.

The decrease in D50 with increased distance underscores the impact of architectural design on outdoor acoustic environments. Buildings can create complex sound fields that affect how sound waves travel and interact. For instance, closely spaced buildings can lead to increased reflections and reverberation, which may degrade the clarity of speech. Yang et al. (2017) emphasized that thoughtful architectural planning is essential for enhancing speech intelligibility in public spaces such as parks, plazas, and transit stations.

The implications of D50 measurements extend beyond mere acoustics; they inform urban planning and design strategies aimed at improving community well-being. By understanding how different building configurations affect D50 values, urban planners can make informed decisions about

building placement, height, and materials to optimize acoustic performance. Strategies such as incorporating vegetation or designing open spaces can also help mitigate noise and enhance clarity.

In summary, D50 serves as a vital index for assessing speech clarity in outdoor urban environments. The relationship between distance and D50 highlights the importance of architectural design in shaping acoustic experiences. As cities continue to grow and evolve, integrating acoustic considerations into urban planning will be crucial for fostering environments that support effective communication and enhance quality of life.

2.4. RaSTI in Urban Outdoor Environments

The Rapid Speech Transmission Index (RaSTI) is a critical acoustic parameter that quantifies speech intelligibility in various environments, particularly in urban outdoor settings. Defined as an acoustic descriptor that relates to the clarity of speech, RaSTI provides essential information for designing effective public address (PA) systems and enhancing communication in public spaces. This literature review synthesizes key findings regarding RaSTI's relevance and application in urban outdoor environments, emphasizing its implications for architectural design and urban planning.

RaSTI is measured on a scale from 0 to 1, with values categorized as follows: 0-0.3 (bad), 0.3-0.45 (poor), 0.45-0.6 (fair), 0.6-0.75 (good), and 0.75-1.0 (excellent) (Yang et al., 2017). This categorization allows for a nuanced understanding of speech clarity in different contexts, making it particularly useful for evaluating the effectiveness of PA systems in outdoor spaces such as parks, plazas, and transit stations.

Research conducted by Yang et al. (2013, 2017) indicates that RaSTI values tend to decrease with increasing source-to-receiver distances, suggesting a decline in speech intelligibility as distance increases. This trend highlights the importance of proximity to sound sources for effective communication in outdoor environments. The findings suggest that direct sound dominates at shorter distances, positively influencing early sound energy and consequently enhancing RaSTI values.

2.4.1. Architectural Design Considerations

The architectural design of urban spaces significantly influences RaSTI outcomes. Studies have shown that various design elements, such as building height, layout, and materials, can impact sound propagation and clarity. For instance, Yang et al. (2013, 2017) noted that the spatial configuration surrounding outdoor areas affects how sound waves travel and interact with surfaces, ultimately influencing speech intelligibility. In particular, the arrangement of buildings can create complex acoustic environments where sound reflections and reverberation play crucial roles in determining RaSTI values. For example, closely spaced buildings may lead to increased reflections that degrade speech clarity, while open spaces can facilitate clearer communication by allowing sound to propagate more freely.

The implications of RaSTI measurements extend beyond acoustics; they inform urban planning strategies aimed at improving community well-being. By understanding how different architectural configurations affect RaSTI values, urban planners can make informed decisions about building placement, height, and materials to optimize acoustic performance in public spaces. Moreover, incorporating green spaces and vegetation into urban designs has been shown to mitigate noise levels and enhance speech intelligibility. Research indicates that vegetated façades can contribute to overall noise reduction while improving the acoustic comfort of outdoor environments (Yang et al., 2017).

In summary, RaSTI serves as a vital index for assessing speech intelligibility in urban outdoor environments. The relationship between distance and RaSTI underscores the importance of architectural design in shaping acoustic experiences. As cities continue to grow and evolve, integrating RaSTI assessments into planning processes will be essential for creating spaces that facilitate effective communication and enhance the quality of life for residents.

2.5. Sound pressure level (SPL) in Urban Outdoor Environments

Sound Pressure Level (SPL) is a critical acoustic metric widely used to quantify the intensity of sound in urban outdoor environments. Expressed in decibels (dB), SPL measures the pressure

variation caused by sound waves relative to a reference pressure, typically 20 μPa , which is the threshold of human hearing. The calculation follows the formula $\text{SPL} = 20 \log_{10}(p/p_0)$, where p is the root mean square of sound pressure. SPL serves as a fundamental parameter for assessing noise pollution and its impacts on urban planning, human comfort, and environmental health.

SPL analysis is pivotal in urban planning, enabling the design of spaces that mitigate noise pollution and enhance overall environmental quality. Urban sound environments are influenced by multiple factors, including architectural features, building layouts, and material properties. Recent research emphasizes the role of facade modifications and urban morphologies in controlling SPL. For instance, Krimm et al. (2017) highlight the importance of SPL measurements in evaluating facade designs aimed at noise reduction, demonstrating that architectural interventions can significantly attenuate sound levels in urban contexts.

2.5.1. SPL and Building Morphologies

Building morphologies play a substantial role in shaping the propagation and attenuation of sound in urban environments. Gonzalez et al. (2018) note that SPL is affected by the characteristics of sound sources, distance from the source, and environmental conditions. Similarly, Flores et al. (2017) identify urban morphology—such as street topologies and line-of-sight angles as key determinants of SPL. U-shaped street configurations and larger line-of-sight angles amplify sound levels due to reduced obstruction and increased transmission.

Hornikx et al. (2018) demonstrate that SPL variations are influenced by urban configurations and atmospheric conditions. Their findings reveal significant increases in SPL, especially at higher frequencies, under downward refracting atmospheric conditions. This underscores the complex interplay between urban topology and environmental factors in SPL propagation.

Material properties of urban facades and surfaces are crucial for SPL attenuation. Crippa et al. (2019) demonstrate that fully absorptive facades can reduce SPL by 9-11 dB, effectively halving perceived noise levels. Such interventions highlight the potential of architectural designs to mitigate urban noise pollution.

Magrini and Lisot (2016) emphasize the influence of the height-to-width ratio (H/W) in urban streets on SPL attenuation. Narrow streets with higher H/W ratios exhibit less sound attenuation, whereas wider streets show minimal SPL variation. This finding underscores the need to consider geometric configurations in urban noise control strategies.

The application of SPL extends to specific scenarios, such as aircraft noise and wind turbine noise. Flores et al. (2017) analyze the effects of urban morphology on aircraft noise, demonstrating that SPL measurements in urban environments are contingent on street layouts and facade configurations. Qu and Kang (2017) investigate SPL variations caused by wind turbine noise, revealing that built environment morphology significantly affects facade noise resistance.

Badino et al. (2019) explore the role of acoustic cladding on facades in reducing SPL. Their study shows that sound-absorbing materials can achieve up to a 10 dB reduction in SPL, underscoring the importance of material selection in urban acoustic design. Additionally, Calleri et al. (n.d.) assess SPL across a broad frequency range, linking facade material properties to subjective auditory perceptions and spatial assessments.

SPL analysis is integral to addressing noise pollution, a growing concern in urban environments. By understanding and managing SPL, planners and designers can create healthier, more sustainable urban spaces. The integration of SPL metrics with urban morphology studies provides a robust framework for mitigating noise impacts on human populations and wildlife.

The reviewed literature highlights the significance of SPL as a metric for understanding and managing urban sound environments. From the role of building morphologies to the impact of material properties and environmental factors, SPL serves as a key parameter in urban noise control strategies. Future research should continue to explore the interplay between architectural designs, urban configurations, and environmental conditions to develop comprehensive noise mitigation approaches.

3. Literature Review on Noise Sources in Urban Outdoor Environments

Identifying and characterizing noise sources is a critical step in managing urban acoustics. As the Table 2-2 shows, this section reviews the primary noise sources investigated in urban environments, including road traffic, wind turbines, and human activities. It highlights their acoustic impacts and relevance to understanding the interactions between noise sources, urban morphology, and façade design in Algerian cities. A summary of the noise sources investigated in urban outdoor environments is provided in Table 2-2.

Table 2-2:

Overview of Noise Sources in Studies Evaluating Urban Outdoor Acoustic Environments

Author	Title	Publication Title	Database	Noise source
(Wiener et al., 1965)	Sound Propagation in Urban Areas	The Journal of the Acoustical Society of America	Silverchair	Sirens
(Aylor et al., 1973)	Reverberation in a city street	The Journal of the Acoustical Society of America	Silverchair	1/3-octave pink noise
(Yeow, 1977)	Decay of sound levels with distance from a steady source observed in a built-up area	Journal of Sound and Vibration	Science Direct	Firecrackers
(C. P. TANG, personal communication, 1978)	Reverberation time in a high-rise city	Journal of Sound and Vibration	n.d	mechanical noise
(Kang, 2000)	Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries	The Journal of the Acoustical Society of America	Silverchair	road traffic
(Kang, 2001)	Sound Propagation in Interconnected Urban Streets: A Parametric Study	Environment and Planning B: Planning and Design	SAGE Journals	road traffic

(Iu & Li, 2002)	The propagation of sound in narrow street canyons	The Journal of the Acoustical Society of America	Silverchair	The Elevated and Mechanical (conditioners, cooling towers, and sirens)
(Kang, 2005)	Numerical modeling of the sound fields in urban squares	The Journal of the Acoustical Society of America	Silverchair	road traffic
(Picaut et al., 2005).	Experimental study of sound propagation in a street	Applied Acoustics	Science Direct	Impulse noise (fixed pistol)
(Yang et al., 2013)	Acoustic characteristics of outdoor spaces in an apartment complex	Noise Control Engineering Journal	Ingenta Connect	white noise and starter pistols
(Jang, Kim, et al., 2015)	Scale-model method for measuring noise reduction in residential buildings by vegetation	Building and Environment	Science Direct	Road traffic
(Lee & Kang, 2015)	Effect of Height-To-Width Ratio on the Sound Propagation in Urban Streets	Acta Acustica United With Acustica	discovery.ucl.ac.uk	road traffic generated by omnidirectional point sources
(Yang et al., 2017)	An experimental study on the acoustic characteristics of outdoor spaces surrounded by multi-residential buildings	Applied Acoustics	Science Direct	white noise and starter pistols
(Krimm et al., 2017)	Updated urban facade design for quieter outdoor spaces	Journal of Facade Design and Engineering	journals.open.tudelft.nl	Aircraft
(Calleri et al., 2018)	Evaluation of the influence of building façade design on the acoustic characteristics and auditory perception of urban spaces	Building Acoustics	SAGE Journals	voices and human activities

(Badino et al., 2019)	Effect of façade shape and acoustic cladding on reduction of leisure noise levels in a street canyon	Building and Environment	Science Direct	Human Activity and Leisure Noise (talking people)
(Badino et al., 2021)	Façade design through parametric modelling for environmental noise mitigation in a courtyard	Proceedings of Euronoise 2021	iris.polito.it	Human Activity and Leisure Noise

In urban environments, various noise sources contribute to the acoustic landscape, and these can be broadly categorized into a few key types. The Traffic-Related Noise category includes studies on road traffic and related sources. One such study used ribbon tweeters to replicate road traffic noise in a scale model, focusing on high frequencies from 1 kHz to 40 kHz. This approach aimed to assess the noise reduction effect of vegetation in urban environments (Jang, Kim, et al., 2015). Other research explored the broader impact of road traffic and urban activities on sound propagation, highlighting the significance of architectural measures in mitigating traffic noise (Kang, 2000, 2001, 2005). Additionally, a study on automobile air-horns examined how sound levels vary with distance in built-up areas, emphasizing the role of surrounding buildings in shaping sound propagation (Yeow, 1977). Road traffic, as a primary noise source, continues to be a major focus in many urban noise studies, with research examining how it affects sound propagation and potential architectural solutions for noise control (Montes González et al., 2018).

Human activity and leisure noise play a significant role in shaping urban soundscapes. The COVID-19 pandemic brought a major shift in how people interact with their environment, initially leading to a drastic reduction in noise levels due to lockdowns and restrictions (Lecocq et al., 2020). During this period, many urban areas experienced an unprecedented quietness, heightening awareness of environmental sounds and their significance in daily life. Soundscapes, once dominated by human activities, briefly reflected a new balance between natural and built environments.

As restrictions eased, outdoor socializing and dining became more prominent, leading to a resurgence of human-generated noise (Caniato et al., 2021). This shift not only restored familiar

urban soundscapes but also reshaped perceptions of public spaces and the role of sound in social interactions. Research on leisure noise, particularly from people talking, has gained prominence in this context. For example, one study modeled the noise from a group of people talking in urban courtyards and outdoor terraces (Badino et al., 2021). Similarly, research in the San Salvario neighborhood focused on small group conversations, simulating these sounds based on interviews and questionnaires to better understand the evolving sonic environment (Calleri et al., 2018).

Impulse noise sources, such as those used in the study of Impulse Noise Sources, are also significant in urban acoustics. For example, a study used a fixed pistol as an impulse noise source to investigate sound propagation in street canyons, measuring sound pressure levels and reverberation times at various locations (Picaut et al., 2005). Firecrackers were similarly used as an impulse source to explore external reverberation in dense urban environments, with the research focusing on how distributed noise sources, like traffic, influence transient sound levels and background noise levels (Yeow, 1977). Another study examined white noise and starter pistols in apartment complexes, aiming to understand their effects on sound attenuation and reverberation times in outdoor spaces (Yang et al., 2013, 2017). White noise, defined as a signal with equal intensity (power) across all frequencies, results in a flat frequency spectrum when displayed linearly. In acoustics, it's widely used for testing sound systems and measuring sound pressure level (SPL) attenuation because it provides a uniform stimulus across the entire frequency range. From an auditory perception perspective, white noise sounds like a hiss, as higher frequencies dominate due to the sensitivity of human hearing.

The Elevated and Mechanical Noise Sources category covers noise from devices such as air conditioners, cooling towers, and sirens. One study examined the impact of elevated noise sources like air conditioners and cooling towers in narrow street canyons, noting their role in shaping the overall sound field due to reflections and interference effects from building facades (Iu & Li, 2002). Sirens were also studied to understand their attenuation rates in urban areas, with the research revealing significant differences between street-level and elevated sources (Wiener et al., 1965). Additionally, piling operations, particularly from sheet steel and H-steel piles, were used to measure reverberation times in high-rise environments, offering insights into how different mechanical noise sources affect urban acoustics (C. P. TANG, personal communication, 1978).

Finally, Environmental and Propagation Studies focus on how different factors, such as environmental conditions and the geometry of urban spaces, influence sound propagation and acoustics. For instance, the decay of 1/3-octave pink noise — a signal where intensity decreases by 3 dB per octave, giving equal power per octave and resulting in more energy in lower frequencies — was investigated to understand sound absorption and reverberation effects in urban settings. Pink noise is widely used in acoustic studies for evaluating room acoustics and simulating how sound behaves in spaces, as it mimics natural sounds and aligns closely with human auditory perception. Compared to white noise, it sounds deeper and more balanced, making it particularly useful in understanding sound scattering and absorption. In this context, ivy foliage being examined for its role in sound scattering and absorption (Aylor et al., 1973).

Other studies looked at the use of omnidirectional point sources and line sources to analyze sound pressure levels and reverberation times in urban streets with different geometries (Lee & Kang, 2015). Additionally, research on urban noise sources and aircraft noise explored the impact of reflective materials on sound propagation, highlighting the importance of tailored acoustic solutions in urban environments (Krimm et al., 2017).

Together, these studies emphasize the diverse and complex nature of urban noise environments, highlighting the influence of traffic, human activities, mechanical noise sources, and environmental factors in shaping the overall acoustic characteristics of urban spaces (Figure 2.2).

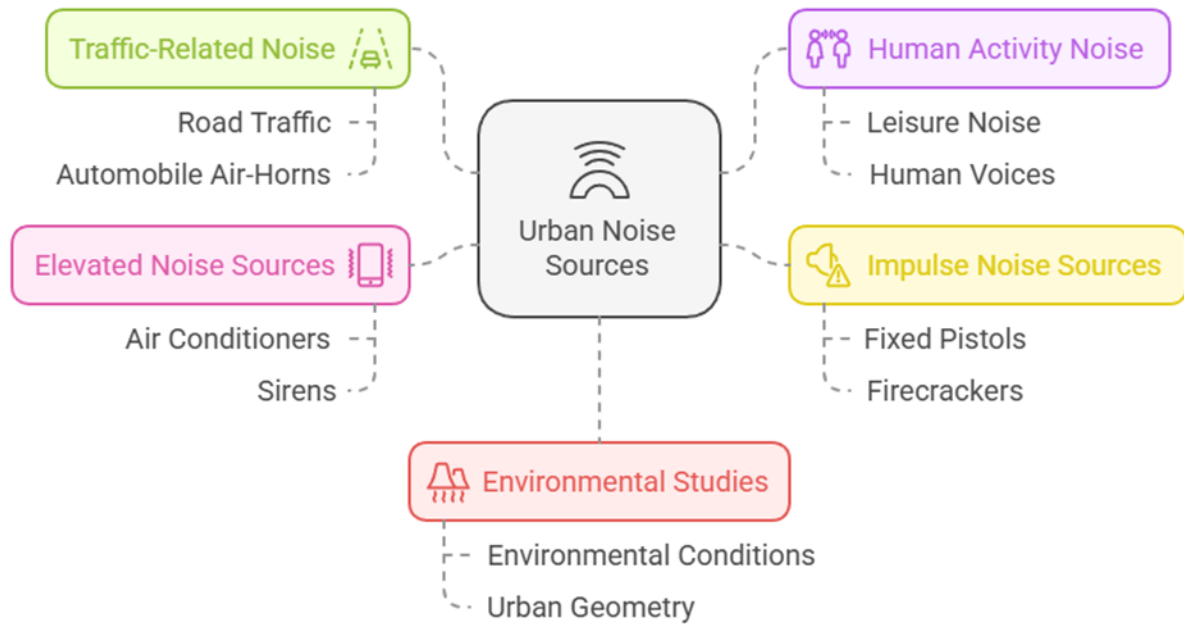


Figure 2-2: Urban noise source types extracted through the body of the literature. Source: (author).

The literature highlights a wide range of noise sources that contribute to the acoustic environment of urban outdoor spaces. These include traffic noise, leisure noise, impulsive noise, elevated noise sources, human-generated noise, and white/pink noise. Understanding the characteristics of these sources and their interactions with urban structures is essential for developing strategies to mitigate noise pollution and enhance the acoustic comfort of urban spaces. The research reviewed also demonstrates the importance of considering various factors, including architectural design, vegetation, and urban planning, in managing urban noise environments effectively.

4. Sound propagation and built morphology in outdoor sound environment

The configuration of the constructed environment significantly affects the acoustic characteristics of outdoor spaces (Benameur, 2023; Benameur et al., 2022; Bouzir, 2018; Bouzir et al., 2020; Bouzir & Zemmouri, 2017; Guedes et al., 2011; Oliveira & Silva, 2010; Silva et al., 2014; B. Wang & Kang, 2011). Its many attributes possess the capacity to alter noise levels. The

configuration and organization of the building plan, as a crucial feature, may influence the acoustic characteristics of the sound environment.

Sound propagation in outdoor urban environments is significantly influenced by architectural boundaries, particularly building layouts, façade designs, and courtyard shapes (Figure 2-3). This section explores the role of these design elements in shaping the acoustic environment. By reviewing studies on building configurations, façade designs, and courtyard geometries, we aim to understand their effects on acoustic parameters such as sound pressure level (SPL), reverberation time (RT), and speech intelligibility indices. The insights provided will help establish the relevance of these design aspects to this thesis, which focuses on the acoustic behavior of urban spaces, especially in academic settings.

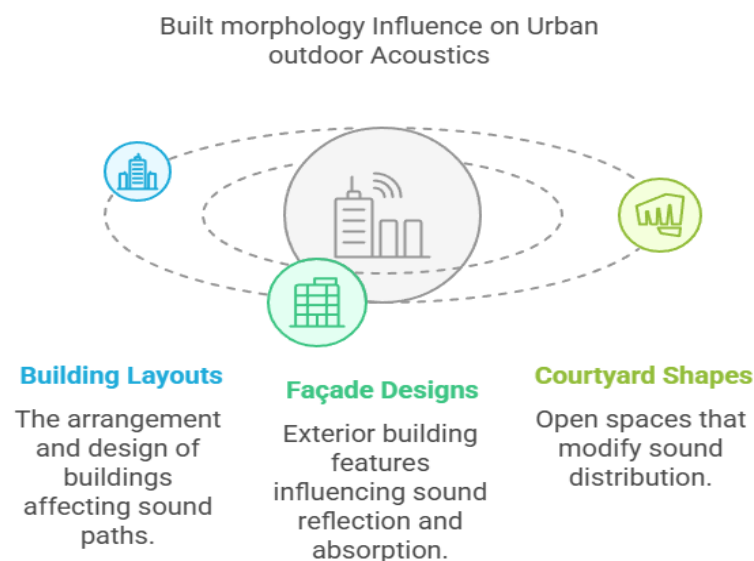


Figure 2-3:Part of Built Morphology's Influence on Urban Outdoor Acoustics. Source: (author)

Understanding the mechanisms of sound propagation and the role of physical boundaries is essential for creating acoustically comfortable urban environments. As the Table 2-3 and 2-4 show, this section delves into how building layout, façade design, and courtyard configurations

influence sound behavior, offering a foundation for strategies to mitigate noise and enhance acoustic performance.

4.1. Building Layout Effects on Outdoor Sound Environment

Building layout shapes and arrangements are pivotal in altering the acoustic characteristics of outdoor environments. This subsection reviews key studies that explore the influence of building configurations, including linear, square, U-shaped, and parallel layouts, on sound propagation. The findings reveal how these configurations affect parameters like sound attenuation, reverberation time, and noise exposure, emphasizing their relevance to urban noise management strategies.

Table 2-3

Studies on the Acoustic Impacts of Urban Morphology and Building Layout Configurations.

Author	Title	Publication Title	Data base	Aim of the study
(Yang et al., 2013)	Acoustic characteristics of outdoor spaces in an apartment complex	Noise Control Engineering Journal	Ingenta Connect	The effect of building's design and arrangement such as linear, and parallel
(Thomas et al., 2013)	Reverberation-based urban street sound level prediction	The Journal of the Acoustical Society of America	Silverchair	The effect of roadway width on building height
(Ariza-Villaverde et al., 2014)	Influence of urban morphology on total noise pollution: Multifractal description	Science of The Total Environment	ScienceDirect	The effect of roadway width on building height
(Lee & Kang, 2015)	Effect of Height-To-Width Ratio on the Sound Propagation in Urban Streets	Acta Acustica United With Acustica	discovery.ucl.ac.uk	The effect of roadway width on building height
(Echevarria Sanchez et al., 2016)	The effect of street canyon design on traffic noise exposure along roads	Building and Environment	ScienceDirect	flat vertical, flat upwardly inclined, flat downwardly inclined, upwardly stepped convex, downwardly

				stepped, and concave surfaces
(Yang et al., 2017)	An experimental study on the acoustic characteristics of outdoor spaces surrounded by multi-residential buildings	Applied Acoustics	ScienceDirect	building's design and arrangement such as linear, square, U-shaped, and parallel
(Flores et al., 2017)	A Case Study of the Influence of Urban Morphology on Aircraft Noise	Acoustics Australia	Springer Link	building's design and arrangement such as linear and parallel
(Han et al., 2018)	Analysis of the relationships between environmental noise and urban morphology	Environmental Pollution	ScienceDirect	continuous, interconnected structures. The dispersed arrangement and irregular shapes of structures
(Eggenschwiler et al., 2022)	Urban design of inner courtyards and road traffic noise: Influence of façade characteristics and building orientation on perceived noise annoyance	Building and Environment	ScienceDirect	the orientation of walls (parallel versus non-parallel)

Prior work has studied how the properties of fabric environments connected with building plan shape impact the acoustic atmosphere of outdoor spaces. The effect of roadway width on building height was investigated by Ariza-Villaverde et al. (2014), Lee and Kang (2015), and Thomas et al. (2013). The results show that the H/W ratio had an effect on the variability of sound properties. Echevarria Sanchez et al. (2016) looked at how the overall shape of a structure affects the amount of noise that people are exposed to, specifically in regard to the street canyon effect. The results indicated that flat vertical, flat upwardly inclined, flat downwardly inclined, upwardly stepped convex, downwardly stepped, and concave surfaces could have a significant impact on the amount of noise that people are exposed to. Eggenschwiler et al.(2022) conducted research to examine how building rotation, specifically the orientation of walls (parallel versus non-parallel), affects the feeling of discomfort caused by noise. The rotation of the building, which caused the walls to be non-parallel, was shown to be associated with a decrease in noise disturbance when compared to the initial orientation, in which the walls were parallel. This outcome was affected by the decrease in sound intensity, but the favorable impact persisted even when the sound levels were same for both spinning and parallel structures.

Further research indicates that various morphological aspects of building layouts may influence the acoustic environment. The studies Flores et al. (2017), Yang et al. (2013) and (2017) examine the impact of building configuration and arrangement on acoustical parameters including RT, EDT, D50, and RASTI, as well as the reduction of sound pressure levels in outdoor areas. They underline that the building's design and arrangement such as linear, square, U-shaped, and parallel—significantly impact the acoustic environment.

Han et al. (2018) seeks to investigate the influence of geographical landscape characteristics on Urban Environment Noise (UEN) and transportation noise within the Shenzhen metropolitan region of China. The research demonstrated significant relationships between urban morphology and regional traffic noise levels (RN/TN). The design and architecture of buildings significantly correlate with registered nurses (RNs). The configuration of buildings correlates with traffic noise (TN), and continuous, interconnected structures next to highways are more effective in mitigating the effects of traffic noise (TN). The dispersed arrangement and irregular shapes of structures contribute to the mitigation of regional noise (RN). Buildings are more effective in noise mitigation when distributed across urban areas rather than concentrated in a single location.

While outdoor spaces at universities may have some similarities to urban streets, squares, and built-up areas, they come in a broad range of layouts, styles, and sizes. Due to the changes in the arrangement of buildings, the materials that are used, and the layout of the façade, it is necessary to do additional work in order to assess the acoustic characteristics of outdoor areas within these different cognitive frameworks.

4.2. Façade Design Effects on Outdoor Sound Environment

Façade design is a critical element in shaping the sound environment of urban areas. This subsection examines the impact of façade height, material, and configuration on sound propagation. By analyzing studies on vertical greenery systems, height-to-width ratios, and aeroacoustic performance, it highlights the complex interplay between façade features and noise levels. These insights inform the development of façade designs that optimize acoustic comfort.

Table 2-4:

Studies on the Acoustic Impacts of Urban Morphology and Building Facade Configurations

Author	Title	journal	Database	Aim of the study
(Thomas et al., 2013)	Reverberation-based urban street sound level prediction	The Journal of the Acoustical Society of America	Silverchair	The relationship between building facade height and sound levels.
(Naish et al., 2013)	Speech interference and transmission on residential balconies with road traffic noise	The Journal of the Acoustical Society of America	PubMed	Effect of the residential balconies and the height of the opposite facade on road traffic noise
(Ismail, 2013)	Quiet environment: Acoustics of vertical green wall systems of the Islamic urban form	Frontiers of Architectural Research	Science Direct	Investigated the sound propagation characteristics of vertical greenery systems on street facades
(Ariza-Villaverde et al., 2014)	Influence of urban morphology on total noise pollution: Multifractal description	Science of The Total Environment	Science Direct	Examine the relationship between street width to building height ratio and noise pollution in urban areas
(Can et al., 2015)	Accounting for the effect of diffuse reflections and fittings within street canyons, on the sound propagation predicted by ray tracing codes	Applied Acoustics	Science Direct	Emphasizing the role of height to width (H/W) ratios in sound attenuation.
(Magrini & Lisot, 2016)	A simplified model to evaluate noise reduction interventions in the urban environment	Building Acoustics	SAGE Journals	The relationship between building facade height and sound levels.

(F. Liu & Kang, 2018)	Relationship between street scale and subjective assessment of audio-visual environment comfort based on 3D virtual reality and dual-channel acoustic tests	Building and Environment	Science Direct	The effects of facade configurations (The height of buildings (H)) on comfort evaluations in urban environments.
(Dragna et al., 2022)	Sonic boom reflection over an isolated building and multiple buildings	The Journal of the Acoustical Society of America	Silverchair	Impact of building height on noise reflection and aeroacoustic performance

The impact of building facade height on the sound environment has been a subject of interest in various research studies. Can et al. (2015) explored the influence of geometrical and acoustical parameters on sound levels, emphasizing the role of height to width (H/W) ratios in sound attenuation. Ariza-Villaverde et al. (2014) utilized multifractal analysis to examine the relationship between street width to building height ratio and noise pollution in urban areas. Ismail (2013) investigated the sound propagation characteristics of vertical greenery systems on street facades, highlighting the benefits of installing greenery for sound attenuation. Liu and Kang (2018) studied the effects of different facade configurations, including the height parameter, on acoustic comfort in urban settings. Thomas et al. (2013) and Magrini and Lisot (2016) also contributed insights on the relationship between building facade height and sound levels. Furthermore, Dragna et al. (2022) and Xu and Xu (2018) explored the impact of building height on noise reflection and aeroacoustic performance, respectively. Naish et al. (2013) developed a regression model to predict speech interference levels on residential balconies and the height of the opposite facade exposed to road traffic noise. These studies collectively contribute valuable insights into understanding the complex relationship between building facade height and the sound environment.

The studies mentioned regarding the impact of building facade height on the sound environment may not provide a comprehensive understanding of the complexities involved in sound propagation in urban settings. While some studies suggest a direct relationship between building

height and sound levels in the street context, other factors such as surrounding landscape and urban layout such as the courtyard may also play a significant role in determining the sound environment.

4.3. Courtyard Shape Effects on Outdoor Sound Environment

Courtyards play a crucial role in mitigating background noise in outdoor environments, particularly from external sources such as road traffic (Yang et al., 2017). Their enclosed or semi-enclosed geometry acts as a natural shield, significantly reducing noise intrusion and creating a more controlled acoustic environment. Studies indicate that courtyards can lower external noise levels by approximately 4–9 dB(A), depending on variables such as building layout, façade height, and courtyard dimensions (Bakker et al., 2023). This reduction enhances acoustic comfort by limiting disruptive urban noise; however, it also alters the internal soundscape. Lower background noise levels increase the signal-to-noise ratio (S/N), making sounds from human conversation, pedestrian activity, and other internal sources more pronounced. Without appropriate acoustic treatments, this amplification can lead to excessive reverberation and noise buildup, potentially affecting both outdoor and adjacent indoor spaces (Yang et al., 2017).

Several architectural and material factors influence the acoustic efficiency of courtyards. The height of surrounding buildings plays a vital role in noise attenuation—taller façades provide greater shielding from external noise but can also contribute to prolonged reverberation if surfaces are overly reflective inside the courtyard (Hamouta et al., 2024). The materials used for courtyard surfaces further affect sound behavior; highly reflective materials, such as concrete or glass, intensify sound reflections and increase reverberation time (RT), whereas absorptive materials like porous stone or vegetation help dissipate sound energy (Crippa et al., 2019; Eggenschwiler et al., 2024). Additionally, façade articulation impacts sound diffusion—smooth, flat surfaces create strong reflections, whereas textured or perforated façades help scatter sound, improving overall acoustic comfort (Badino et al., 2021). Integrating green walls, vegetation, and permeable surfaces can further enhance acoustic performance, as plants act as natural sound absorbers, reducing high-frequency noise and minimizing reflections. By strategically considering these elements, courtyards can be optimized to function not only as effective noise barriers but also as pleasant,

balanced sound environments conducive to both social interaction and relaxation (Bakker et al., 2023).

5. Urban outdoor sound environment in Algerian context

Noise pollution in Algeria has emerged as a critical environmental concern, driven by rapid urbanization and growing traffic volumes, especially in cities like Biskra, Guelma, and Annaba. These regions face significant challenges in managing noise, with urban planning strategies often falling short of addressing the scale of the problem.

The Algerian government has recognized noise pollution as a concern since the 1980s, implementing laws such as the Executive Decree No. 93-184, which sets noise limits in urban areas to 70 dB, aligning with WHO standards, although this is often exceeded in residential zones (Bouzir et al., 2017; Bouzir & Zemmouri, 2018).

Studies in Biskra have shown that noise levels frequently surpass these limits, with traffic identified as the primary source of noise pollution, affecting public health and quality of life (Bouzir et al., 2017; Bouzir & Zemmouri, 2018). Similarly, research in Guelma highlights the discomfort and health risks posed by noise pollution, with residents experiencing stress and anger due to high noise levels from road traffic and neighbors (Ali & Zohra, 2022; Boulemaredj & Amel, 2023). In addition, another research investigates environmental noise assessment in Annaba City, Algeria, examining the effects of executive decrees N°93-184 and N°03-410 on permissible noise levels. It underscores the health risks of noise pollution, including increased psychiatric admissions and other complications identified by the WHO. An extensive measurement campaign revealed noise levels between 55 dB and 96 dB, primarily from transportation, often surpassing legal limits, raising concerns about public health and environmental quality (Boulemaredj, n.d.).

Despite these challenges, there is a lack of comprehensive noise mapping and standardized models for noise assessment in Algeria, which hinders effective management and mitigation efforts (Boulemaredj & Amel, 2023). The literature suggests that noise pollution is not only a public health issue but also a social concern, impacting mental health and contributing to cardiovascular diseases (Ali & Zohra, 2022; Boulemaredj, n.d.). Efforts to address noise pollution

in Algeria include the development of noise maps and the enforcement of national regulations, although these are often not fully implemented or adhered to (Boulemaredj, n.d.). The need for improved public awareness and stricter enforcement of noise regulations is evident, as is the necessity for more detailed studies and data collection to inform policy and urban planning (Ali & Zohra, 2022; Boulemaredj, n.d.). Overall, while there are legislative frameworks in place, the practical application and public awareness of noise pollution's impacts remain limited, necessitating further research and action to mitigate its effects on Algerian society.

- Morphology of building impact on outdoor acoustic in Algerian context

The relationship between urban spatial configuration and environmental soundscape has been the subject of various studies. One such study, conducted by (Benameur et al., 2021), aimed to investigate this relationship in two distinct areas: the historic center of Pisa in Italy and the downtown of Biskra in Algeria. The researchers employed Space Syntax theory to predict noise level distribution across these urban areas. The study found a close relationship between the measured sound levels and Space Syntax theory's global and local indexes, such as Normalized Choice and Integration. This result highlighted the effectiveness of Space Syntax in describing sound phenomena in different urban contexts, emphasizing its value in understanding the acoustic environment of diverse cities.

In another study conducted in Biskra, the acoustic environment of the city's urban layouts was examined, with a particular focus on the lack of acoustic data and standards for urban planning in Saharan settlements. The researchers adopted a multidisciplinary approach, combining both objective measurements and subjective assessments. Their findings revealed a moderate to high positive correlation between syntactic measures at both global and local scales, emphasizing the significant role spatial variables play in shaping urban acoustic patterns and noise pollution (Benameur, 2023).

Similarly, a study on an oasis university campus used a multisensory approach to explore the interactions between luminous, thermal, and auditory environments. The architectural design was found to effectively mask mechanical noise while enhancing the soundscape with natural sounds,

such as water fountains. These findings indicated a significant correlation between the luminous and auditory dimensions, highlighting how these factors influence environmental perception (Berkouk et al., 2022).

Further investigation into Biskra's urban morphology revealed its impact on road noise distribution. The study, which used noise mapping and Pearson correlation tests across ten community housing areas, demonstrated a strong connection between urban form and noise levels. This underscored the critical role that urban design plays in creating sustainable acoustic environments (Bouzir & Zemmouri, 2017).

In the oasis cities of El Kantara and Sidi Okba, urban morphology was shown to significantly influence soundscapes. Areas with older urban fabrics, characterized by low traffic noise, were identified as Hi-Fi soundscapes, while regions near national roads, dominated by traffic noise, were classified as Lo-Fi soundscapes. This distinction emphasized the loss of sound identity in areas heavily affected by traffic (Bouzir et al., 2020).

Noise pollution in Biskra was also studied in relation to national and international recommendations. Through an extensive in-situ measurement campaign, the research revealed that urban morphology strongly impacts the quality of the sound environment, with over 90% of measurements in old urban fabrics exceeding international noise level limits. This highlighted the severity of noise pollution across urban areas (Bouzir & Zemmouri, 2018).

A study examining soundscapes in Biskra's public spaces found that areas near roads with high mechanical flow were the most unpleasant and noisy. These areas had high A-weighted equivalent continuous sound pressure levels, correlating unpleasantness and loudness with the presence of mechanical and non-mechanical sounds. This emphasized the importance of urban design in improving soundscape quality (Bouzir & Zemmouri, 2018).

Finally, research on the relationship between acoustic environments and spatial configurations in Biskra provided valuable insights into how urban morphology influences sound propagation and noise levels. Data collected from 240 measurement stations offered crucial information for urban

planning and soundscape management, underscoring the importance of spatial configurations in shaping urban soundscapes (Benameur et al., 2022).

6. Outdoor sound environment at the university context

6.1. Outdoor spaces design at university context

Outdoor spaces at universities play a crucial role in enhancing the overall campus environment and student experience. These spaces are not merely aesthetic additions but serve as vital components of a healthy and engaging campus life. They provide opportunities for social interaction, relaxation, and informal learning, which are essential for student well-being and academic success (Lau et al., 2014; Salama, 2008). The design of outdoor spaces can significantly impact students' stress levels and mental health, as they offer a break from the structured indoor environments and foster a sense of community and belonging (Lau et al., 2014). For instance, green spaces and healing gardens are known to have restorative effects, promoting relaxation and reducing stress among students (Lau et al., 2014). Moreover, the integration of open spaces with campus buildings can enhance the usability and functionality of these areas, making them more inviting and conducive to various activities (Salama, 2008). The literature suggests that well-designed outdoor spaces can also improve wayfinding and accessibility, which are critical for creating a user-friendly campus environment (Salama, 2008). Additionally, the presence of natural elements such as trees and greenery is associated with higher student satisfaction and a positive perception of campus quality (Agrawal & Yadav, 2021). The ecosystem approach to campus design emphasizes the importance of these spaces in nurturing student growth and development, highlighting their role in evoking student potential and enhancing consciousness (Kaiser, 1975). Overall, the thoughtful design and utilization of outdoor spaces are integral to achieving a supportive and dynamic university environment that caters to the diverse needs of its community.

6.2. Outdoor sound environment at the university context

The sound environment in university settings significantly influences academic, social, and health-related outcomes for students and staff. Noise pollution, a common issue in educational institutions, stems from sources such as traffic, construction, campus activities, and inadequate

building acoustics. Research has demonstrated that noise levels in university contexts frequently exceed recommended thresholds, adversely impacting concentration, cognitive performance, and well-being.

Studies from diverse contexts underscore the prevalence and effects of noise pollution. For instance, at Mahindra University, indoor noise levels in classrooms and laboratories often exceeded the World Health Organization's (WHO) recommended limit of 55 dB, reaching up to 80 dB, posing risks to students' physical and mental health (Magrini & Lisot, 2016). Similarly, research at Chinese universities highlights the contribution of campus activities, sports, and road traffic to low satisfaction with the acoustic environment, adversely affecting academic performance and well-being (Su et al., 2013). At Balasore in India, traffic noise around university campuses ranged from 70.4 to 121.2 dB, far surpassing permissible limits and underscoring the role of vehicular traffic as a major noise source (Goswami et al., 2011).

In Brazil, studies conducted at the Federal University of Parana revealed that noise levels at nearly 90% of measurement points exceeded the 55 dB(A) limit, causing concentration difficulties and irritation among students and staff (Zannin et al., 2013). Similar issues were observed at Cukurova University in Turkey, where noise mapping showed that most of the campus was exposed to traffic noise levels detrimental to effective learning (Çolakkadıoğlu et al., 2018).

The detrimental effects of noise on cognitive performance are well-documented. Excessive noise can impair attention, disrupt communication, and hinder academic achievement. For example, research in schools has demonstrated that chronic exposure to traffic and aircraft noise negatively affects reading abilities and memory, suggesting similar vulnerabilities in university students (Xie et al., 2011). Additionally, noise combined with environmental stressors, such as air pollution, has been linked to exacerbated cognitive decline, emphasizing the compounded risks in polluted urban university settings (Tzivian et al., 2017).

Effective management of the sound environment is essential to mitigate these adverse effects. Strategies such as noise mapping, sound insulation, improving building acoustics, controlling traffic flow, and strategic campus planning can help reduce noise pollution. Raising awareness

among students and staff about the impacts of noise is another critical step in fostering healthier, more conducive learning environments. These measures, alongside comprehensive studies on acoustic environments, are vital for enhancing academic performance, well-being, and overall quality of life on university campuses.

7. Conclusion

This chapter has provided a comprehensive review of noise sources, propagation mechanisms, and their impacts on urban outdoor environments, with a particular emphasis on acoustic parameters that influence sound perception and quality. By examining reverberation time (RT20), early decay time (EDT), definition index (D50), rapid speech transmission index (RaSTI), and sound pressure level (SPL), this study established a framework for assessing urban soundscapes and their implications for public spaces. These acoustic parameters are essential for evaluating how noise interacts with the built environment, affecting both human perception and overall urban livability.

A key focus of this chapter was the role of urban morphology in shaping sound propagation and noise distribution. The spatial arrangement of buildings, façade designs, and courtyard geometries significantly influence sound attenuation, reverberation patterns, and speech intelligibility in outdoor settings. Research findings indicate that enclosed courtyards and dense urban layouts tend to sustain higher reverberation times due to multiple reflective surfaces, whereas open configurations promote greater sound dissipation. These findings underscore the necessity of integrating acoustic considerations into urban planning and architectural design to mitigate excessive noise while enhancing speech clarity and environmental comfort.

In addition to discussing general urban noise challenges, this chapter examined the specific context of noise pollution in Algeria, focusing on cities such as Biskra, Guelma, and Annaba. Studies on these urban environments highlighted how variations in building density, street configurations, and open space designs affect noise levels and sound propagation. The findings revealed that unplanned urban expansion, increased motorized traffic, and insufficient noise barriers contribute to elevated noise pollution levels, exacerbating public health concerns and diminishing overall urban quality.

Furthermore, the chapter explored the acoustic environment in university settings, emphasizing the adverse effects of noise pollution on student concentration, cognitive performance, and psychological well-being. Given that educational institutions rely heavily on effective verbal communication and focused learning, excessive noise in outdoor spaces can hinder academic productivity and social interactions. The need for strategic acoustic interventions—such as optimized courtyard layouts, façade treatments, and vegetation barriers—was emphasized to foster acoustically comfortable learning environments on university campuses.

In conclusion, this chapter highlights the interdisciplinary nature of urban noise management, bridging insights from environmental acoustics, urban planning, and architectural design. Addressing noise pollution requires a holistic approach that integrates policy regulations, design innovations, and material advancements to create sustainable and livable urban soundscapes. Future research should further explore the long-term effectiveness of noise mitigation strategies, the role of psychoacoustics in urban planning, and advanced modeling techniques for predicting noise behavior in complex environments. By prioritizing acoustic quality in urban development, cities can enhance public health, social well-being, and the overall functionality of outdoor spaces, ensuring more inclusive and sustainable urban living conditions.

Chapter 3

Methodology

Chapter 3: Methodology

1. Introduction

This chapter outlines the methodological approach used to investigate the influence of building morphology on the outdoor acoustic environment. The study aims to systematically analyze how different architectural configurations affect key acoustic parameters, such as reverberation time (RT), early decay time (EDT), sound pressure level (SPL) attenuation, and speech intelligibility (RaSTI). To ensure the reliability and accuracy of the results, a structured measurement protocol was established, adhering to standardized acoustic assessment techniques.

The methodology consists of several key components: (1) a detailed description of the case study areas, including their architectural characteristics and spatial configurations; (2) the research approach, which defines the study design and objectives; (3) data collection techniques, covering the measurement procedures, equipment, and signal processing methods; (4) environmental conditions, highlighting the steps taken to minimize external factors that could influence the results; and (5) analysis methods used to interpret the measured data.

The selected case study sites, located within Batna 1 University, were chosen based on their representative architectural features and variation in façade heights, courtyard geometries, and enclosure degrees. Acoustic measurements were conducted using impulse response techniques with a starter clapper as the sound source, ensuring consistency across different locations. Additionally, sound pressure level attenuation was measured using a directional speaker and white noise, analyzed through EASERA software.

By detailing the methodology, this chapter provides a clear framework for understanding how the study was conducted and ensures transparency in data collection and analysis. The structured approach enhances the validity of the findings and allows for potential replication in similar urban and architectural contexts. Figure 3-1 provides a visual summary of the methodological framework, illustrating the key components of the study, including case study classifications, experimental setup, and acoustic analysis parameters.

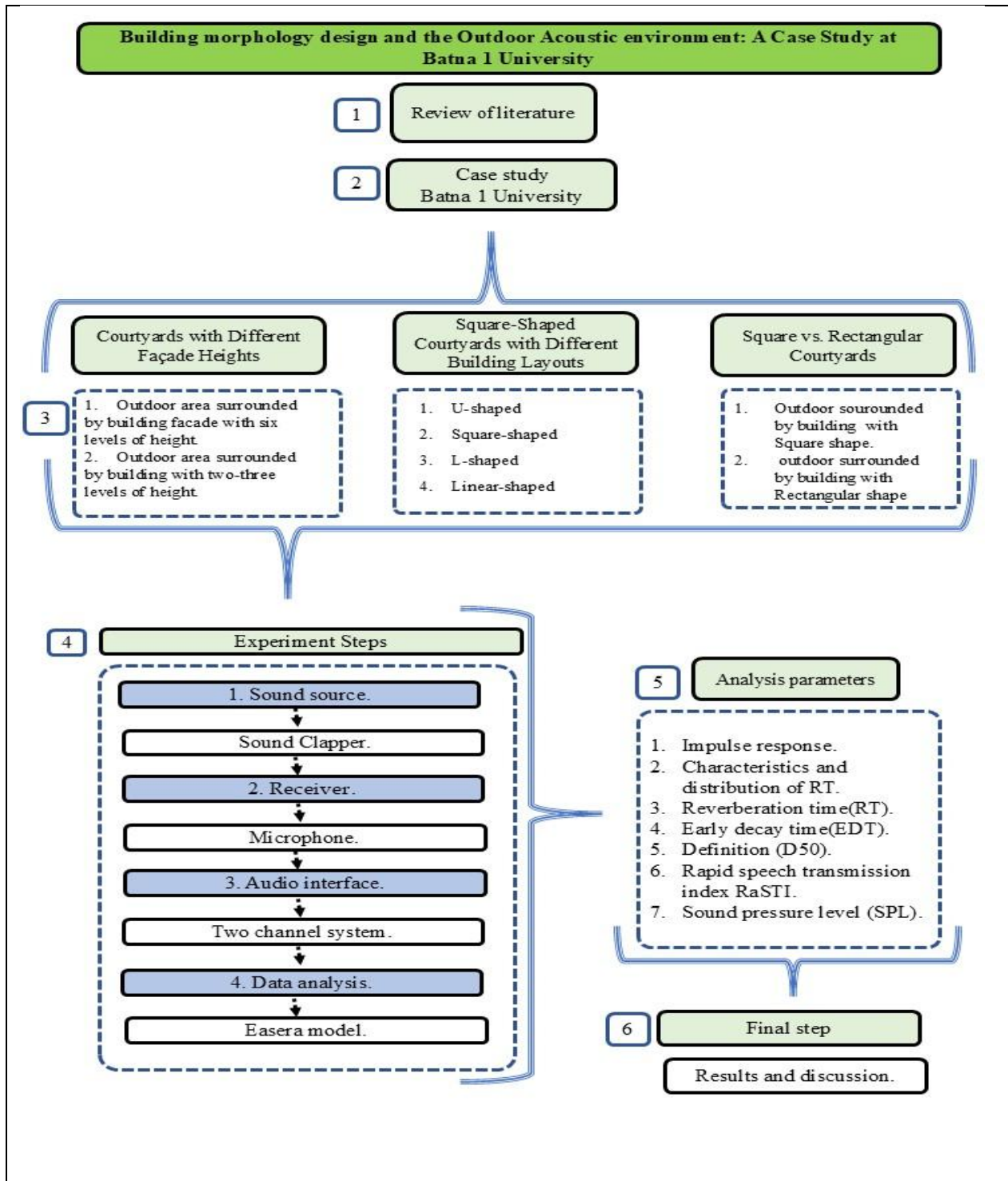


Figure 3-1: Methodological Framework of the Current Research. Source: (author)

2. General context

The city of Batna (Figure 3-2), located in eastern Algeria, approximately 435 kilometers from the nation's capital, Algiers. It is situated at the crossroads of routes connecting Constantine, Biskra, and Khenchela, lies on a plateau surrounded by mountains with elevations ranging from 714 to 2192 meters. The region comprises two main areas: the North-East and North-West, characterized by rugged mountainous terrain with steep slopes exceeding 25°, and a lower-altitude section with gentle slopes under 8°. Batna's urban area has seen significant growth over the years, expanding from 1331 hectares in 1987 to over 2056 hectares in 2001, and from 2852 hectares in 2013 to more than 2880 hectares in 2018 (Abdelhalim, 2022, p. 4).

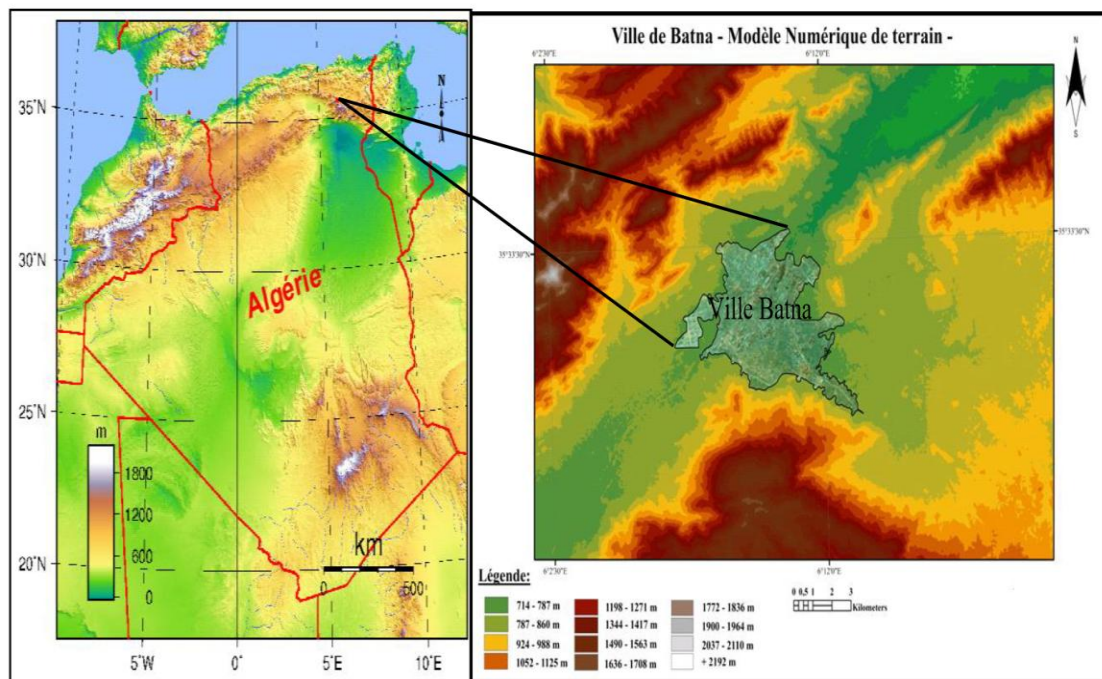


Figure 3-2: Batna city location- source: (Abdelmoumene et al., 2020, p. 158)

According to Meteoblue data, Batna City experiences a semi-arid climate with notable seasonal variations. The average annual temperature shows a rising trend between 14°C to 16°C from 1979 to 2023 (Figure 3-3) Annual precipitation is stable, averaging about 400 mm, with most rainfall occurring in the spring (Figure 3-4).

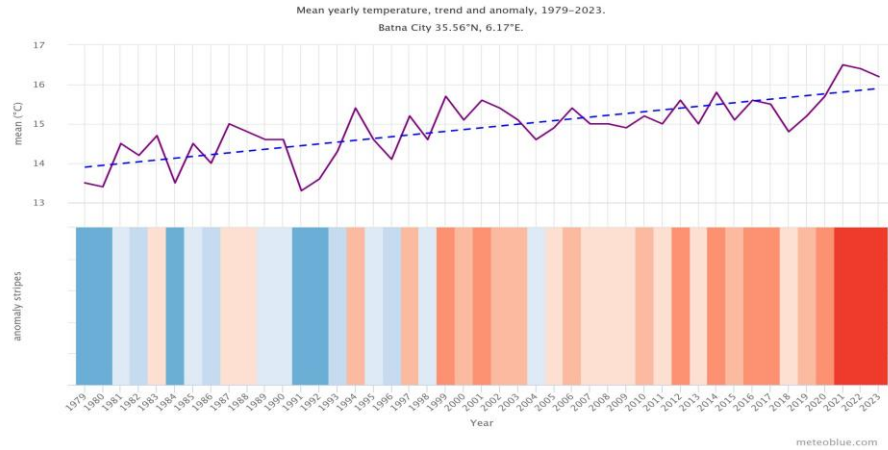


Figure 3-3 : Average annual temperature in Batna city from 1979 to 2023. source: (*Climate Change Batna City*, n.d.)

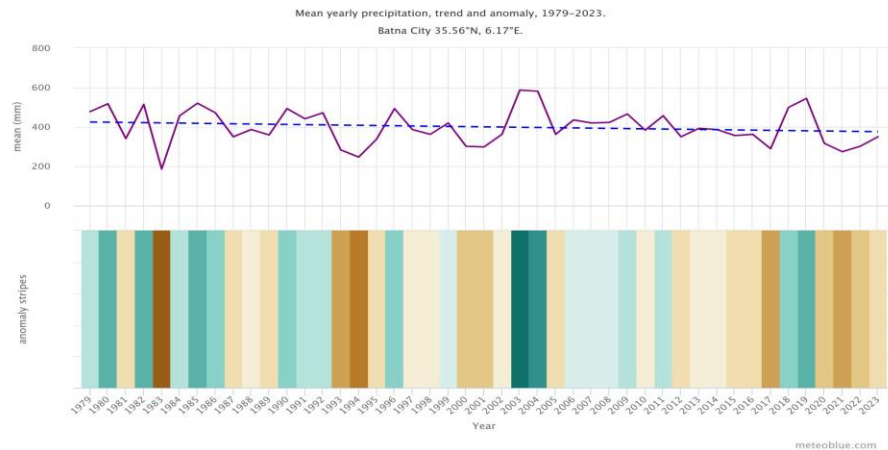


Figure 3-4: Average annual rainfall in Batna city from 1979 to 2023. source: (*Climate Change Batna City*, n.d.)

Throughout 2023 and 2024 (Figure 3-5 and Figure 3-6), temperatures peak above 30°C in the summer, while winters are cooler, with lows around 0°C. Rainfall is mainly in spring and early fall, especially in May, June, and September. Relative humidity is higher in cooler months, and wind patterns remain relatively steady year-round. These conditions highlight the region's typical hot, dry summers and cooler, wetter winters.

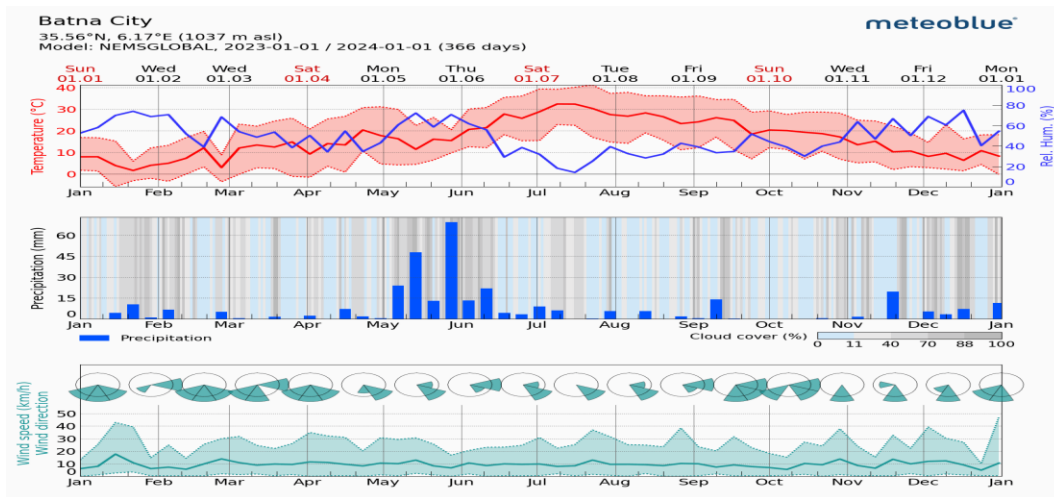


Figure 3-5: Temperature, precipitation and wind speed in Batna city through 2023. source: (Weather Archive Batna City, n.d.)

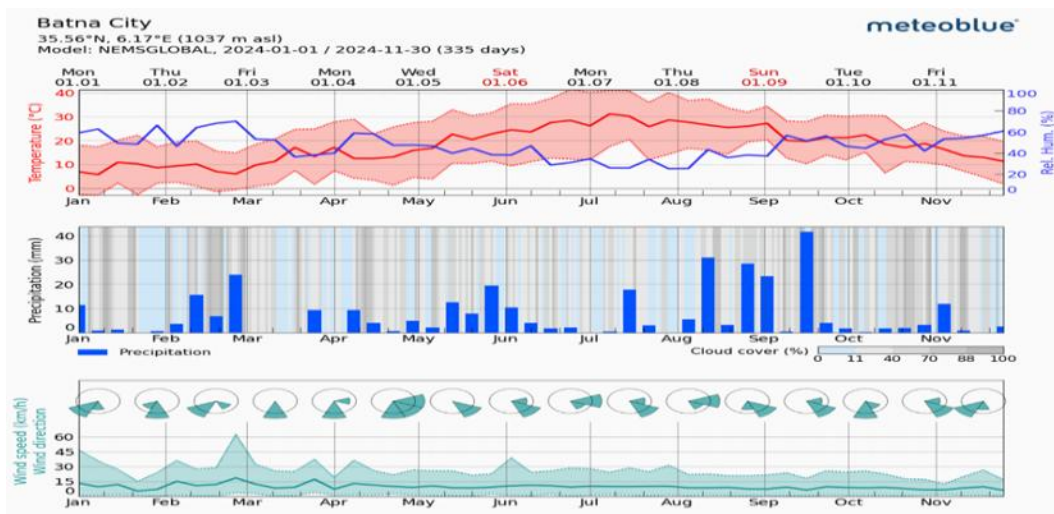


Figure 3-6: Temperature, precipitation and wind speed in Batna city through 2024. source: (Weather Archive Batna City, n.d.)

The population of Batna city has experienced significant growth over the decades, driven by natural increase and migratory dynamics. According to the 2008 General Population and Housing Census (RGPH), the population was 290,645, with an annual growth rate of 1.6% from 1998 to 2008. This growth continued, reaching 378,136 by 2018, as reported by Abdelhalim (2022). Earlier records show that Batna's population was 55,017 in 1966, 98,962 in 1977, 184,069 in 1987,

and 247,520 in 1998. Recent estimates from the United Nations' World Urbanization Prospects (Figure 3-7) place Batna's metro area population at approximately 352,000 in 2024, reflecting an annual growth rate of 1.73% since 2023 (*Batna, Algeria Population 2024*, n.d.). This steady increase underscores Batna's role as a regional hub and its expanding urban agglomeration, which includes the city and adjacent suburban areas. Historically, the population density in 2008 was 2,484 residents per square kilometer over an area of 117 km², illustrating the city's continued urbanization and development.

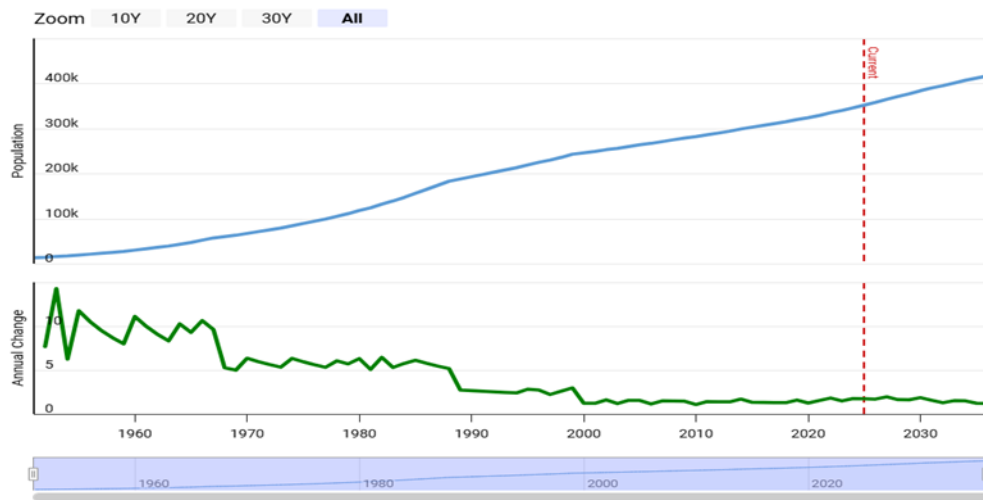


Figure 3-7: Population evolution of Batna city. source: (*Batna, Algeria Metro Area Population 1950-2024*, n.d.)

The city of Batna, despite significant population growth and the emergence of new residential areas such as Hamla 1 and Hamla 2, still has most administrative and commercial facilities concentrated in the city center. The latter attracts a large number of people for reasons related to employment and major facilities, which results in a significant mobility dynamic towards the city center, accompanied by a very high demand for transportation (Aouragh, 2015).

The housing stock in Batna grew from 27,082 units in 1987 to 43,917 in 1998, an increase of 16,800 units. It then rose from 62,932 units in 2008 to 77,757 units in 2012, adding over 19,000 units. A comparison of population growth and housing stock reveals a strong correlation of 99.75%. Moreover, the exponential trend of this growth highlights the phenomenon of urban sprawl, as the housing stock is expanding at a faster pace than the population (Abdelhalim, 2022).

Batna city has an extensive and evolving road network that reflects its urban growth and increasing attractiveness. According to Boubakour (2004), as cited by Guehtar and Saidi (2008), the urban road network was initially 94 kilometers long, structured into distinct configurations: circumvention routes, exchange networks penetrating the city, central road service networks, and local road services for individual districts. More recent data by Abdelhalim (2022) highlights the expansion of this network to a total of 451 kilometers, comprising 12% (51 km) primary roads, 5% (22 km) secondary roads, and 83% (378 km) tertiary roads, underscoring the city's rapid development and the need for efficient connectivity.

According to Kasdallah (2013), the city of Batna is one of the largest and most important economic center of the state (fifth class according to the Algerian city row dynamic). It becomes in a short time a pole of attractiveness and engine of economic growth of the province, where the majority of economic activities are focused in major sectors; the trade (45.50%), the services (38.08%) and industry (16.41%).

Batna city, home to 302,585 residents (0.81% of the national population), has emerged as a key transportation hub in Algeria. The city's vehicle fleet, though steadily growing, is notably aging. By 2012, Batna's 95,000 vehicles represented 2% of the national fleet, translating to a vehicle density of 0.31 vehicles per inhabitant—more than twice the national average of 0.13 vehicles per inhabitant (Aouragh, 2015). This elevated density contributes to substantial traffic flow, increased congestion, and significant environmental impacts, such as air and noise pollution (Aouragh, 2015; Guehtar & Saidi, 2008).

Batna's mobility issues are intensified by its function as a travel hub. High levels of inflows and outflows cause frequent congestion, especially during peak hours. Additionally, the concentration of transport exchanges in the city center results in inefficient trips, particularly for commuters from peripheral areas. These factors combine to exacerbate traffic insecurity and amplify environmental nuisances (Guehtar & Saidi, 2008).

3. Examining the Acoustic Environment of Batna 1 University as a representative Urban Site

Urban soundscapes play a crucial role in shaping the quality of life in cities. Universities, as dynamic urban sites with high population density and diverse architectural forms, present valuable case studies for acoustic analysis. This thesis focuses on Batna 1 University due to its representative urban context and variety of noise sources, including traffic from surrounding roads and internal pedestrian activity. The study aims to assess the acoustic impact of building façade design on outdoor sound propagation and attenuation.

Batna 1 University was founded in 1977 with the establishment of two initial institutes and quickly grew into a prominent academic institution. By 1979, it had added faculties of Biology, Exact Sciences, and Economics, and the Agricultural Institute was introduced in 1984 (Le Décret N° 77-91, 1977; Le Décret N°84-49-50-51-52, 1984). Initially operating from a regional hospital, the university developed its own infrastructure and transitioned into a full-fledged university in 1989 under Executive Decree No. 89/136 (Le Décret exécutif N° 89-136, 1989). Student enrollment grew from 10,000 in 1989 to over 59,000 by 2013(Onec, 2024), with structural reorganizations in 1998 and 2004 introducing new faculties and specialized institutes (Le Décret Exécutif N° 04-247, 2004; Le Décret Exécutif N° 98-389, 1998). In 2015, the university was divided into two independent institutions, Batna 1 University remaining on its original campus and Batna 2 University established at the Fesdis campus. This restructuring allowed both universities to grow independently, enhancing their academic and administrative capacities (Le Décret exécutif N°15-181, 2015).

Batna 1 University is located in the heart of Batna city and is surrounded by major roads and a railway, contributing to a complex acoustic environment. The campus hosts a population of approximately 40,000 students and features a combination of different buildings levels and different layout buildings, characterized by concrete walls, large glass windows, and enclosed and semi enclosed courtyards. These architectural features make the site an ideal model for studying the interaction between urban morphology and acoustic behavior.

3.1. Selection criteria for case study of Batna 1 university

The selection of Batna 1 University as the case study site was guided by a set of well-defined criteria that align with the objectives of the research. These criteria encompass architectural, urban, and environmental characteristics that are essential for examining the acoustic behavior of outdoor spaces. Additionally, practical considerations such as accessibility, safety, and standardization of measurements ensure the feasibility and reliability of the study. The unique features of the university campus, coupled with its relevance to the local urban context, make it an ideal setting for addressing the research gaps in the acoustic analysis of outdoor environments.

3.1.1. Architectural characteristics

The architectural characteristics of Batna 1 University make it a suitable case study for examining the acoustic behavior of outdoor spaces. The university features several enclosed and semi enclosed outdoor spaces, surrounded by buildings, which create well-defined boundaries. These enclosed and semi enclosed spaces provide an ideal setting to observe how sound is reflected and absorbed within a constrained environment.

The campus also exhibits a variation in building heights, ranging from low-rise structures to taller buildings with up to six levels. This diversity allows for an in-depth analysis of how building height influences sound propagation and reverberation patterns. The contrast between these structures offers valuable insights into the acoustic effects of vertical enclosures in outdoor spaces.

Additionally, the façade materials play a crucial role in shaping the sound environment. The buildings are primarily constructed with concrete walls and large glass windows—materials known for their distinct acoustic properties. While concrete surfaces contribute to sound reflection, glass elements introduce variations in absorption and transmission. The combination of these materials presents an opportunity to explore their impact on the overall acoustic dynamics of the university's outdoor spaces.

3.1.2. Noise Sources from Urban and within Campus Environments

Batna 1 University is situated in an urban area characterized by multiple noise sources, both from the surrounding urban environment and within the campus itself. These varied noise contributions create a complex acoustic landscape, making the university an ideal case study for assessing the impact of environmental noise on outdoor spaces (Figure 3-8).

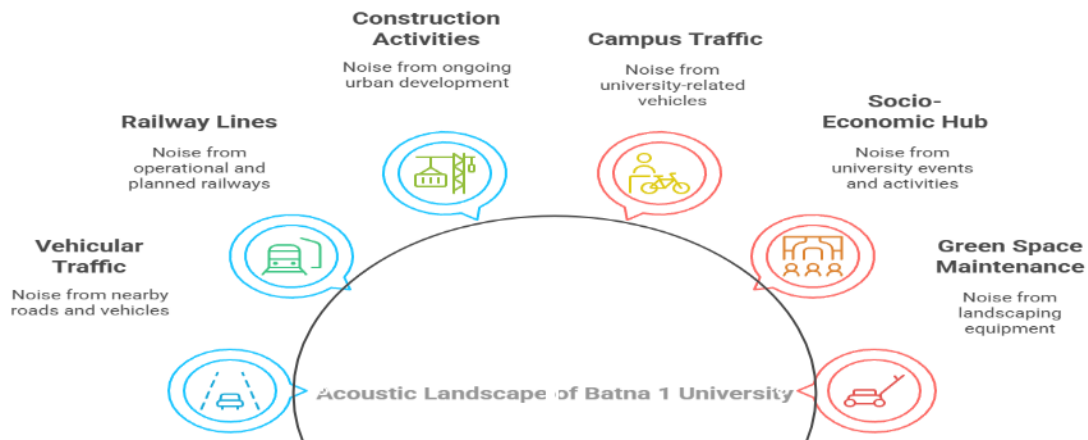


Figure 3-8: Acoustic Landscape of Batna 1 University: Key Noise Sources and Their Impact.

Source: (author)

One of the most significant noise sources is vehicular traffic from nearby roads. According to a study by Guehtar and Saidi (2009), Batna 1 University is among the locations most affected by noise pollution, primarily due to road traffic (Figure 3-9). The intersection near the university, particularly at El Hadj Lakhdar, experiences noise levels that frequently exceed the standard threshold of 65 dB during peak hours, reaching as high as 95 dB (Figure 3-10).



Figure 3-9: Map Showing the University's Location Beyond the High Noise Pollution Zones of Batna City . Source: (Guehtar & Saidi, 2009), adapted by author.

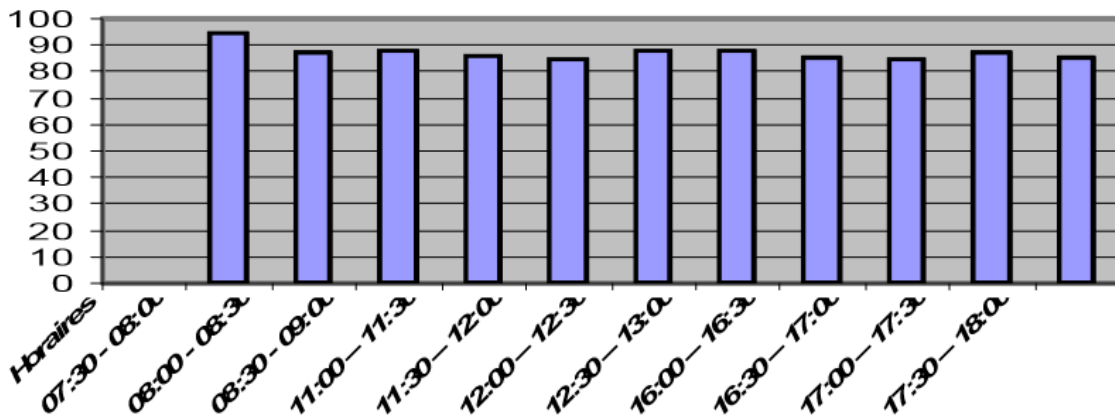
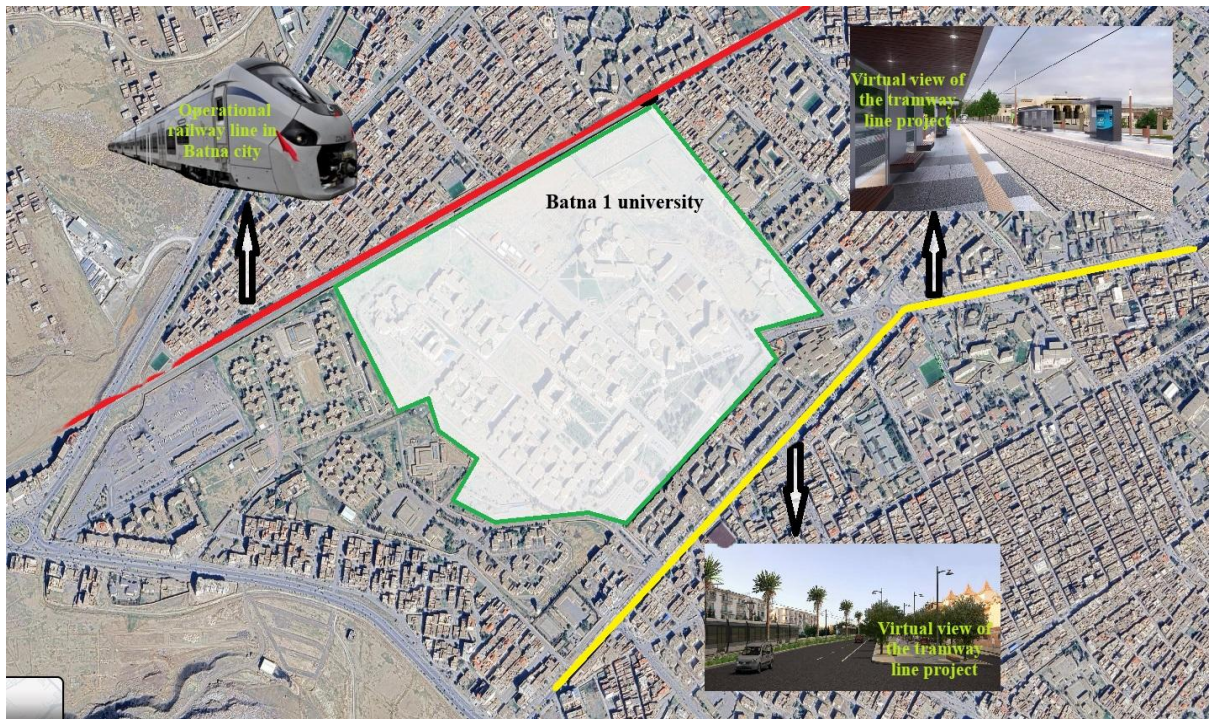


Figure 3-10: Noise levels in the crossroads of batna1 university. source:(Guehtar & Saidi, 2009)

In addition to road traffic, the presence of railway lines further amplifies the noise pollution on campus. Batna 1 University is bordered by two railway lines (Figure 3-11), one of which is currently operational, contributing to the ambient noise levels. The second line is part of a major infrastructure project planned for the city of Batna, with one of its proposed routes passing through the university. If constructed, this railway expansion is expected to introduce an additional noise source, further shaping the university's soundscape and presenting new challenges for acoustic management.



— Batna 1 university — Operational railway line — Tramway line project

Figure 3-11: Existing and Planned Railway and Tramway Lines in Batna City. source: (*Google Maps*, n.d.), adapted by author.

Beyond transportation noise, construction activities in and around the university also play a critical role in shaping the outdoor acoustic environment. Batna 1 University is surrounded by ongoing urban development projects, with construction sites generating considerable noise from heavy machinery such as excavators, cranes, and cement mixers. Moreover, as shown in Figure 3-12, the university is in close proximity to several incomplete construction sites, where work has been stalled despite the implementation of Law 08/15 on construction regularization. These unfinished structures not only extend the duration of construction-related noise exposure but also highlight broader issues of urban development and regulatory enforcement.



Figure 3-12: Incomplete construction sites serve as persistent hubs for noise generation.
Source: (author).

The road traffic noise within the campus is notably influenced by the movement of motorcycles and vehicles used by students, faculty, and staff. Although precise data on the number of vehicles is unavailable, the campus population—comprising approximately 28000 students, 1200 teachers, and 1374 administrative staff—suggests a significant volume of vehicular activity. This internal traffic serves as an additional noise source, complementing the external noise sources surrounding the university. Additionally, to alleviate traffic congestion in Batna city, there is significant pressure from the civil community to relocate the student service bus stations (Figure 3-13)—currently operating with more than 30 buses—to within the university campus. This relocation would further contribute to the overall noise levels.



Figure 3-13: Current Location of Student Service Bus Station Proposed for Relocation Within the University. Source: (author)

It is worth noting that Batna 1 University serves as a significant socio-economic hub. It hosts a 600-seat conference auditorium, providing a venue for large academic and professional gatherings. Additionally, the university is equipped with an incubator and entrepreneurship center, fostering innovation and supporting business ventures. Furthermore, it functions as a regional examination center for competitive exams, attracting participants from various locations. These activities not only highlight the university's dynamic role in the community but also contribute to the diverse soundscape.

The maintenance of green spaces within Batna 1 University generates significant noise due to the use of mechanical equipment. Routine landscaping tasks, such as mowing lawns, trimming hedges, and blowing leaves, involve powered tools that produce noticeable noise levels, particularly during peak working hours. While necessary for campus upkeep, these activities contribute to the overall soundscape of the outdoor environment. Moreover, as the university continues to expand and renovate its infrastructure, construction activities frequently take place. The use of heavy machinery, including drills, jackhammers, and cranes, results in intermittent yet intense noise pollution. Although temporary, these disturbances have a considerable impact on the acoustic conditions of the university's outdoor spaces.

Batna 1 University is characterized by a high student population, with enrollment figures ranging from 28,378 to 33,873 over the past five academic years (*Power BI Report*, n.d.). This large student body contributes to a dynamic and lively campus atmosphere, where social interactions, academic activities, and daily movement generate significant noise levels throughout the day.

The presence of thousands of students within lecture halls, libraries, corridors, and outdoor gathering spaces results in continuous background noise, including conversations, footsteps, and the general bustle of campus life. Courtyards, cafeterias, and recreational areas often become focal points for social interactions, amplifying the ambient noise levels, especially during peak hours. Additionally, the influx of students during class transitions leads to concentrated movement across the campus, further intensifying the overall soundscape. Beyond academic and social activities, organized events, protests, and student gatherings add to the acoustic environment. Public announcements, group discussions, and celebrations contribute to fluctuating noise levels, creating an ever-changing sound dynamic that varies based on the time of day and academic calendar.

This high-density population not only influences the university's social and academic life but also plays a significant role in shaping its acoustic environment. Understanding the impact of human-generated noise is crucial for assessing overall sound conditions on campus and exploring potential strategies for noise management in educational settings.

3.1.3. Additional Selection Criteria for Choosing Batna 1 University as a Case Study

Beyond its architectural characteristics and diverse noise sources, Batna 1 University offers several key advantages that make it an ideal setting for studying outdoor acoustic behavior (Table 3-1). The controlled noise sources, Measurement Setup, its accessibility, safety, and suitability for standardized measurement setups ensure reliable data collection. The study's adherence to ISO 3382 standards further enhances its scientific rigor, while the university's unique context addresses a significant research gap in Algeria regarding the impact of building morphology on outdoor acoustics.

Table 3-1

Additional Selection Criteria for Choosing Batna 1 University as a Case Study

Criterion	Justification
Minimal Noise Interference	Low background noise and Controlled noise sources make the site ideal for studying outdoor acoustic behavior.
Ease of Access	The campus is easily accessible, allowing regular and reliable data collection without logistical challenges.
Safety	The controlled environment ensures the safety of both equipment and researchers during measurements.
Measurement Setup	The site allows consistent placement of sound sources and receivers, ensuring comparability across different spaces.
ISO Compliance	The study follows ISO 3382 standards for RT20, EDT, and SPL attenuation measurements.
Novelty and Contribution	Batna 1 University provides a unique context due to the lack of research in Algeria on building morphology's impact on outdoor acoustics.

One of the key advantages of selecting Batna 1 University for studying outdoor acoustic behavior is the ability to conduct measurements with minimal background noise, particularly during the evening and nighttime. Unlike highly dynamic urban environments, where fluctuating ambient noise can interfere with data collection, the university campus provides quieter periods that allow for precise and controlled acoustic measurements. This low background noise level enables researchers to isolate and analyze the specific generated noise sources (impulse noise and white noise) without significant interference with other noise such as traffic, mechanical tools, or human activity. As a result, the accuracy and reliability of data collection are significantly improved, ensuring that measured acoustic parameters truly reflect the influence of the built environment rather than external noise fluctuations.

Batna 1 University is its accessibility and logistical feasibility. The campus is easily reachable, allowing for regular and consistent data collection without major operational constraints. This ensures that acoustic measurements can be performed systematically, enhancing the reliability and comparability of results. Additionally, the controlled environment of the university offers a secure setting for both researchers and measurement equipment, reducing potential risks associated with data collection in uncontrolled urban spaces.

Furthermore, the structured layout of the university facilitates controlled and repeatable measurement setups. The placement of sound sources and receivers can be carefully standardized, ensuring consistent data collection. For example, using a directional speaker positioned at a height of 1.5 meters allows for accurate comparisons of acoustic behavior across different locations on campus. This methodological consistency strengthens the validity of the study's findings.

The research conducted at Batna 1 University also adheres to international acoustic measurement standards. Key parameters such as RT20, Early Decay Time (EDT), and Sound Pressure Level (SPL) attenuation can be measured in accordance with ISO 3382 guidelines. Aligning the study with recognized standards enhances its scientific rigor and ensures that the results can be compared with existing research in the field of architectural acoustics.

Lastly, the selection of Batna 1 University as a case study is particularly relevant given the significant research gap in Algeria regarding the impact of building morphology on outdoor acoustic environments. By investigating this topic in a local context, the study provides valuable insights that can contribute to architectural and urban planning strategies. The findings may also serve as a foundation for future research on the acoustic implications of built environments in similar urban settings.

3.2. Description of the study sites

This study aims to investigate the impact of building morphology on the sound environment in seven outdoor spaces within the campus of Batna 1 University (Figure 3-14), located in the city of Batna, in the Aurès region, in northeastern Algeria. These selected spaces represent a variety of architectural and spatial characteristics, making them ideal for studying the influence of building design, materiality, and spatial configurations on outdoor acoustic behavior.

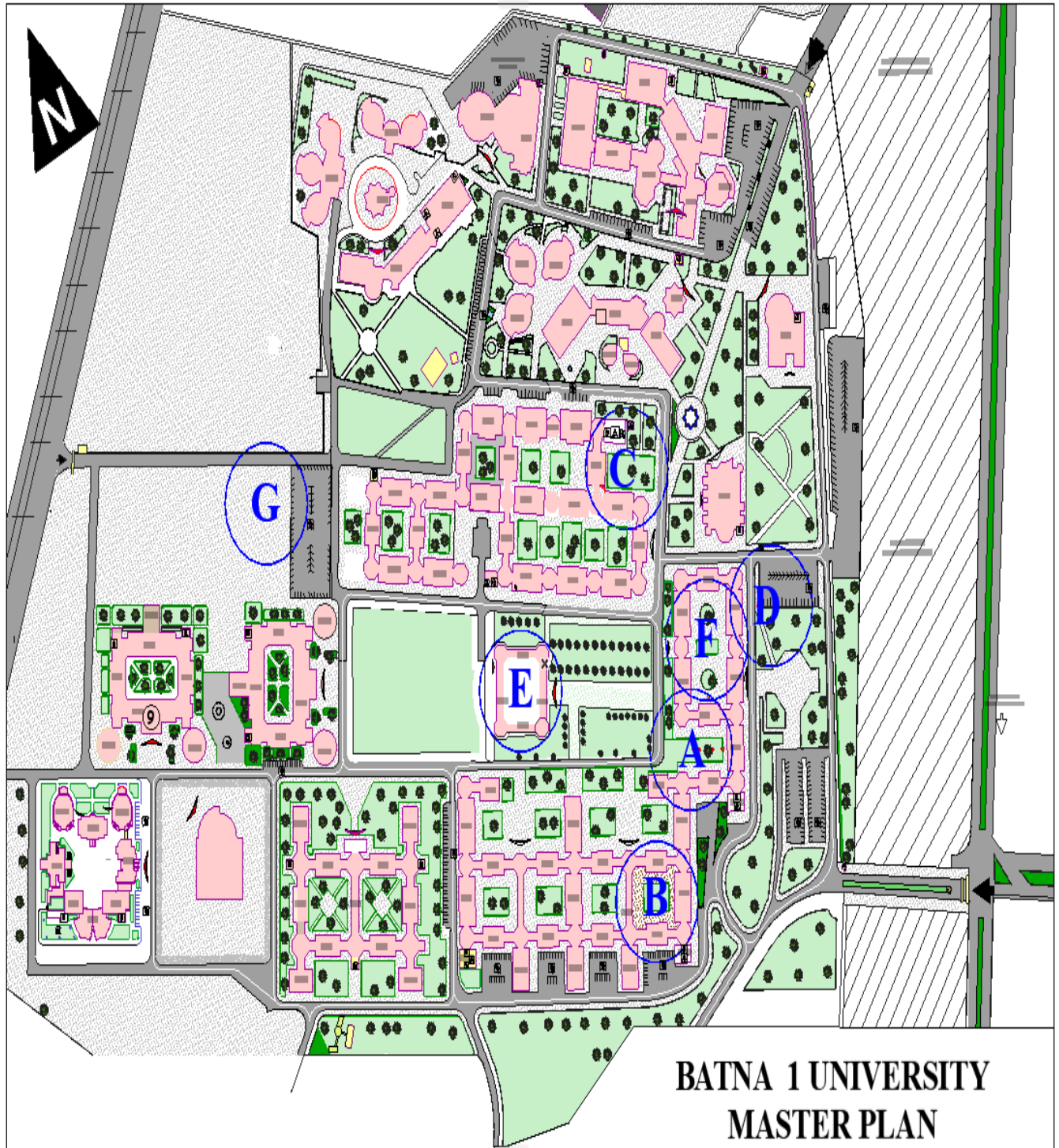


Figure 3-14: University of Batna1, Master Plan and measurements' station's location. Source: (author).

The university campus provides a unique context due to its integration of diverse building heights, façade designs, and courtyard layouts, all situated within a dynamic urban environment. As a significant educational and socio-economic hub in the region, the campus experiences high levels of activity from its large student body, faculty, staff, and visitors. Additionally, the campus is subjected to various external noise sources, such as road traffic, railway proximity, and construction activities, alongside internal sources like mechanical tools and vehicles. These factors contribute to a complex soundscape that underscores the relevance of examining outdoor acoustic environments in such settings.

By focusing on the interplay between building morphology and the acoustic environment, the study seeks to enhance understanding of how architectural and urban planning decisions can influence noise propagation, reverberation, and overall acoustic quality in outdoor spaces. This research is particularly valuable in the context of Algeria, where limited studies address the relationship between the built environment and outdoor acoustics, offering insights that may inform sustainable urban and architectural design practices.

To address the aims of this study, the seven selected outdoor spaces were grouped into three distinct cases. Each case was chosen to explore different aspects of building morphology and their effects on the outdoor sound environment, allowing for an in-depth analysis of how architectural configurations influence key acoustic parameters such as reverberation time (RT) and sound pressure level (SPL).

The three selected case studies are designed to explore the effects of building morphology on the acoustic environment within outdoor spaces at Batna 1 University. Each case provides a unique perspective on how architectural configurations, such as building layout, façade height, and courtyard shape, influence acoustic properties like reverberation time (RT) and sound pressure level (SPL).

3.2.1. Case 01-Square-Shaped Courtyards with Different Building Layouts

The outdoor areas were selected based on their proximity to university buildings and their frequent use by students, as illustrated in Figure 3-14 and 3-15. The selection process also considered the architectural features and layout configurations of these spaces. All selected areas share common characteristics, including a nearly square shape of approximately 40 m by 40 m, façades constructed of concrete walls and large glass windows, and façade heights ranging from 2 to 3 floors.



(A) U-shaped



(B) square-shaped



(C) L-shaped



(D) linear-shaped

Figure 3-15: Photographs of each measurement stations related to case 1: Square-Shaped Courtyards with Different Building Layouts. Source: (author).

Despite these similarities, each outdoor space is surrounded by a distinct building layout. These architectural configurations act as reflective surfaces that can influence sound behavior, leading to extended reverberation time (RT) and elevated sound pressure levels (SPL) due to stronger

reflections compared to open environments. The building layouts enclosing these outdoor spaces are categorized into four types: square-shaped ($\square$), U-shaped (U), L-shaped (L), and linear-shaped (—).

3.2.2. Case 02-Courtyards with Different Façade Heights-

As illustrated in Figure 3-14 and 3-16, the study examines two outdoor areas designed as courtyards, both situated within university buildings and regularly frequented by students. These courtyards were selected for their architectural similarities, including their nearly square layout (approximately 36 m by 36 m), concrete walls, large glass windows, and full enclosure by surrounding buildings.



(E) Building with six levels of height



(B) Building with two-three levels of height

Figure 3-16: Photographs of each measurement stations of case 02: Courtyards with Different Façade Heights. Source: (author).

The primary distinction between the two courtyards lies in the height of their surrounding building façades. One courtyard is enclosed by buildings with six levels, while the other is surrounded by buildings with 2–3 levels. This variation in façade height significantly influences the acoustic properties of the spaces. Specifically, taller façades enhance sound reflections, potentially leading to longer reverberation times (RT) and higher sound pressure levels (SPL) compared to more open or lower-enclosed areas.

This configuration provides an opportunity to analyze how differences in building height affect acoustic behavior within similarly shaped, enclosed outdoor environments. It allows for a focused

investigation into the relationship between façade height and key acoustic parameters, offering insights into the impact of building morphology on sound propagation.

3.2.3. Case 03: Square vs. Rectangular Courtyards

The outdoor areas selected for this study are located within two enclosed courtyards on the university campus, as shown in Figures 3-14 and 3-17. These spaces were chosen for their proximity to university buildings, their frequent use by students, and their distinct architectural configurations. Both courtyards share certain similarities, including façades constructed of concrete walls and large glass windows, with heights ranging from 2 to 3 floors.



(F) Rectangular Courtyards



(B) Square Courtyards

Figure 3-17: Photographs of each measurement stations of case 03: Square vs. Rectangular Courtyards. Source: (author).

The two courtyards differ primarily in their shapes: one courtyard is nearly square, measuring approximately 40 m by 40 m, while the other is rectangular with approximately 40 m by 80 m. These variations in courtyard shape allow for an investigation into how geometric layout influences acoustic behavior. The architectural configurations of the façades act as reflective surfaces that influence sound propagation, potentially leading to differences in reverberation time (RT) and sound pressure level (SPL) between the two spaces. By focusing on these distinct yet comparable courtyards, the study aims to analyze how courtyard shape impacts acoustic characteristics within enclosed outdoor environments.

4. Measurement protocol

To provide a comprehensive understanding of the experimental setup and methodology, the Figure 3-14 illustrates key aspects of the research process. This figure illustrates the workflow of this research for analyzing the impulse response, including RT, EDT, D50, RaSTI, and SPL. The study followed the guidelines of ISO 3382, which are primarily intended for room acoustics, to guide the outdoor acoustic measurements. While ISO 3382 is designed for environments with defined volumes, its application to outdoor spaces, which lack such boundaries, presents certain challenges.

To overcome these challenges, this study builds on the approaches established by previous research that applied room acoustic parameters to outdoor environments. Notably, studies by Yang et al. (2013) and Yang et al. (2017) have successfully investigated acoustic characteristics in outdoor spaces surrounded by buildings and in apartment complexes. These studies show that room acoustic parameters can provide valuable insights, even in open or semi-enclosed environments.

4.1. Experimental Workflow and Measurement Process

The workflow, as shown in Figure 3-18, provides a structured and systematic overview of the measurement procedure. The process begins with the installation of the equipment, ensuring accurate and reproducible data collection across all study locations. This step establishes a controlled and consistent measurement environment. Calibration is then performed to verify the accuracy and reliability of the instruments. The measurement phase follows, involving either impulse response recording using a starter clapper or white noise playback via a directional speaker. Subsequently, data recording captures the acoustic responses at various receiver positions. Finally, the collected data undergo post-processing using the EASERA software for detailed analysis. This flowchart enhances the clarity of the methodology, providing a comprehensive representation of the measurement protocol.

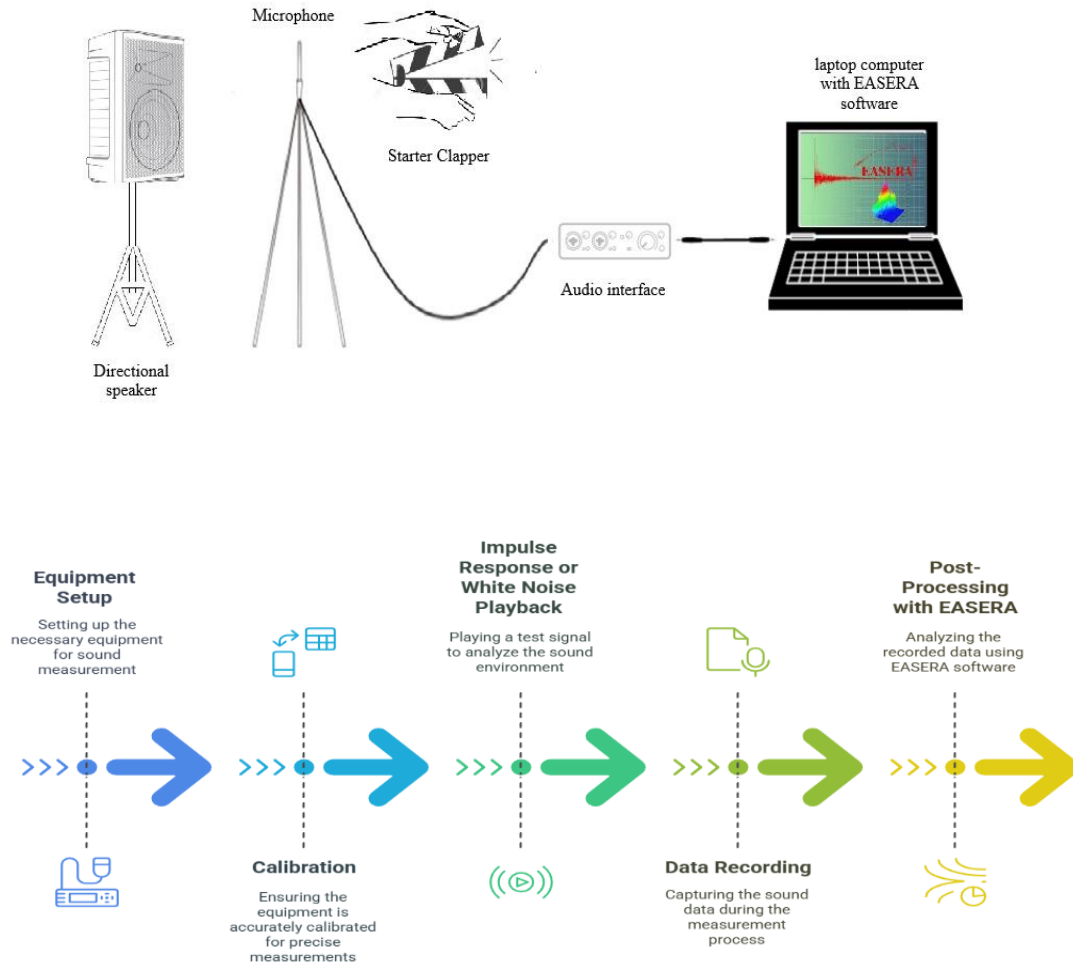


Figure 3-18: Experimental setup and methodology to measure impulse response and SPL.
Source: (author).

The measurement metrics, equipment, procedures, standards, and environmental conditions considered in this study are clearly and structurally explained in Table 3-2. It highlights the use of the EASERA software and a starter clapper for reverberation-related metrics such as RT20, EDT, RaSTI, and D50, ensuring consistency in data acquisition. The adherence to ISO 3382 standards reinforces the reliability of the methodology. Additionally, the sound pressure level (SPL) attenuation measurement is conducted using a directional speaker and calibrated microphone, ensuring accurate assessment of sound propagation, and a real-time analyzer (RTA) within the EASE software by AFMG. The controlled environmental conditions, particularly maintaining low background noise and ensuring a sufficient signal-to-noise (S/N) ratio, contribute to the precision

and validity of the results. This structured approach enhances the robustness of the study and ensures reliable acoustic analysis.

Table 3-2:

Summary of Acoustic Measurement Metrics, Equipment, Procedures, and Conditions

Measurement metric	Equipment/software Used	Measurement Procedure	Standards Followed	Environmental sound Conditions
Reverberation Time (RT20)	Starter clapper, calibrated microphone EASERA software	Impulse response measurement using a clapper	ISO 3382	Impulse to Noise Ratio (INR) sufficient
Early Decay Time (EDT)	Starter clapper, calibrated microphone EASERA software	Derived from impulse response curve	ISO 3382	Impulse to Noise Ratio (INR) sufficient
Speech Intelligibility (RaSTI)	Starter clapper, calibrated microphone EASERA software	Analysis of modulation transfer function for speech clarity	ISO 3382	Impulse to Noise Ratio (INR) sufficient
Definition (D50)	Starter clapper, calibrated microphone EASERA software	Derived from impulse response to quantify early-to-late sound ratio	ISO 3382	Impulse to Noise Ratio (INR) sufficient
Sound Pressure Level (SPL) Attenuation	Directional speaker, calibrated microphone, EASERA software	White noise playback and SPL measurement at set distances	ISO 3382	Signal to noise ratio S/N is sufficient

4.1.1. Sound Sources for SPL Attenuation and Reverberation Time Measurement

To measure SPL attenuation with distance, white noise was selected as the sound source due to its broad frequency spectrum and consistent power distribution across all audible frequencies, ensuring more precise and reliable measurements. The uniformity and repeatability of white noise make it an ideal choice for controlled testing, providing consistent and comparable data when evaluating the acoustic properties of outdoor spaces. The white noise was emitted from a directional speaker positioned at a height of 1.5 meters (Figure 3-19). The signal-to-noise ratio (S/N) at a distance of 1 meter from the source was 56 dB (unweighted). This level of sound power

was sufficient to accurately measure SPL attenuation up to 40 meters between the source and the receiver. At 40 meters, the S/N ratio decreased to approximately 28 dB (unweighted).



Figure 3-19: Directional speaker used for generating white noise. Source: (author).

Reverberation time is defined as the duration required for the sound level in a space to decrease by 60 dB after the sound source has been turned off (Beranek & Mellow, 2019). Impulsive sources, such as signal guns and balloon pops, are commonly used to measure reverberation time in practice (Kang, 2007; Yang et al., 2013, 2017). In this study, a starter clapper was used as the impulsive sound source (Figure 3-20). This choice was based on the clapper's sharp onset, broad frequency spectrum (Seetharaman & Tarzia, 2012), and its ability to minimize the influence of background noise (Yang et al., 2017). These characteristics are crucial for accurately measuring reverberation time, as they allow for precise detection of the sound's onset, capture a wide range of audible frequencies, and provide a cleaner signal for analysis. Each measurement was based on the average of five consecutive claps.



Figure 3-20: Starter Clapper Used to generate the Impulsive Noise. Source: (author).

4.1.2. EASERA Pro: Advanced Software for Acoustic Measurement and Analysis

The acoustic characteristics, including RT, EDT, D50, RaSTI, and SPL were measured and analyzed using the EASERA software from AFMG (Figure 3-21). The choice to use EASERA was based on its noise compensation algorithm, which effectively reduces the impact of background noise on RT calculations, as well as its proven accuracy in environments where background noise and reflections can be controlled, such as the semi-enclosed courtyards examined in this study. These conditions are essential for ensuring reliable and precise acoustic measurements.

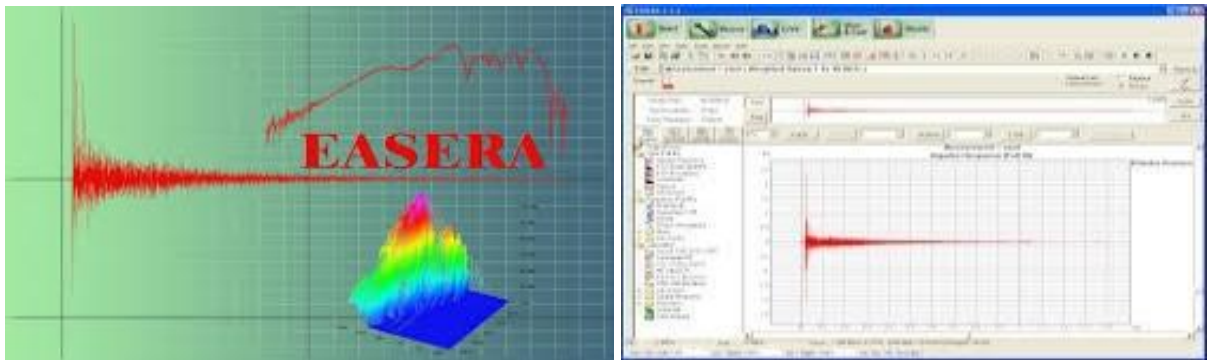


Figure 3-21: Using EASERA Software for Impulse Response and SPL measurement and Analysis. Source: (author).

EASERA is specifically designed to handle complex acoustic environments, including outdoor spaces with large reflective surfaces and significant reverberation potential. The software offers predefined templates for various environments, such as "stadium" settings, which share similar acoustic characteristics with our study areas. In particular, the courtyards analyzed in this research present challenges comparable to those found in stadiums, including a combination of direct sound and reflections from surrounding structures.

4.1.3. Measurement Equipment and Receiver

To ensure accurate and reliable acoustic measurements, the study employed a Dayton Audio EMM-6 ½-inch omnidirectional measuring microphone as the primary sound receiver (Figure 3-

22). This microphone was chosen for its high sensitivity, flat frequency response, and low self-noise, making it well-suited for precise acoustic data collection in outdoor environments. The microphone was connected to a Scarlett Solo Focusrite audio interface (Figure 3-22), which served as an analog-to-digital converter, ensuring high-fidelity signal transmission to the analysis software. The interface provided low-latency, high-resolution audio conversion, preserving the integrity of the captured signals.

The receiver (microphone) was systematically positioned at a height of 1.5 meters above the ground to maintain consistency across all measurement locations. This height was selected based on standard acoustic measurement protocols to approximate the ear level of a seated listener and to minimize interference from ground reflections.

To ensure the accuracy and reproducibility of the measurements, a calibration procedure was conducted before each measurement session. A sound level calibrator was used to verify the microphone's sensitivity and ensure that the recorded data remained free from drift or inconsistencies over time. This step was critical in maintaining the validity of the recorded acoustic parameters, particularly when comparing results across different measurement locations.



Figure 3-22: Focusrite Scarlett Solo Audio Interface (Right) and Dayton Audio EMM-6 1/2-inch Measuring Microphone (Left). Source: (author).

The INR was found to be 22 dB at 125 Hz, 30 dB at 250 Hz, 39 dB at 500 Hz, 51 dB at 1000 Hz, 63 dB at 2000 Hz, 63 dB at 4000 Hz, and 49 at 8000 Hz at a distance of 40 m, which is considered to be the greatest source to receiver distance.

For accurate RT measurement of T20 and T30, respectively, ISO 3382-2 recommends an INR of at least 35 dB and 45 dB. Based on the INRs in the one band displayed above, the RT calculation method was based on T20 (-5 dB to -25 dB) in one-octave bands from 500 Hz to 8000 Hz for source to receiver distances within 40 m. Table 3-3 presents the INR values at a distance of 40 m for different frequency bands, along with their compliance with the ISO 3382-2 criteria for T20 and T30. The RT calculation was based on T20 for frequencies where the INR met the required threshold.

In this study, the 125 Hz and 250 Hz octave bands were excluded from the analysis because their Impulse-to-Noise Ratio (INR) values fell below the minimum threshold required for reliable measurements, as outlined in ISO 3382. This procedure follows the approach adopted in previous outdoor acoustic studies, such as those by Yang et al. (2013) and Yang et al.(2017), where low-frequency bands were also omitted due to insufficient INR values. In outdoor environments, low frequencies are particularly prone to background noise and environmental interference, which can compromise data accuracy. Excluding these bands therefore ensured that the analysis relied solely on robust and reliable measurements.

Table 3-3

INR Values at 40 m and Corresponding RT Assessment Method

Frequency (Hz)	INR at 40m (dB)	T20 Criterion (≥ 35 dB)	T30 Criterion (≥ 45 dB)	RT Calculation Method
125	22	Below threshold	Below threshold	Not considered
250	30	Below threshold	Below threshold	Not considered
500	39	Meets requirement	Below threshold	T20 applied
1000	51	Meets requirement	Meets requirement	T20 applied
2000	63	Meets requirement	Meets requirement	T20 applied
4000	63	Meets requirement	Meets requirement	T20 applied
8000	49	Meets requirement	Meets requirement	T20 applied

The measurements were taken under the meteorological conditions specified in Table 3-4, and were all conducted on the same day during the winter season to maintain consistency and reduce the impact of weather variations between the sites. This approach ensures the comparability of results across the different measurement zones. The slight exceedances in two cases (5.25 and 5.59 m/s) are considered negligible in terms of their potential influence on the results.

Table 3-4

Meteorological Conditions During Measurements for each site

Weather condition	Site (A)	Site (B)	Site (C)	Site (D)	Site (E)	Site (F)	Site (G)
Temp. (°C)	12.1	12.7	12.7	13.1	12.7	12.7	12.7
Humidity (%)	35	35	35	48	35	10	10
Wind speed (m/s)	<2.2	<5.25	<5.25	<5.59	<5.25	<5.25	<5.25

Ground surface materials significantly influence outdoor sound propagation and reflections through their absorption and scattering properties. In this study, the ground surfaces of the investigated spaces were mainly composed of natural soil and green cover, which minimized their effect on the acoustic outcomes. Only the linear-shaped site differed, featuring a paved surface that may have enhanced sound reflections. Therefore, the observed variations in the acoustic results are more likely attributed to the architectural configurations rather than to ground surface differences.

4.2. Data collection procedure

To provide a clear understanding of the measurement setup used in this study, Tables 3-5 details the number and positions of both source and receiver points within each measurement zone. Figure 3-23 illustrates the spatial arrangement of these points across all studied regions, utilizing a total of 37 points to measure impulse responses and sound pressure levels (SPL). The distribution of these points was designed to ensure comprehensive coverage of the acoustic characteristics of each outdoor space, accounting for variations in sound propagation and reflection patterns. This

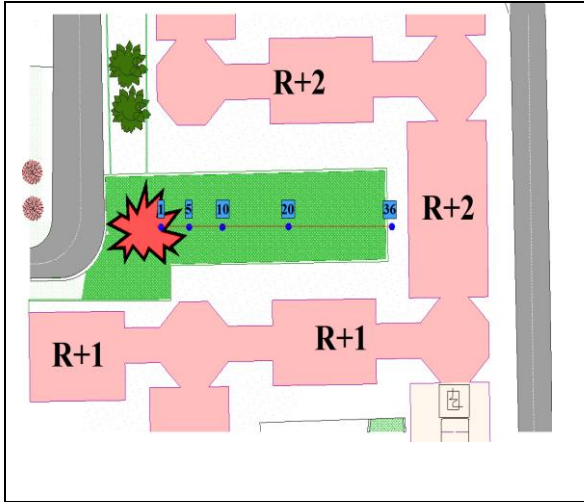
systematic placement allowed for capturing accurate and representative acoustic data across different architectural configurations and measurement conditions.

Table 3-5

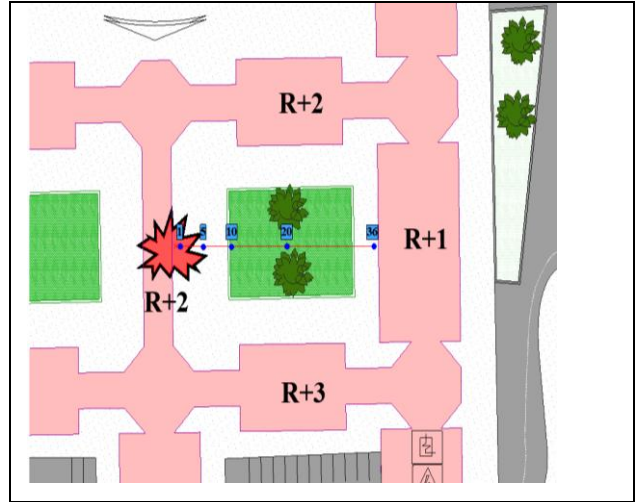
Number and positions of both source and receiver points within each measurement zone

sites	Height (level numbers)	Building surrounding shape	Number of sources	Number of receivers	Source receiver distance(m)	Measurement parameter	
						SPL attenuation	Impulse response
(A)-	1-2levels	U-shaped	01	05	1-5-10-20-36	x	x
(B)-	1-3 levels	Square-shaped	01	05	1-5-10-20-36	x	x
(C)-	2-3levels	L-shaped	01	05	1-5-10-20-36	x	x
(D)-	2-3levels	Linear shaped	01	06	1-5-10-20-40-60	x	x
(E)-	6 levels	Square shaped	01	05	1-5-10-20-36	x	x
(F)-	1-3levels	Rectangular shape	01	06	1-5-10-20-40-76	x	x
(G)-	Semi free field	Semi free field	01	05	1-5-10-20-40	x	x

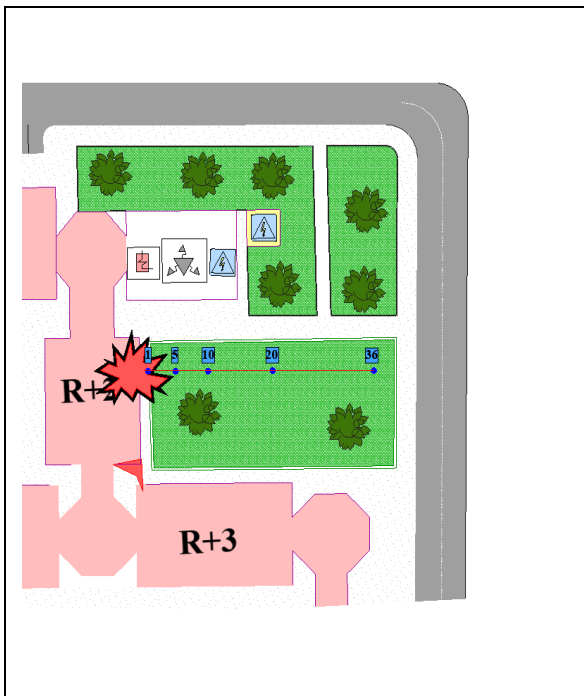
Although the source of sound—either starting clappers for reverberation time (RT) or speakers for SPL attenuation—remained unchanged across all outdoor areas, the positions of the receiver points, which were microphones, were adjusted along their line of sight. The distance between the source and receiver in each measurement zone was determined by considering the size of the outdoor spaces. This distance was logarithmically scaled within a range of approximately 40 meters across both areas to analyze the distribution of reverberation time (RT) and the attenuation of sound pressure levels (SPL) in the outdoor environments.



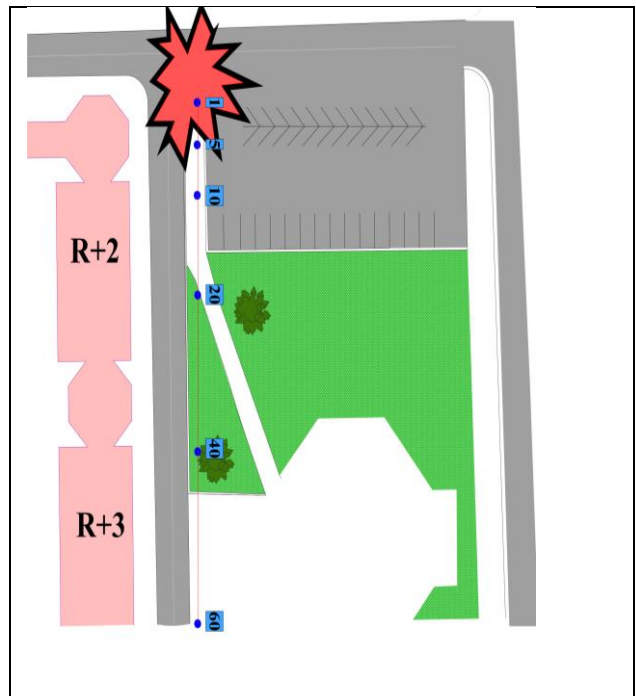
(A) Site 1



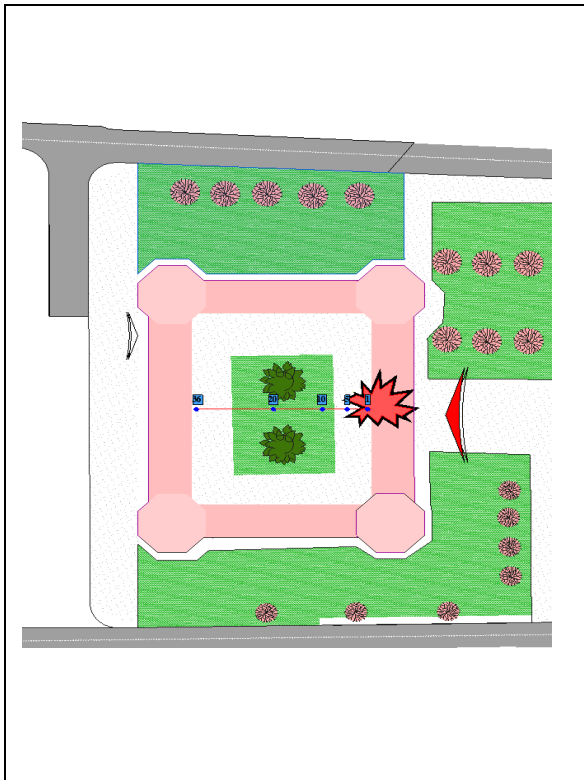
(B) Site 2



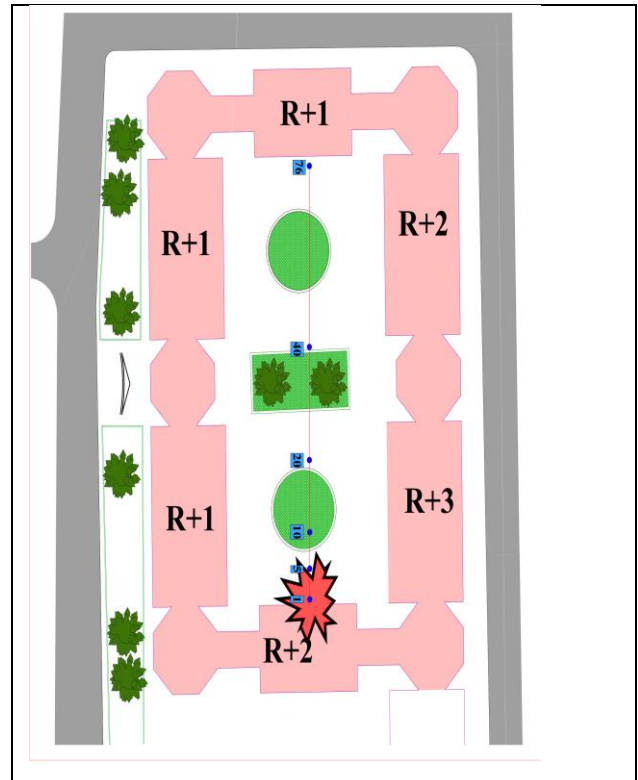
(C) Site 3



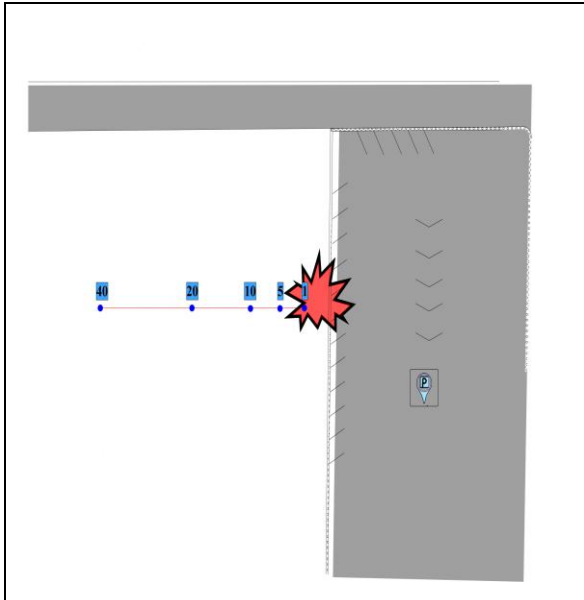
(D) Site 4



(E) Site 5



(G) Site 6



(H) Site

Figure 3-23: *Locations of source to receiver points in the 7 spaces.* Source: (author).

5. Conclusion

This chapter has outlined the methodological framework adopted to examine the impact of building morphology on the outdoor acoustic environment. By employing a structured approach that includes case study selection, standardized measurement techniques, and controlled environmental conditions, the study ensures the reliability and accuracy of the collected data.

The chosen methodology integrates impulse response measurements, sound pressure level attenuation analysis, and speech intelligibility assessment, providing a comprehensive evaluation of acoustic behavior in enclosed outdoor spaces. The use of standardized protocols, such as employing a starter clapper for reverberation time measurements and white noise for SPL analysis, enhances the reproducibility of the study. Furthermore, the selection of case study sites with distinct morphological characteristics allows for a comparative analysis of different architectural configurations.

By detailing each stage of the research process, this chapter establishes a solid foundation for the subsequent analysis and discussion of results. The next chapter will present and interpret the findings, highlighting the acoustic variations observed across different spatial configurations and their implications for outdoor sound environments.

The measurement methodology using a starter clapper demonstrated reliable reproducibility of RT20 above 500 Hz, confirming its suitability for assessing outdoor acoustic environments. The signal-to-noise ratio (S/N) and the Impulse-to-Noise Ratio (INR) were sufficient to ensure accurate RT20 measurements across various source-receiver distances. Specifically, the INR values exceeded the recommended threshold, ensuring that background noise did not compromise measurement reliability. Additionally, the measured data can serve as a reference for validating acoustic simulations, particularly in evaluating the accuracy of computational models for predicting sound propagation in outdoor spaces. These findings validate the robustness of our approach, indicating that it can be effectively applied to analyze sound propagation and reverberation characteristics in outdoor spaces, even in complex urban environments. Furthermore, the methodology provides a solid foundation for future studies exploring the acoustic

effects of different architectural configurations through both empirical measurements and simulation-based analyses.

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Chapter 4

Results and discussion

Chapter 4: Results and discussion

1. Introduction

This chapter presents and analyzes the results of the study investigating the influence of building layout and façade design on the outdoor sound environment within the main campus of the University of Batna 1 (Haj Lakhdar), where specific outdoor spaces were analyzed. The findings focus on key acoustic parameters, including impulse response, reverberation time (RT20), early decay time (EDT), and sound pressure level attenuation, to assess variations in sound reflections and propagation across different spatial configurations. The analysis provides insights into how architectural design elements, such as the shape of outdoor spaces, façade heights, and the positioning of buildings, contribute to acoustic behavior in open environments.

The first section examines the impact of building layout on outdoor acoustics, analyzing reverberation time distribution, impulse response characteristics, and decay curves at a receiver distance of 20 meters. Different spatial configurations—U-shaped, square-shaped, linear, and L-shaped layouts—are compared in terms of their effect on sound energy distribution and reverberation characteristics. Additionally, the study evaluates RT20 variations across octave bands, providing a comparative analysis of maximum, average, and minimum values within the selected locations.

The second section focuses on the impact of façade design on the outdoor sound environment, specifically addressing how façade heights influence acoustic parameters. The assessment includes sound pressure level attenuation trends at different distances from the source, impulse response variations, and RT20 behavior across frequency bands. The study compares two façade height categories—buildings with six levels and buildings with two to three levels—to examine their impact on outdoor sound propagation in enclosed outdoor environments. Additionally, the study investigates the correlation between RT20 and source-receiver distance, demonstrating how taller façades (six levels) contribute to prolonged reverberation and altered sound decay patterns, whereas shorter façades (two to three levels) allow for quicker sound dissipation.

The third section explores the role of courtyard shape in shaping the outdoor acoustic environment, focusing on how variations in enclosure geometry influence sound reflections, diffraction, and spatial decay patterns. By comparing different courtyard configurations—square courtyards and rectangular courtyards—the study highlights how enclosed versus semi-enclosed spaces affect sound propagation, SPL attenuation, and reverberation behavior. The findings emphasize that more enclosed courtyard layouts, such as square courtyards, tend to sustain higher reverberation times due to multiple reflective surfaces, while more open rectangular courtyards exhibit greater sound dissipation.

By integrating findings from both sections, this chapter provides a comprehensive understanding of how urban morphology shapes outdoor acoustic conditions and offering insights relevant to architectural design strategies aimed at optimizing acoustic comfort in open spaces.

2. Assessment of Building Layout effect on the Outdoor Sound Environment

The assessment of building layout effects on the outdoor sound environment at Batna 1 University aims to investigate how building configurations influence acoustic characteristics in outdoor spaces. This section provides an in-depth analysis of reverberation time, room acoustic parameters, and sound pressure levels, offering insights into the acoustic behavior shaped by varying building morphologies. Through detailed measurements and data interpretation, the study evaluates key acoustic indicators such as Reverberation Time (RT), Early Decay Time (EDT), Definition (D50), Rapid Speech Transmission Index (RaSTI), and Sound Pressure Level (SPL). The findings help illustrate the relationship between building layout and outdoor acoustic performance, contributing to a broader understanding of sound propagation in enclosed outdoor spaces.

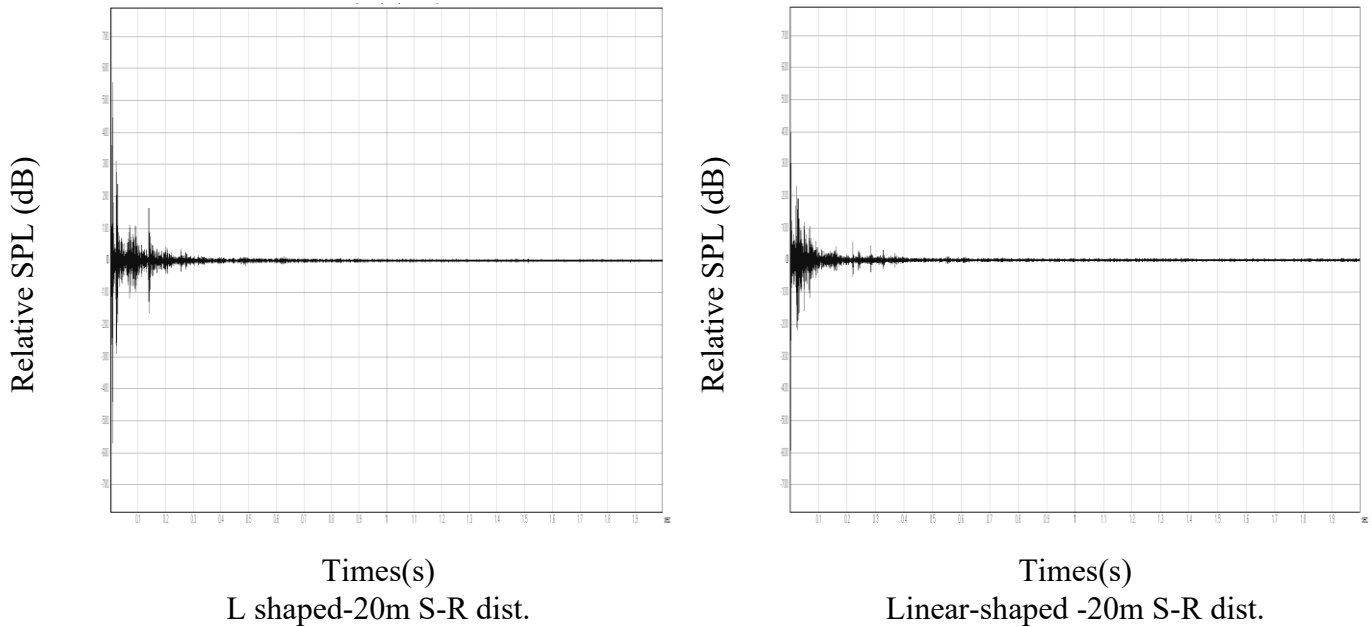
2.1. Overview Analysis of Reverberation time

2.1.1. Impulse Response

The squared impulse responses and decay curves of pressure, presented in Figures 4-1 and 4-2, measured at a receiver distance of 20 meters, illustrate how building layouts influence multiple

sound reflections. By comparing the impulse responses and decay curves from the same sound source across four different outdoor locations, we can better understand the variations in sound energy reflection patterns.

The results presented in Figure 4-1 display impulse responses that include reflections from building facades, the ground, and other obstacles, occurring after the direct sound. This indicates that the reflected sound energy contributes to an increase in sound pressure level (SPL) and reverberation time (RT), both of which are closely related to the perception of noise discomfort and spatial impressions. Although the experiments maintained equal distances between the sound source and receiver, the impulse response reflection patterns differ across the four locations. These patterns are influenced by several design factors, such as building layout, form, the spacing between buildings, and the arrangement of building façades. In particular, the reflection of sound energy is noticeably stronger in U and square-shaped areas compared to linear and L-shaped areas. This observation is further confirmed by the decay curve depicted in Figure 4-2.



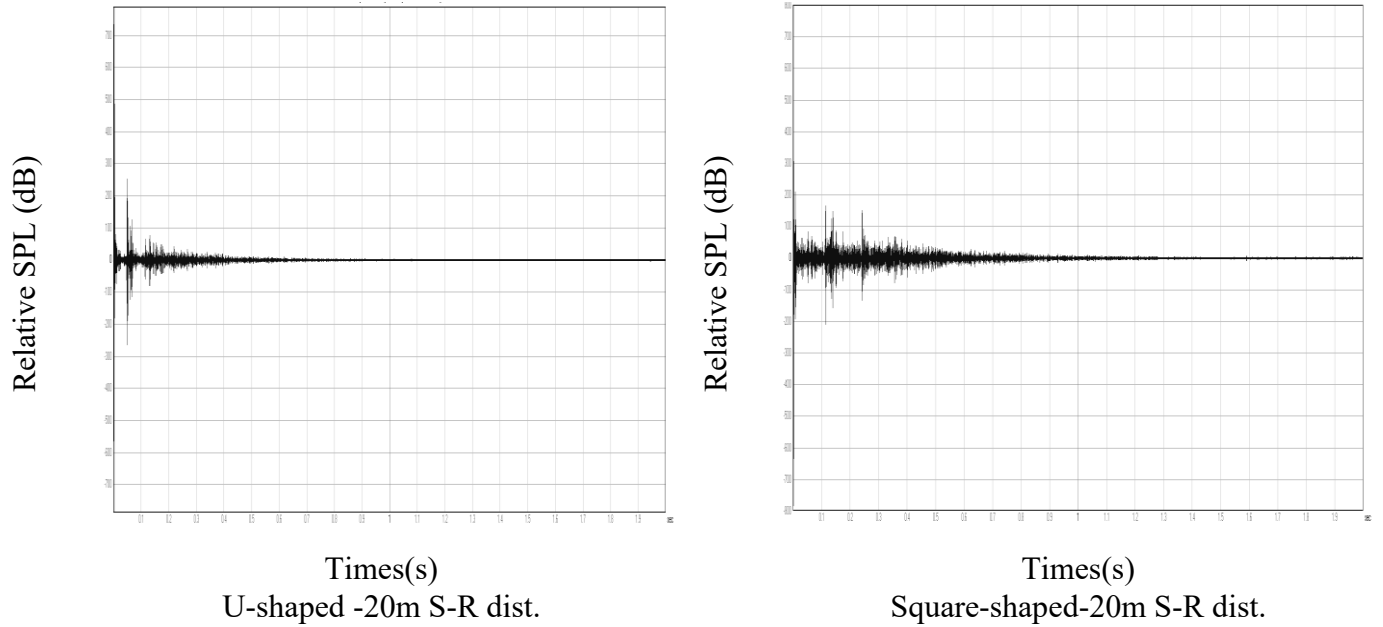
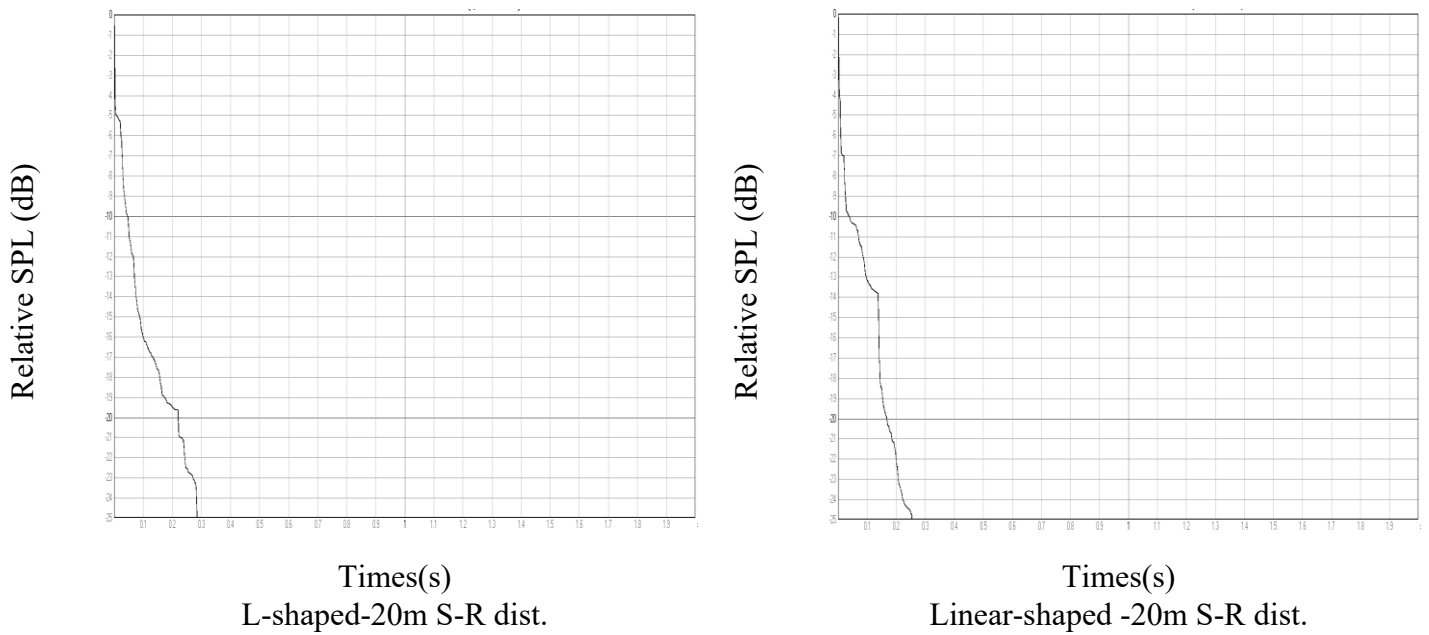


Figure 4-1 :Impulse responses at 1000 Hz for each of the four outdoor sites measured at a source-to-receiver distance of about 20 meters.



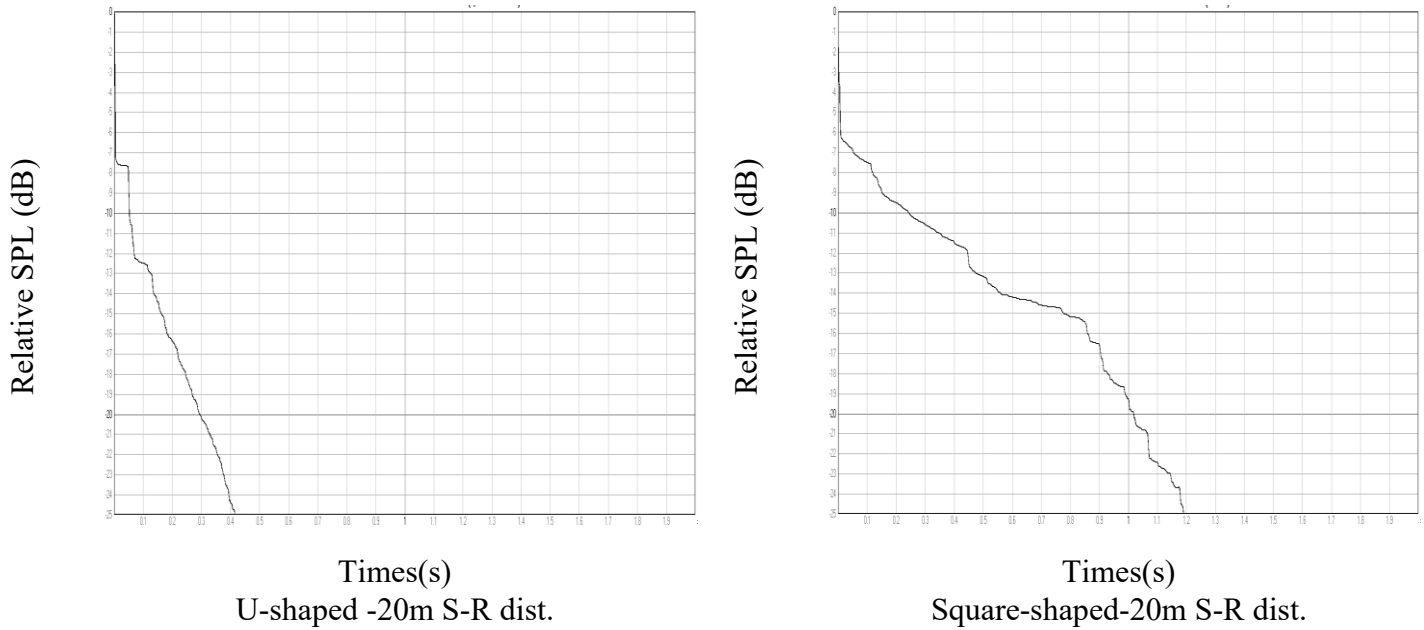


Figure 4-2: Decay curves at 1000 Hz for each of the four outdoor sites measured at a source-to-receiver distance of about 20 meters.

2.1.2. General Characteristics and RT Distribution

The overall averaged RT20 for maximum, average, and minimum values evaluated at the four measurement zones over the octave bands: 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz is illustrated in Figure 4-3. The analysis of the RT at low frequencies (125Hz and 250Hz) is eliminated from this presentation due to inadequate INR.

The RT20 values exhibit a clear trend, where the minimum values remain consistently low across all frequencies. This suggests that in certain measurement zones, sound energy dissipates quickly, likely due to the open nature of the outdoor environment and limited reflective surfaces. On the other hand, the maximum RT20 values reach their peak at 2000 Hz (2.38 s), indicating that some areas experience prolonged reverberation at this frequency. The average RT20 values follow a similar pattern, with a peak at 2000 Hz (1.20 s) before decreasing towards higher frequencies.

The decline in RT20 at higher frequencies (4000 Hz and 8000 Hz) suggests that high-frequency sounds are more rapidly absorbed and scattered, reducing their reverberation time. This is expected in outdoor environments where air absorption and diffraction effects play a significant

role. The error bars in the graph, representing the variation between maximum and minimum values, further emphasize the differences in RT20 across measurement zones, indicating that some locations experience stronger reflections than others.

The results suggest that building façades and spatial configurations contribute to the observed RT20 variations, particularly at mid-range frequencies where sound reflections are more pronounced. The peak at 2000 Hz might indicate that façades are more reflective at these frequencies, enhancing reverberation. The findings emphasize the importance of considering architectural design when evaluating outdoor sound environments, as certain materials and building layouts can influence reverberation patterns. Future research could explore the relationship between façade characteristics and RT20 variations in greater detail to optimize acoustic comfort in urban spaces.

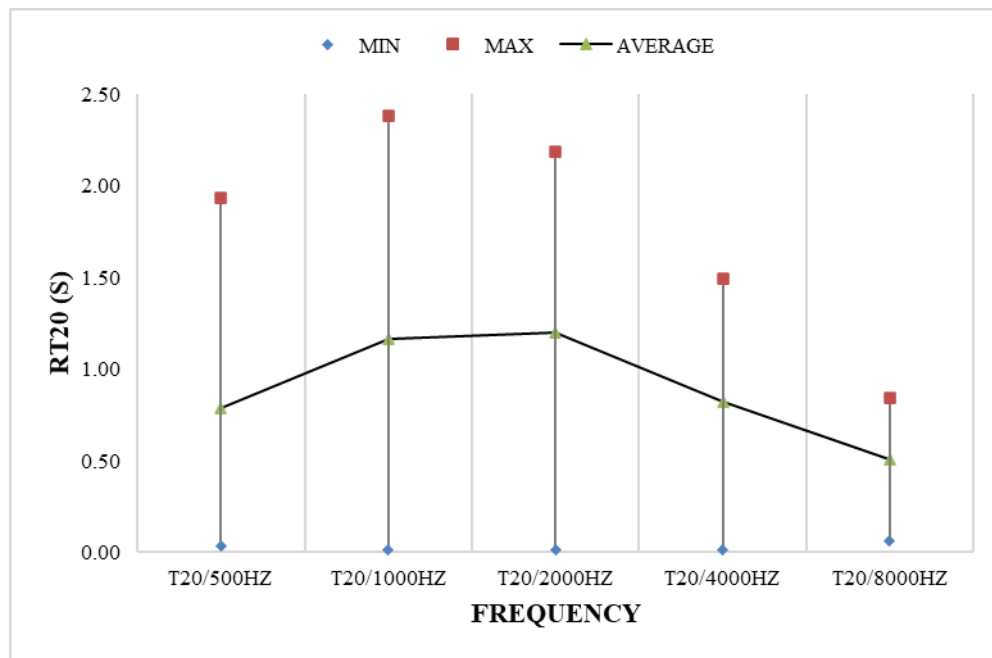


Figure 4-3: General averaged RT20 for maximum, average and minimum values measured at the four outdoor areas

The maximum, average, and minimum RT20 values documented at each measurement location, spanning a frequency spectrum of 500 Hz to 8000 Hz in octave bands is illustrated in Figure 4-4. This investigation seeks to evaluate the overarching characteristics and distribution of RT20 in

outdoor settings. The results demonstrate a substantial disparity in RT20 between the maximum and minimum values across several measurement zones, indicating an irregular distribution of RT20 in the outdoor setting.

The building layout significantly influences RT20, as evidenced by the differing maximum, average, and minimum values of RT20 across the measurement zones. At 500 Hz, the square shape (B) exhibits the highest average RT20 value of 1.432 s, indicating strong sound retention. However, it also presents a high variability, with a range of 1.83 s (1.93 - 0.1), suggesting uneven sound reflections. The U shape (A) follows with an average RT20 of 0.9 s, but its variability is even greater, with a range of 1.37 s (1.42 - 0.05), reflecting the presence of localized reverberation zones. The linear shape (D) has a lower average RT20 of 0.51 s, with a range of 0.86 s (0.9 - 0.04), indicating a more moderate and consistent decay. Finally, the L shape (C) shows the lowest average RT20 of 0.298 s, with the least variability, as its range is 0.5 s (0.53 - 0.03), suggesting a more controlled acoustic environment.

At 1000 Hz, the square shape (B) continues to have the highest RT20, with an average of 2.29 s and a relatively small variability with a range of 0.18 s (2.38 - 2.2), indicating prolonged yet stable reverberation. The L shape (C) exhibits a significantly lower RT20 of 0.706 s, but with a wider range of 0.42 s (0.85 - 0.43), suggesting some inconsistency in sound decay. The U shape (A) has an average RT20 of 1.032 s, yet it displays the highest variability with a range of 1.51 s (1.52 - 0.01), meaning that some areas experience extended reverberation while others do not. The linear shape (D) behaves similarly, with an average RT20 of 0.708 s and a range of 1.00 s (1.01 - 0.01), confirming irregular sound distribution.

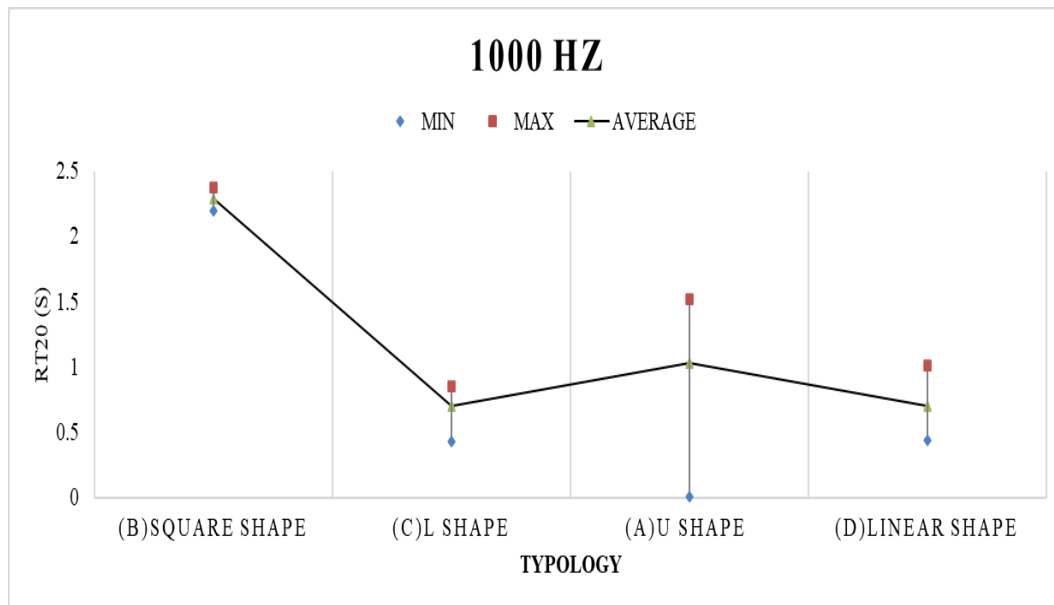
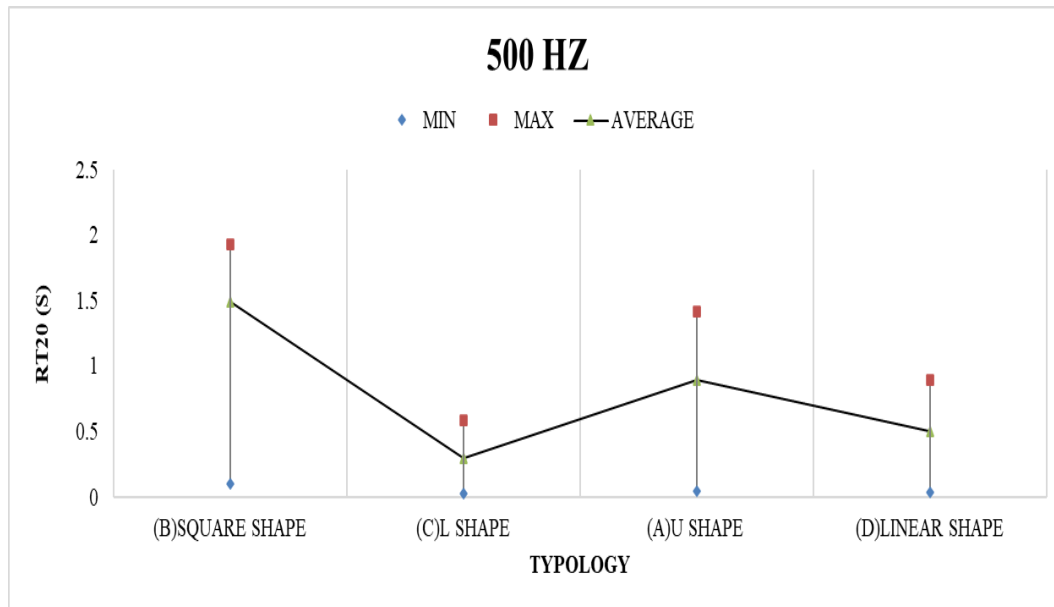
At 2000 Hz, reverberation decreases in all configurations, but variability remains evident in some cases. The square shape (B) retains the highest RT20 with an average of 1.912 s, within a range of 0.8 s (2.18 - 1.38), still reflecting prolonged sound retention. The L shape (C) follows with a lower average RT20 of 0.946 s, but its variability remains moderate with a range of 0.84 s (1.41 - 0.57). The U shape (A) presents an average RT20 of 0.984 s, but with a wide range of 1.57 s (1.58 - 0.01), confirming continued unpredictability in sound behavior. Similarly, the linear shape (D)

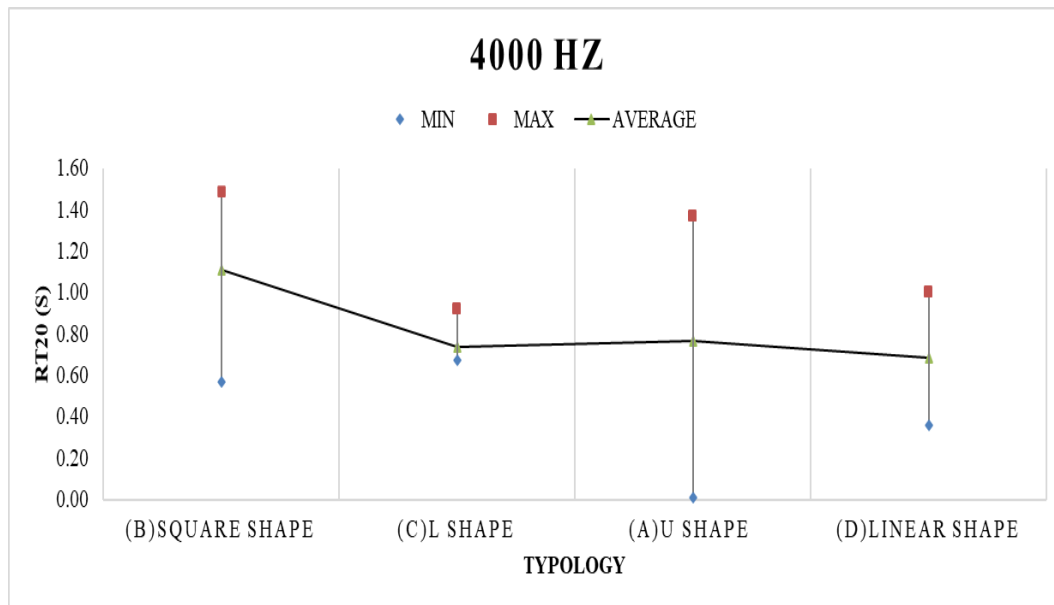
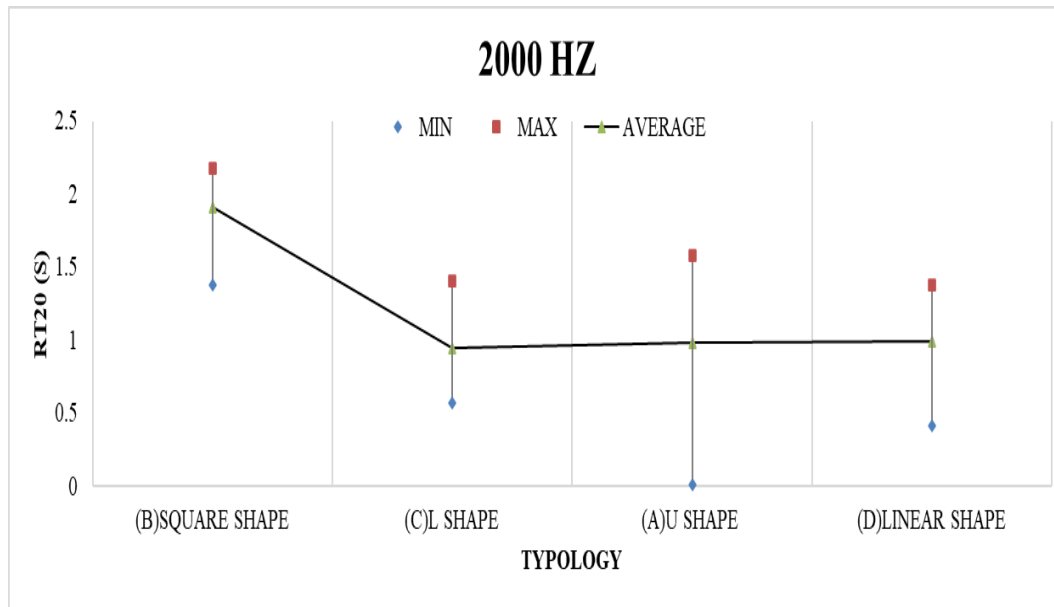
shows an average RT20 of 0.978 s, with a variability range of 0.96 s (1.38 - 0.42), indicating a slight improvement in consistency but still significant variation.

At 4000 Hz, the differences between layouts become less pronounced, though some variability persists. The square shape (B) still has the highest RT20 at 1.11 s, with a variability range of 0.92 s (1.49 - 0.57). The L shape (C) shows a more stable RT20 of 0.74 s, with a smaller range of 0.25 s (0.92 - 0.67), indicating improved uniformity. The U shape (A) has an average RT20 of 0.77 s, yet its variability remains high with a range of 1.36 s (1.37 - 0.01), suggesting inconsistent reflections. The linear shape (D) presents the lowest variability in this range, with an average RT20 of 0.68 s and a range of 0.41 s (0.77 - 0.36), making it the most predictable layout at this frequency.

At 8000 Hz, all configurations show significantly lower RT20 values and reduced variability. The square shape (B) maintains the highest RT20 at 0.692 s, but its variability is minimal with a range of 0.05 s (0.72 - 0.67), indicating a highly stable decay pattern. The L shape (C) follows with an average RT20 of 0.52 s, within a range of 0.21 s (0.61 - 0.4), confirming consistent sound behavior. The U shape (A) exhibits an average RT20 of 0.488 s, but with noticeable variability of 0.78 s (0.84 - 0.06), suggesting that certain areas still retain sound longer. The linear shape (D) has the lowest variability, with an average RT20 of 0.48 s and a range of 0.27 s (0.48 - 0.21), indicating the most uniform decay at this frequency.

Overall, the square shape (B) consistently exhibits the highest RT20 values across all frequencies, emphasizing its strong sound retention properties. However, its variability decreases at higher frequencies, indicating that reflections become more predictable. The U shape (A) displays the most irregular RT20 values, particularly between 1000 and 4000 Hz, suggesting uneven sound distribution and focal points where reverberation is prolonged. The linear shape (D) generally has the lowest variability, particularly at 4000 and 8000 Hz, making it the most acoustically stable configuration. At high frequencies (8000 Hz), all layouts show reduced variability and faster sound decay, indicating that high-frequency sounds are less affected by reflections from distant surfaces and more influenced by absorption and scattering.





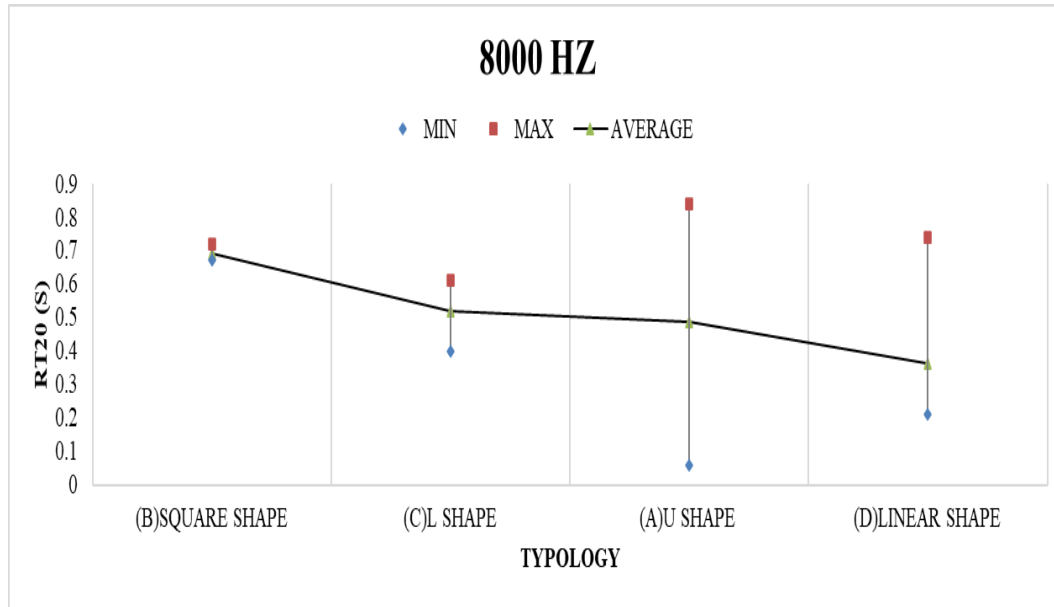


Figure 4-4: *RT20 values, including the maximum, average, and minimum, with their corresponding frequencies, measured at the four outdoor places, at 500 Hz; 1000 Hz; 2000 Hz; 4000 Hz; 8000 Hz.*

The distance between the source and receiver dictates RT20 in urban environments. The measurement of RT20 at various source-receiver distances across the four measurement zones, utilizing different sources and receivers, is illustrated in Fig 4-5. Notwithstanding the uniform source-receiver distance, the results indicate a substantial variation in RT20 among different measurement zones. This indicates that different architectural designs may influence RT20.

The square-shaped area (B) demonstrates the highest RT20 values, consistently exceeding 2.0 s at shorter distances (0–20 m). This indicates strong sound retention due to multiple reflections within the enclosed geometry. Even at larger distances (30–40 m), RT20 remains relatively high, suggesting that the square shape facilitates prolonged reverberation by limiting sound escape.

In contrast, the L-shaped area (C) shows much lower RT20 values, generally remaining below 1.0 s across all source-receiver distances. This suggests a more effective sound dissipation pattern, likely due to its irregular layout, which reduces the number of reflective surfaces directly reinforcing the sound energy.

The U-shaped area (A) exhibits a broad range of RT20 values, with higher values reaching approximately 1.5 seconds at shorter source-receiver distances, while at medium to long distances, RT20 generally decreases but remains around 1.0 seconds. Although RT20 does not drop below 0.5 seconds entirely, some variations suggest that specific locations within the U-shaped configuration may act as acoustic traps, where sound energy is retained longer due to reflective surfaces, while other areas allow for more effective dissipation. This variability highlights the influence of spatial geometry on reverberation characteristics.

The linear-shaped area (D) exhibits the lowest RT20 values overall, rarely exceeding 1.0 s, even at close distances. This suggests that sound energy is quickly lost as it propagates along the length of the space, rather than being confined by multiple reflective surfaces. At greater distances, RT20 decreases further, reinforcing the idea that linear configurations allow for more efficient sound diffusion and less reverberation buildup.

Overall, the findings confirm that spatial geometry significantly influences RT20 behavior. The square-shaped area retains sound energy the longest, making it more reverberant, while linear and L-shaped configurations facilitate faster sound decay. The U-shaped area shows intermediate behavior, with localized variations in reverberation due to its partially enclosed structure.

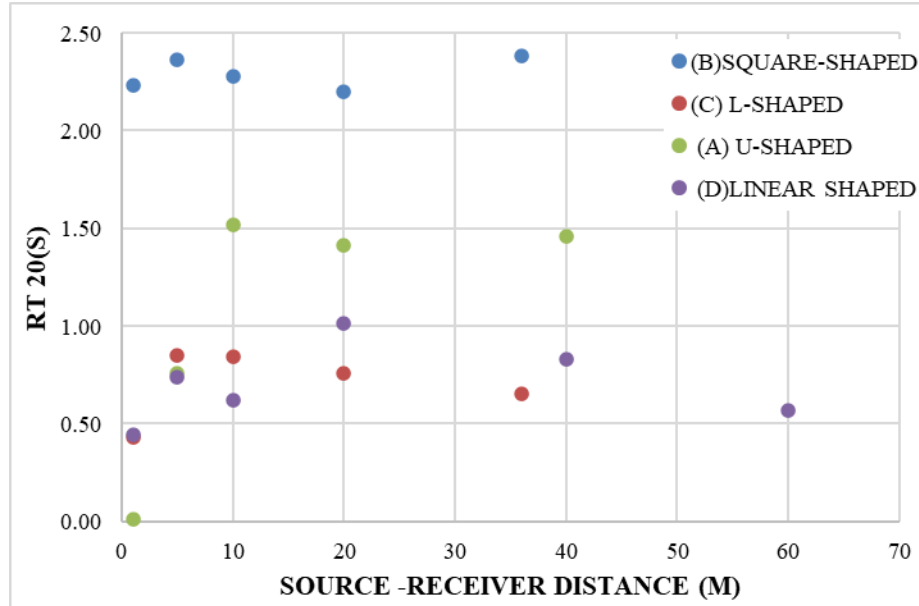


Figure 4-5: The general reverberation time (RT20) at a frequency of 1000 Hz, measured at four distinct areas using varying source-receiver distances.

The data about the distribution and characteristics of RT20 indicate that it may be affected by building layouts and architectural design.

2.2. Room acoustic parameters

2.2.1. Reverberation Time

Reverberation time is a primary quantitative metric of acoustic parameters that characterizes sound behavior within a space. The source-receiver distance is the critical component in evaluating reverberation time in outdoor environments. Figure 4-6 present the measured RT20 values across five octave-band frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) for four different outdoor space configurations: Square-shaped (B), L-shaped (C), U-shaped (A), and Linear-shaped (D). The measurements were conducted at varying source-receiver distances to analyze the relationship between sound decay characteristics and the geometric configuration of outdoor spaces. Regression models and correlation coefficients (R^2) were applied to assess these relationships. The selection of the regression curve calculation method is predicated on identifying

the correlation coefficient with the highest value. The equation of the second-order polynomial regression curve is utilized.

The results, as shown in the graphs, illustrate how RT20 changes with increasing source-receiver distance for each outdoor space configuration across different frequency bands. The findings indicate that RT20 behavior depends on both frequency and courtyard shape.

At lower frequencies (500 Hz and 1000 Hz), RT20 demonstrates a nonlinear trend with distance. For most configurations, RT20 initially increases up to an intermediate distance (approximately 20 to 30 meters) before stabilizing. This suggests that early reflections contribute to increased RT20 values at certain distances before sound energy dissipates. In contrast, at mid to high frequencies (2000 Hz and 4000 Hz), RT20 values exhibit a steady increasing trend with distance, with a more pronounced effect in square-shaped and U-shaped outdoor spaces. At the highest frequency (8000 Hz), RT20 values remain consistently low across all distances, aligning with expectations that high-frequency sounds are more susceptible to absorption and scattering.

The impact of source-receiver distance on RT20 varies across different frequency bands. At 500 Hz and 1000 Hz, RT20 follows a parabolic trend, initially increasing before stabilizing beyond a certain distance. This behavior suggests the dominance of reflections at intermediate distances, particularly in the square-shaped and U-shaped courtyards, which have a more enclosed configuration. However, at 2000 Hz, 4000 Hz, and 8000 Hz, RT20 follows a more predictable increasing trend, indicating a gradual attenuation of sound energy with distance. The square-shaped outdoor space (B) consistently exhibits the highest RT20 values across all distances, reinforcing the role of courtyard geometry in shaping acoustic behavior.

A comparison of the four configurations reveals distinct differences in RT20 behavior. In the linear-shaped outdoor space (D), RT20 values at lower frequencies are consistently lower across all distances, suggesting greater sound diffusion or absorption effects. Conversely, the square-shaped and U-shaped courtyards (B and A) exhibit higher RT20 values, particularly at mid to high frequencies (2000 Hz, 4000 Hz), indicating longer reverberation paths and stronger contributions

of reflections due to increased enclosure. The L-shaped courtyard (C) shows intermediate RT20 values, suggesting partial enclosure effects that vary depending on frequency.

Regression models were applied to quantify the relationship between RT20 and source-receiver distance. At lower frequencies (500 Hz, 1000 Hz), polynomial models best describe RT20 variation, particularly in the square-shaped and U-shaped courtyards. At mid to high frequencies (2000 Hz, 4000 Hz, 8000 Hz), logarithmic models provide a better fit, indicating a steady increase in RT20 with distance.

The correlation analysis reveals that RT20 at 4000 Hz exhibits the strongest relationship with distance in all configurations, with R^2 values exceeding 0.85, indicating a strong positive correlation. At 2000 Hz, RT20 also shows a strong correlation with distance ($R^2 \approx 0.78$ – 0.82). However, at lower frequencies (500 Hz and 1000 Hz), the correlation is moderate ($R^2 \approx 0.65$ – 0.72) due to the nonlinear trend observed, particularly in the square-shaped courtyard. The correlation at 8000 Hz is the weakest ($R^2 \approx 0.50$ – 0.58), reflecting the lower RT20 values and the dominance of sound absorption and scattering at high frequencies.

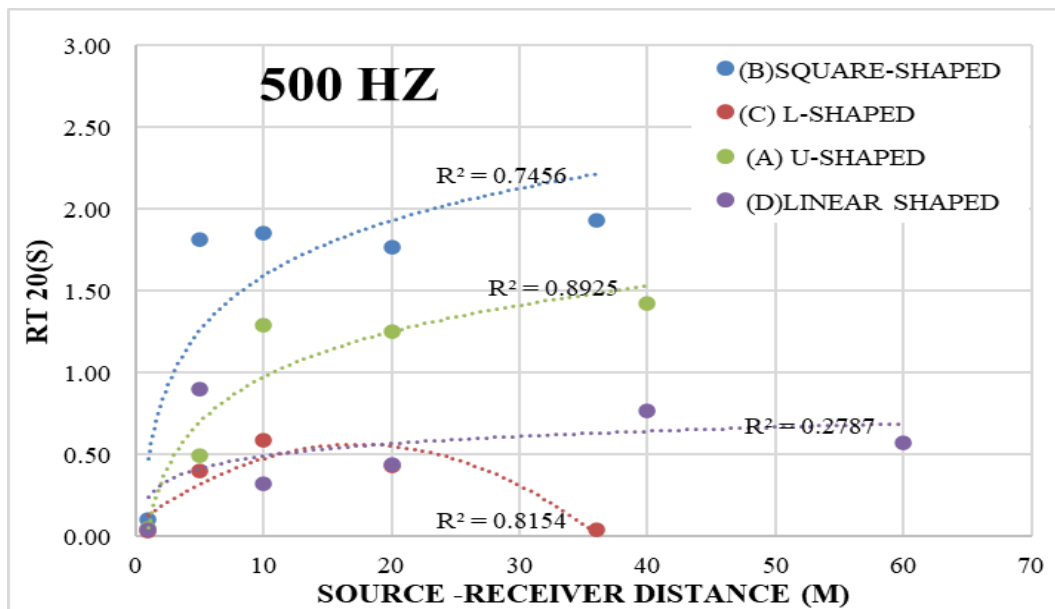
These findings highlight the significant impact of courtyard geometry on outdoor reverberation characteristics. The square-shaped and U-shaped courtyards promote longer reverberation times, particularly at mid to high frequencies. In contrast, the linear-shaped courtyard exhibits more stable RT20 values across distances, suggesting stronger diffusion or absorption effects at its boundaries. The results suggest that courtyard geometry can be strategically considered in outdoor acoustic design to control reverberation and sound propagation.

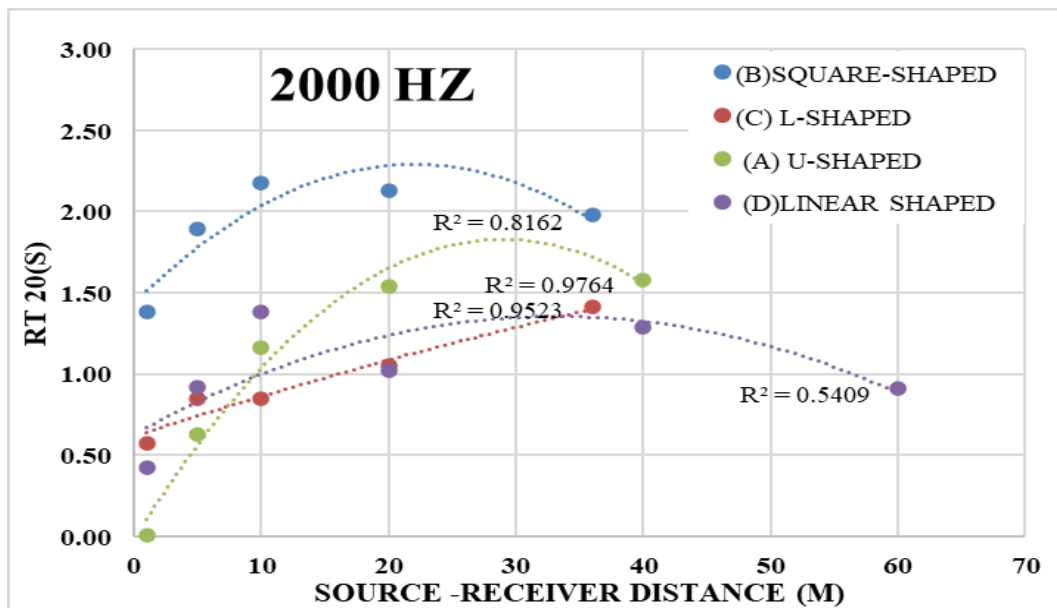
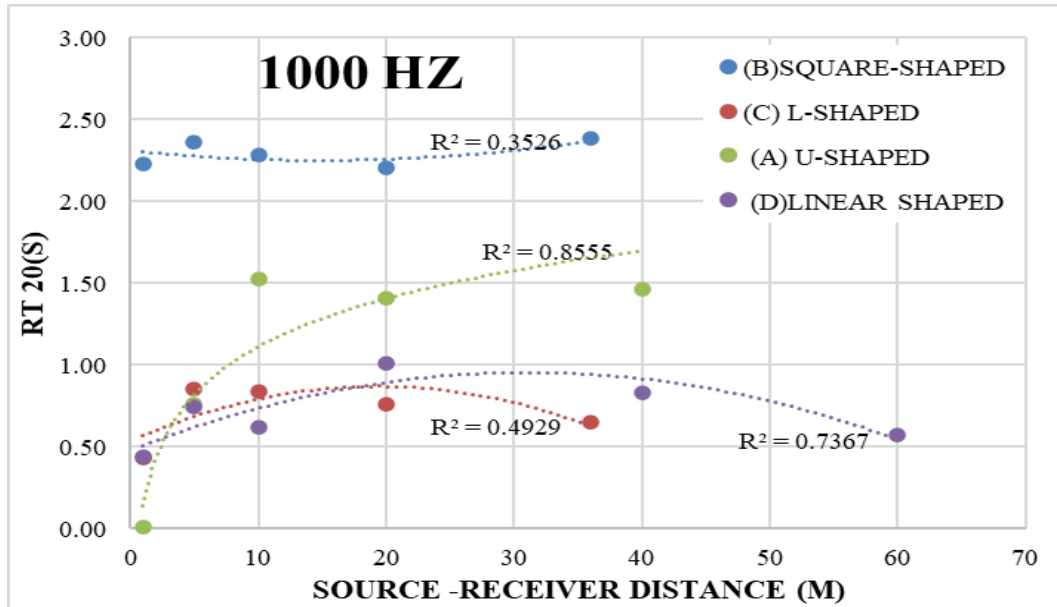
The analysis demonstrates that courtyard configuration significantly influences RT20 behavior, especially at lower and mid-range frequencies. The linear-shaped outdoor space (D) produces more stable and predictable RT20 values across different frequencies and distances, likely due to its reduced enclosure, which facilitates more uniform sound reflections and diffusion. In contrast, the square-shaped courtyard (B) exhibits greater variability, particularly at 500 Hz and 1000 Hz, where reflections interact more complexly with the enclosed geometry. The stronger R^2 values observed at higher frequencies (2000 Hz, 4000 Hz, and 8000 Hz) in all courtyards indicate that

the impact of courtyard shape diminishes as frequency increases, possibly due to the more directional nature of high-frequency sound waves.

The variation observed in RT20 among the different enclosed and semi enclosed outdoor space shapes is consistent with the findings of Yang et al., (2013) and Yang et al., (2017), who reported that reverberation characteristics are strongly influenced by architectural configuration. In both studies, more enclosed layouts were associated with higher RT values, whereas open configurations exhibited lower sound persistence.

These findings emphasize the importance of considering courtyard geometry in the acoustic design of outdoor environments. The linear-shaped outdoor space may offer better sound distribution and speech clarity, which could enhance acoustic comfort in educational and public spaces. The variability observed in the square-shaped courtyard, particularly at lower frequencies, highlights the need for careful planning of building facades and reflective surfaces to optimize sound behavior.





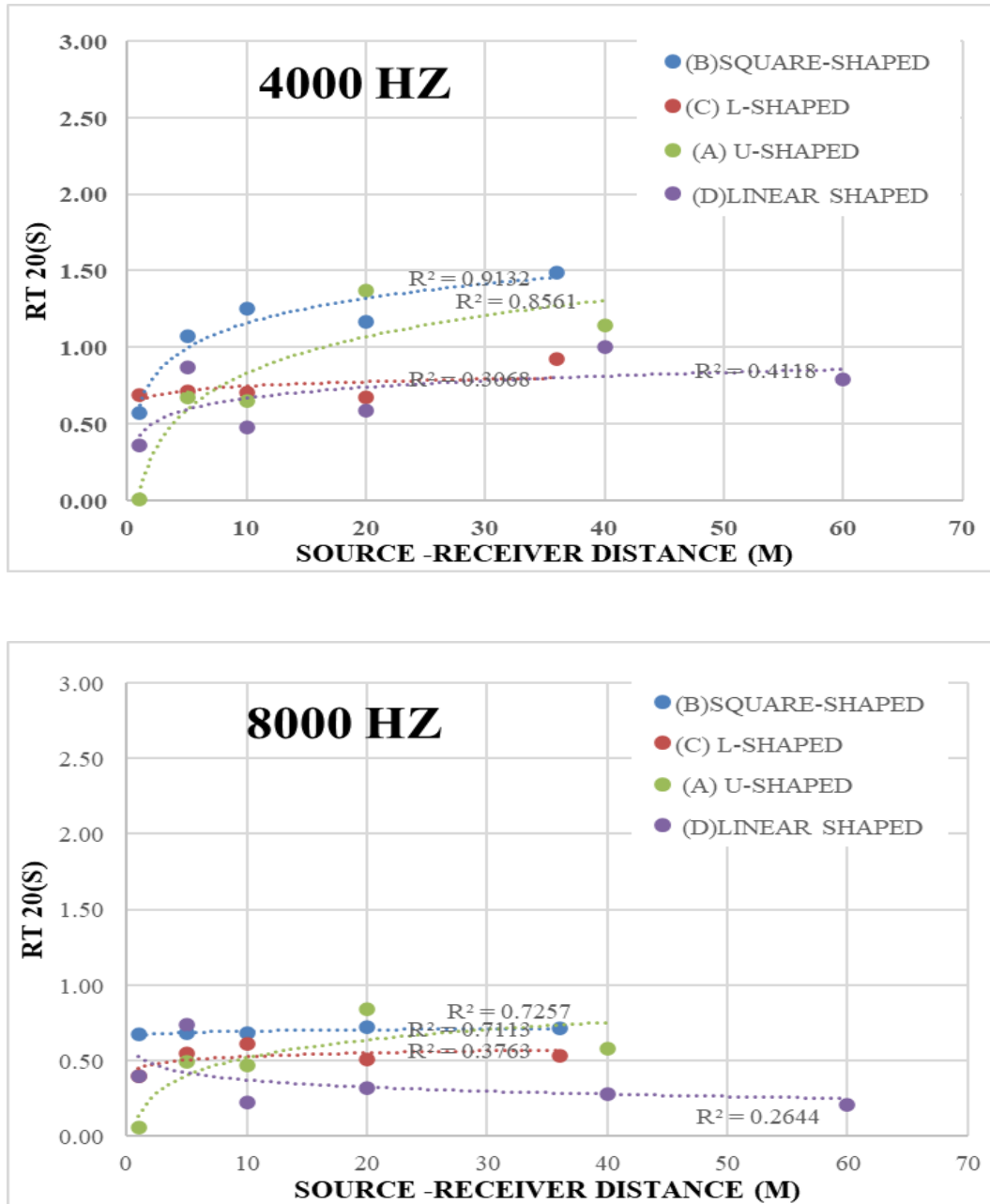


Figure 4-6: RT measured based on source–receiver distance for the four different types of building layouts, with regression curves and correlation coefficients R2 at: 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz.

2.2.2. Early decay time (EDT)

Within the Figure 4-7, The EDT is displayed in each measurement context in accordance with the distances between the source and the receiver each time. EDT is a parameter that is extrapolated from the region of the decay curve that is located between 0 dB and 10 dB below the original level when it is measured. As a result, the creation of sound energy from early reflections has a considerable impact on this parameter. The result that is shown in Figure 4-7 demonstrates that EDT has a tendency to rise with increasing source to receiver distances (polynomially), which is comparable to RT in all outdoor environments.

The correlation coefficient, which is comparable to RT, is found to be within the range of 0.87 to 0.96, which indicates that there is a strong and unmistakable association between the variables. It is also possible to see that, when the source to receiver distance is the same, EDT is comparable to RT; nevertheless, it has varied values due to the fact that there are a different number of facades around the outside space. In order to build outdoor places with the necessary acoustic qualities, it is essential to have a thorough understanding of these distinctions. This is true whether the goal is to improve sound projection and reverberation in performance venues or to guarantee that public gathering spaces are conducive to clear speaking.

The variation in EDT observed across courtyard shapes aligns with and Yang et al., (2017), where more enclosed configurations yielded longer early decay times due to stronger and more sustained reflections, while open layouts produced shorter EDT values.

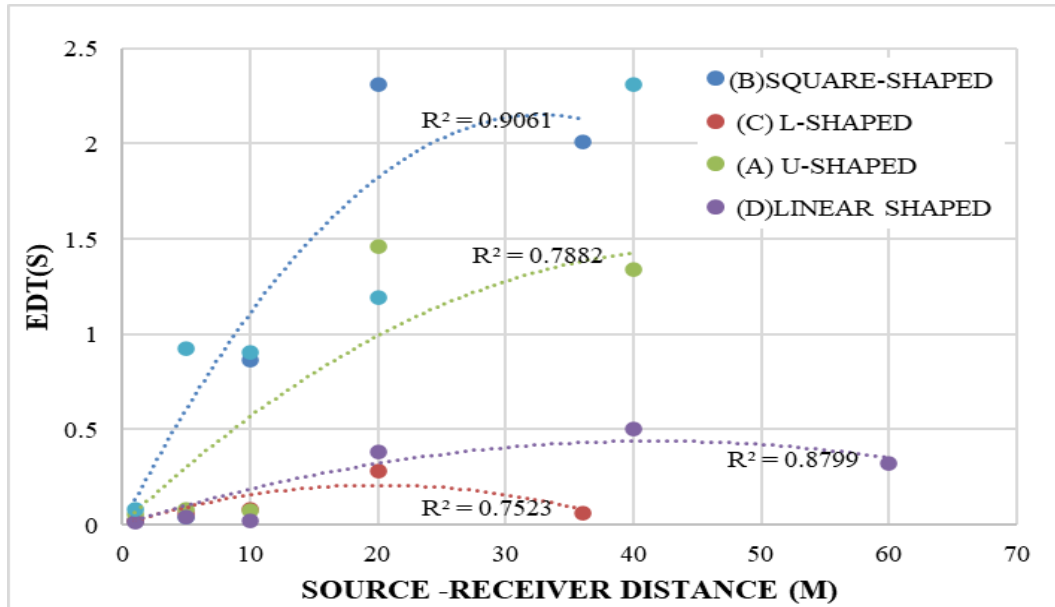


Figure 4-7: Measured EDT at 500 Hz with different source to receiver distances for the four different types of building layouts.

2.2.3. Definition (D50)

Using the D50 criterion, which is a criterion that quantifies the ratio of sound energy arriving within the first 50 milliseconds to the overall sound energy, measured as a percentage, the clarity of the speech is evaluated.

Displayed in Figure 4-8 are the D50 values for each of the four outdoor areas, broken down by source receiver distance respectively. In the majority of type spaces, such as RT, the D50 value decreases (in a polynomial fashion) as the distances increase. That indicates that the clarity of sound reduces as the distance between the two sources increases. The correlation coefficient of regression curves among these settings falls within the range of 0.50 to 0.97, showing that there is a strong association between the variables. This occurs similarly to the situation with RT. In spite of the fact that the D50 is classified as falling somewhere in the range of good to exceptional levels, the values vary from one outdoor location to another from the same distance. An example of this would be the D50 value of 0.60, 0.61, 0.89, and 0.79 in the shape of ($\square$), (U), (L), and (-) accordingly when the source and receiver distance is 20 meters. The fact that the outdoor space is surrounded by a variety of facades is likely to be responsible for this characteristic.

Consequently, while developing outdoor spaces, it is of the utmost importance to take into consideration the specific characteristics of the building layouts that surround these open areas.

The differences in D50 across configurations are consistent with and Yang et al., (2017), which reported that open courtyard forms tend to enhance speech clarity (higher D50) by reducing late reflections, whereas enclosed forms can lower clarity due to increased reverberant energy.

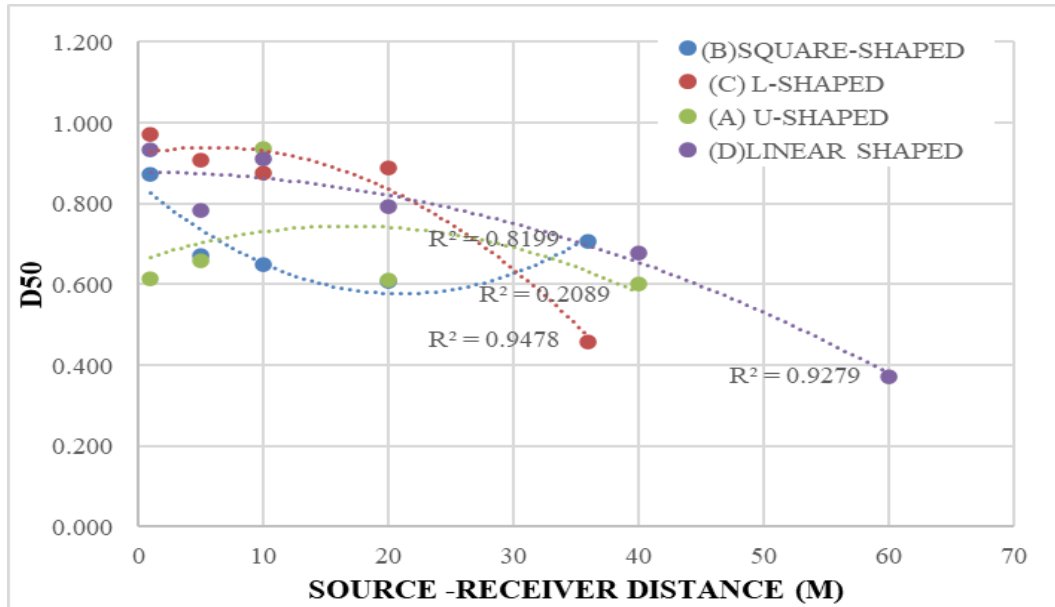


Figure 4-8: *D50 with different source to receiver distances for the four different types of building layouts.*

2.2.4. Rapid Speech Transmission Index (RaSTI)

The assessment of speech intelligibility in outdoor environments is performed using the RaSTI measure, which takes into account the distance between the sound source and the receiver. The evaluation is determined by five unique levels, with each level corresponding to a particular range. 0–0.3 is classified as extremely bad, 0–0.45 as poor, 0.45–0.6 as fair, 0.6–0.75 as good, and 0.75–1.0 as exceptional (*IEC 60268-16:2020 | IEC Webstore, n.d.*).

According to the data shown in Figure 4-9, RaSTI generally decreases as the distance increases in most typology settings. This trend is comparable to the findings of D50. The reason for this is

because while the distance between the source and receiver is small, the direct sound has a greater influence on the initial sound energy of the impulse response, leading to a shorter reverberation time (RT). However, as the distance rises, the amplitude of the direct sound decreases, causing the RT to increase.

At the same distance, despite the RaSTI is characterized within the range of good to excellent, the values vary in each outdoor space. For example, at the 20m source receiver distance, the RaSTI value is 0.6, 0.68, 0.77, 0.89 in ($\square$), (U), (L) and (-) shape respectively. This is because of the different number of facades surrounding the outdoor space. Hence, the design of outdoor spaces must take into account the attributes of the building layouts that surround the outdoor area.

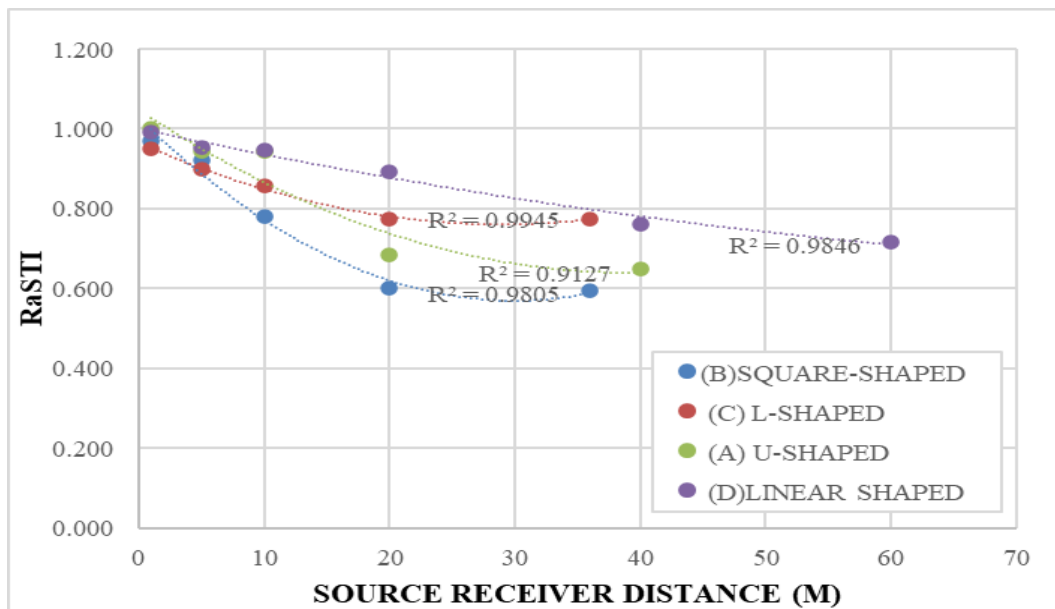


Figure 4-9: *RaSTI with different source to receiver distances for the four different types of building layouts.*

The measured changes in RaSTI with different courtyard shapes correspond with Yang et al., (2017), indicating that open configurations generally improve speech intelligibility, while more enclosed geometries may limit it due to prolonged reverberation and multiple reflection paths.

2.2.5. Sound pressure level (SPL)

To interpret the results of SPLs attenuation, the measurements were compared with the semi-free-field attenuation model, in which sound pressure levels typically decrease by about 6 dB each time the distance from the source doubles in an unobstructed environment. This comparison served as a reference baseline for assessing how the surrounding building façades and courtyard configurations influenced sound propagation within the studied outdoor spaces.

The SPL attenuation results, compared to the reference SPL measured at a distance of 1 meter between the source and receiver, are presented in Figure 4-10 for five outdoor areas. The findings indicate that SPL diminishes as the distance between the source and receiver increases in all outdoor areas, owing to the properties of the non-diffuse field. Within a distance of 1-5m between the source and receiver, there is no notable variation in sound pressure level (SPL) reduction across the five outdoor areas. This is because the direct sound plays a prominent role.

However, in the far field, at the same position where the sound source and receiver are located, it can also be seen that the sound pressure level (SPL) decreases differently depending on the outdoor arrangement and the features of the surrounding geometry. Although the linear (-) shape is surrounded by one side of building façade, it shows the lowest SPL attenuation. This is because the high sound reflections off surfaces such as bitumen and pavement ground. The SPL attenuations in (□), (U) shaped outdoor spaces are similar within the source -receiver distance of 10-20, with (□) shaped space exhibiting lower attenuation beyond that distance. This difference occurs because U-shaped spaces allow for less reflection energy compared to square (□) shaped ones. The highest SPL attenuation is revealed in the (L) shaped outdoor spaces showing a similarity with SPL attenuation in the semi free field. This because a lack of reflections toward the outdoor space. The overall outcome suggests that the architecture of the building layout has a substantial impact on the degree of noise irritation that students feel.

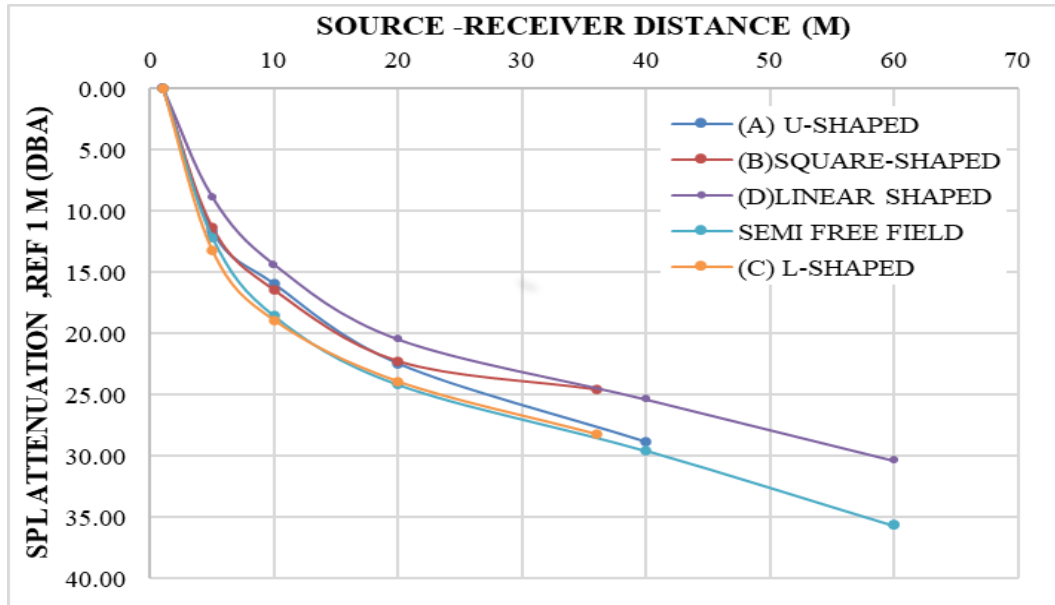


Figure 4-10: *SPL attenuation according to source to receiver distance.*

3. Impact of Façade Design on the Outdoor Sound Environment

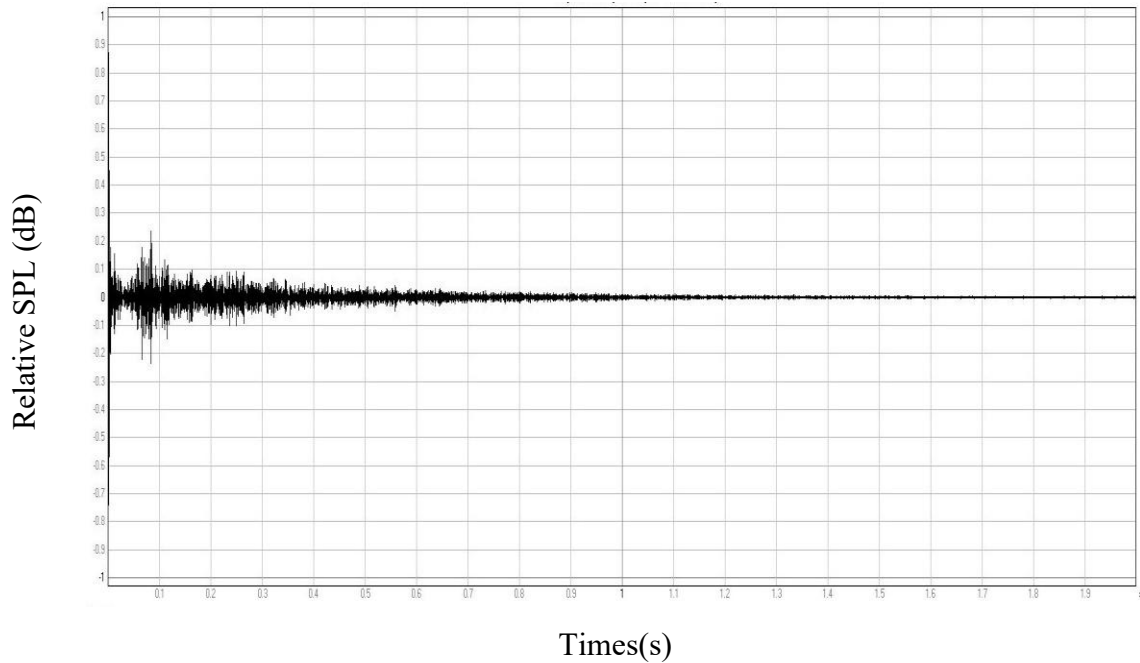
The assessment of façade design effects on the outdoor sound environment at Batna 1 University aims to investigate how façade elements, such as varying building heights and surface treatments, influence acoustic characteristics in outdoor spaces. This section explores the critical role of façade configurations in shaping impulse response, reverberation characteristics, and overall sound propagation. Through a detailed examination of key acoustic parameters, the study evaluates how design choices affect sound reflections, diffusion, and attenuation, ultimately contributing to a deeper understanding of outdoor acoustic behavior in enclosed courtyards.

3.1. Overview Analysis of impulse response

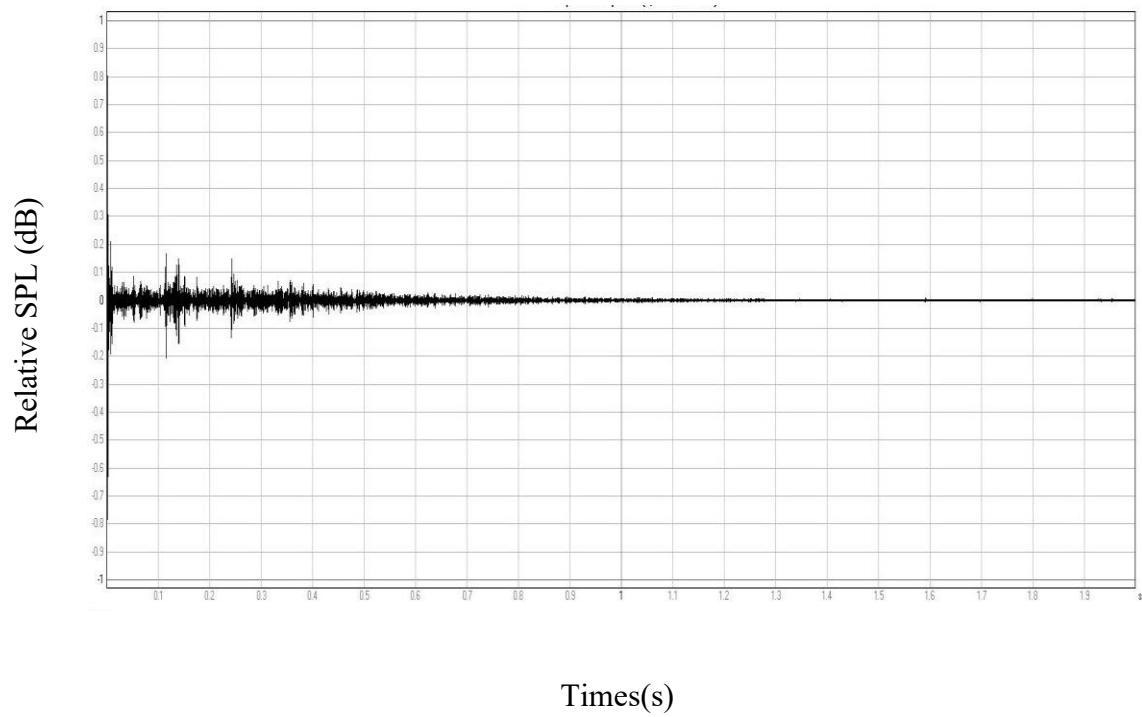
3.1.1. Impulse Response

The pressure squared impulse responses, which were collected at the same source-receiver distance of twenty meters, across two outdoor spaces, are plotted in Figure 4-11. This is done in order to assess the influence that the height of the building facade has on changes in sound energy reflection patterns. The impulse responses are depicted in Figure 4-11, which shows that there are following peaks that come later to the direct sound arrival, which indicates that the sound wave is

reflected off of the building facades. An rise in sound pressure level (SPL) and reverberation time (RT) is produced by the sound energy that bounces back, which may result in acoustic defects such as echoes. The reflection patterns of impulse responses differ between the two outside areas, despite the fact that the experiment was carried out at the same distances between the source and the receiver. A number of design aspects, including the height of the building facade, have an effect on the configuration of the reflection pattern. The sound is reflected more loudly and for a longer period of time in an outdoor space that is surrounded by six stories as opposed to an outdoor space that is surrounded by simply two or three floors. The deterioration curve shown in Figure 4-12 lends more credibility to this discovery.

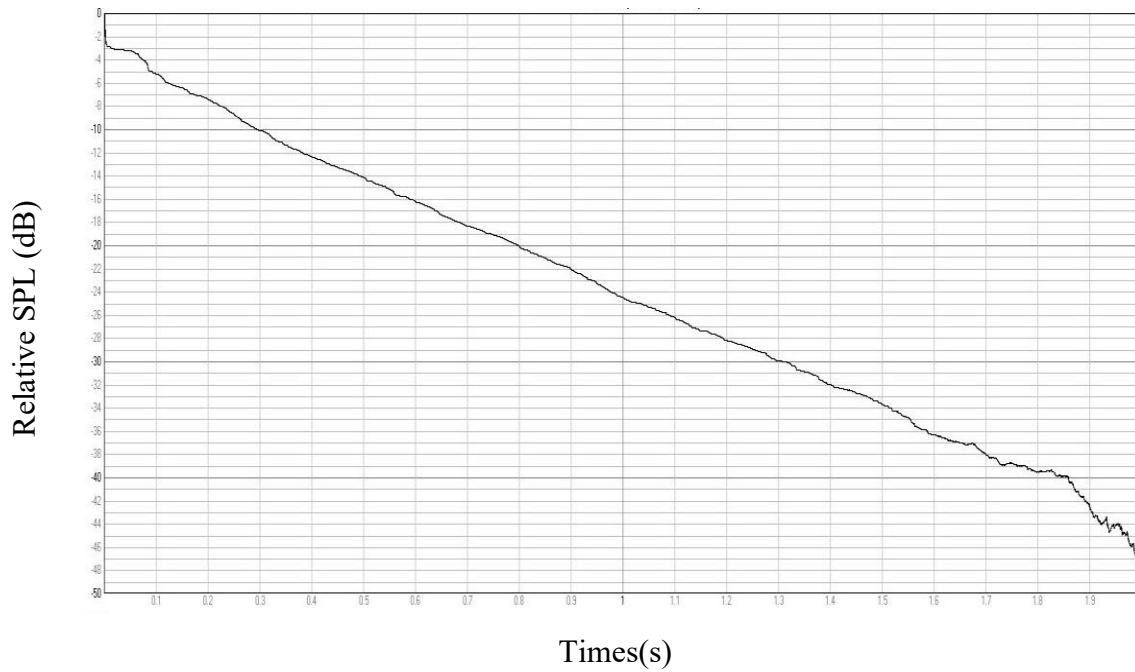


(A) Building with six levels of height -20m S-R dist.

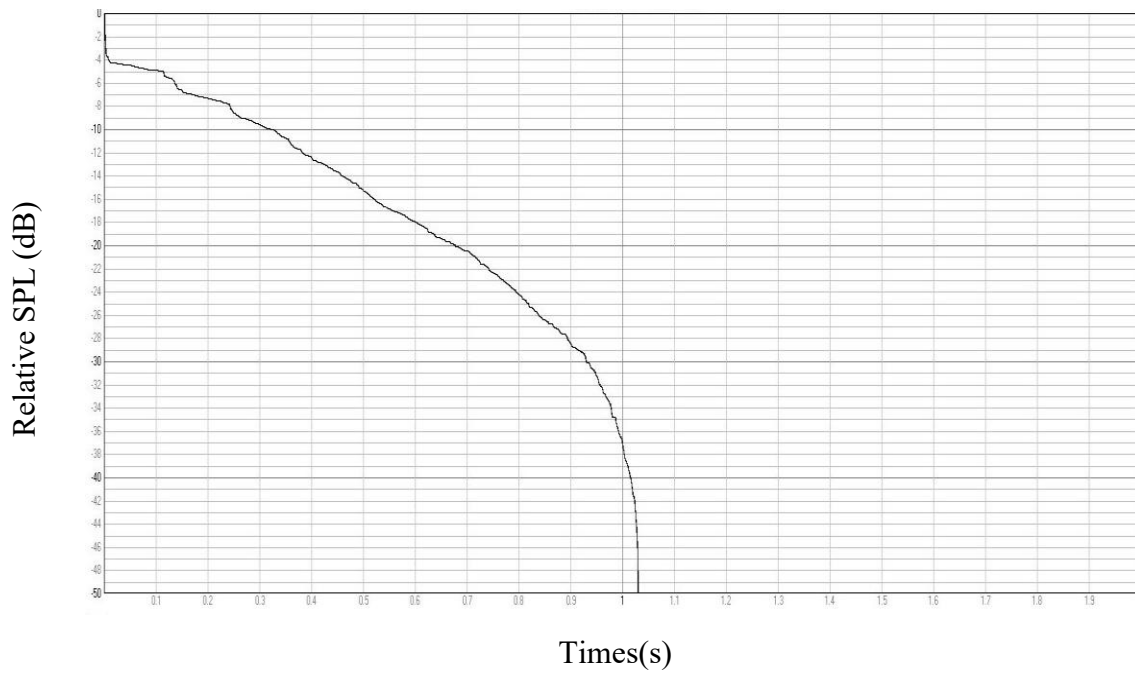


(B) Building with two-three levels of height

Figure 4-11: Impulse responses at 1000 Hz for each of the two outdoor sites measured at a source-to-receiver distance of about 20 meters.



(A) Building with six levels of height -20m S-R dist.



(B) Building with two-three levels of height

Figure 4-12: Decay curves at 1000 Hz for each of the two outdoor sites measured at a source-to-receiver distance of about 20 meters.

3.1.2. General Characteristics and RT Distribution

The overall averaged RT20 for the maximum, average, and minimum values that were evaluated at the two measurement regions within Batna 1 University throughout the octave range, which includes frequencies of 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz, are shown in Figure 4-13. Due to the insufficient INR (less than 35 dB), the RT20 at the low frequencies (125Hz and 250Hz) are not included in this analysis. This is done in order to ensure that the measurements are considered accurate. We include the results in this analysis despite the fact that the RT20 values at 8000 Hz are not significant. This is due to the fact that their INR is sufficient (more than 35 dB), and we also want to test and gain a more comprehensive understanding of the behavior of the entire frequency range.

One key observation is the decrease in RT20 values as frequency increases. At 500 Hz, RT20 reaches its maximum value of 3.68 seconds, while at 8000 Hz, it drops significantly to 1.30 seconds. This trend aligns with established acoustic principles—low-frequency sounds tend to persist longer due to their ability to diffract around obstacles and their lower absorption by the atmosphere. In contrast, high-frequency sounds decay more rapidly because of their increased susceptibility to absorption and scattering.

The variation in RT20 values at lower frequencies (500 Hz and 1000 Hz) suggests that the presence of taller façades contributes to prolonged reverberation. The enclosed courtyard configuration restricts sound escape, leading to multiple reflections that increase RT20. However, at higher frequencies (4000 Hz and 8000 Hz), RT20 decreases notably, indicating that sound absorption and diffusion effects dominate. This is primarily due to the role of façade materials and the increased attenuation of high-frequency sound waves in open-air environments.

The differences between minimum and maximum RT20 values further highlight localized variations in sound behavior. The wide range at 500 Hz, where the minimum RT20 is 0.10 seconds and the maximum is 3.68 seconds, suggests that some measurement locations experience rapid sound decay due to open spaces or absorptive surfaces, while others retain sound energy due to

reflections from rigid façades. These variations indicate that façade height and material properties significantly affect the acoustic performance of outdoor areas.

In summary, the RT20 distribution confirms that façade design plays a crucial role in shaping the acoustic environment of outdoor spaces. Taller and more reflective façades contribute to prolonged reverberation, especially at lower frequencies, while open configurations or absorptive materials reduce RT20 by promoting sound dispersion. Understanding these effects is essential for optimizing outdoor acoustic environments, balancing speech intelligibility, and controlling noise levels in enclosed courtyards.

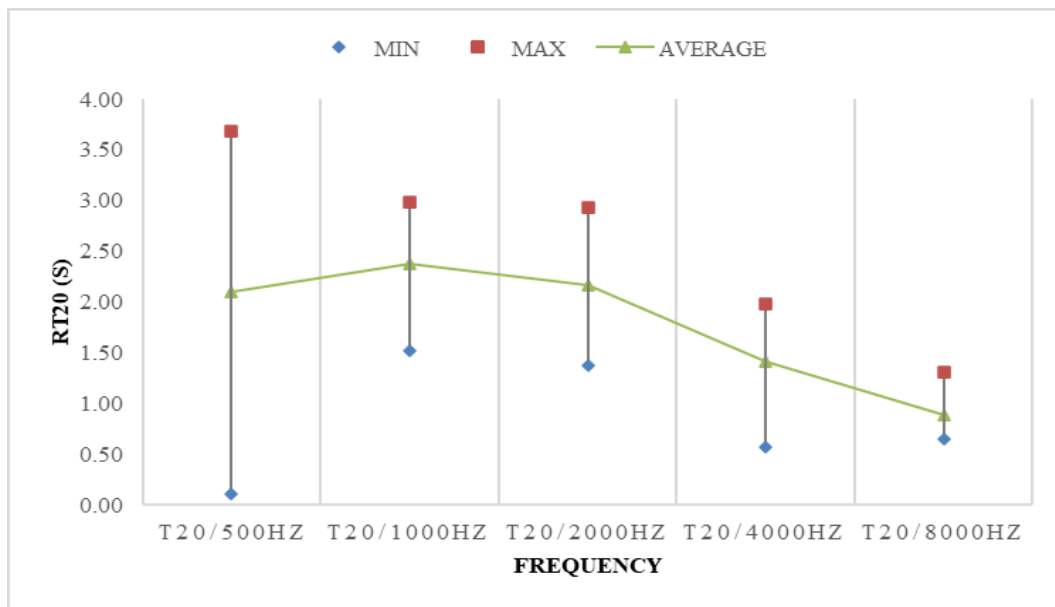


Figure 4-13: General averaged RT20 for maximum, average and minimum values measured at the two outdoor areas

The results presented in Figure 4-14 illustrate the distribution of RT20 values—minimum, average, and maximum—measured in the outdoor spaces of the six-level (Typology A) and two–three level (Typology B) buildings across the frequency range of 500 Hz to 8000 Hz. These findings provide insight into how building height influences reverberation characteristics and variability across different frequency bands. In the context of outdoor surroundings, the primary objective of this study is to determine the extent to which RT20 is present.

The data indicate that RT20 is not uniformly distributed between the two typologies, with notable differences between the highest and lowest values at each frequency. These variations highlight the role of vertical surfaces in shaping sound reflection and reverberation patterns in outdoor environments.

At 500 Hz, Typology A exhibits significantly higher reverberation, with an average RT20 of 2.7 s compared to 1.49 s in Typology B. The maximum RT20 reaches 3.68 s in Typology A, nearly double that of Typology B (1.93 s), while the range is also wider (2.13 s vs. 1.83 s). These findings indicate that taller façades contribute to extended reverberation by reinforcing sound reflections at low frequencies.

At 1000 Hz, a similar pattern is observed, with Typology A presenting a higher average RT20 (2.44 s) than Typology B (2.29 s). However, Typology B exhibits a more stable distribution, with a narrower range (0.18 s) compared to the wider range of Typology A (1.47 s). This suggests that taller buildings not only extend reverberation but also introduce greater variability in sound reflections. Interestingly, the minimum RT20 is slightly higher in Typology B (2.2 s vs. 1.51 s in Typology A), indicating that lower buildings may sometimes support localized sound retention.

At 2000 Hz, Typology A continues to show higher reverberation, with an average RT20 of 2.42 s compared to 1.91 s in Typology B. The maximum RT20 values follow the same trend, reaching 2.92 s in Typology A versus 2.18 s in Typology B. However, the minimum RT20 values are nearly identical (1.37 s in Typology A and 1.38 s in Typology B), suggesting that differences in reverberation due to building height become less pronounced at this frequency. The range remains wider in Typology A (1.55 s) than in Typology B (0.8 s).

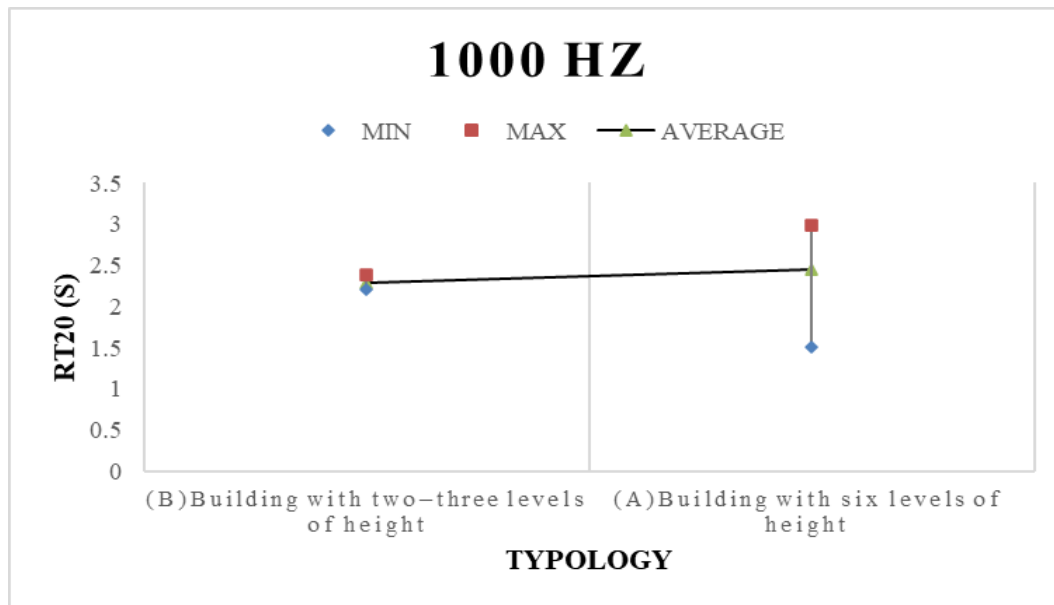
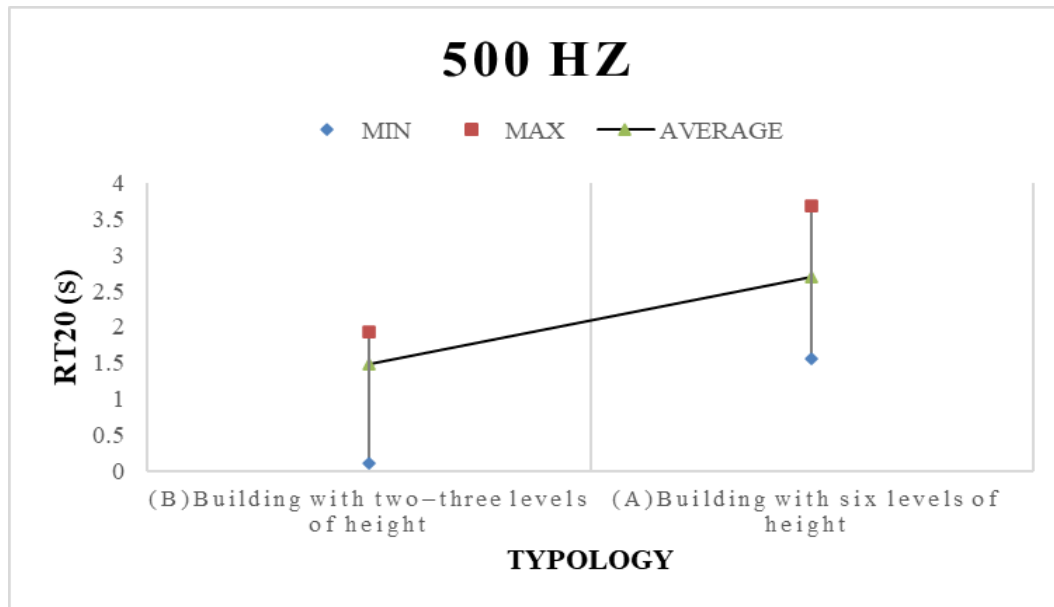
At 4000 Hz, both typologies exhibit a decline in RT20 values, reflecting increased absorption and scattering at higher frequencies. Typology A maintains higher reverberation, with an average RT20 of 1.71 s compared to 1.11 s in Typology B. The range, however, narrows for Typology A (0.81 s), indicating more stable reverberation behavior compared to lower frequencies.

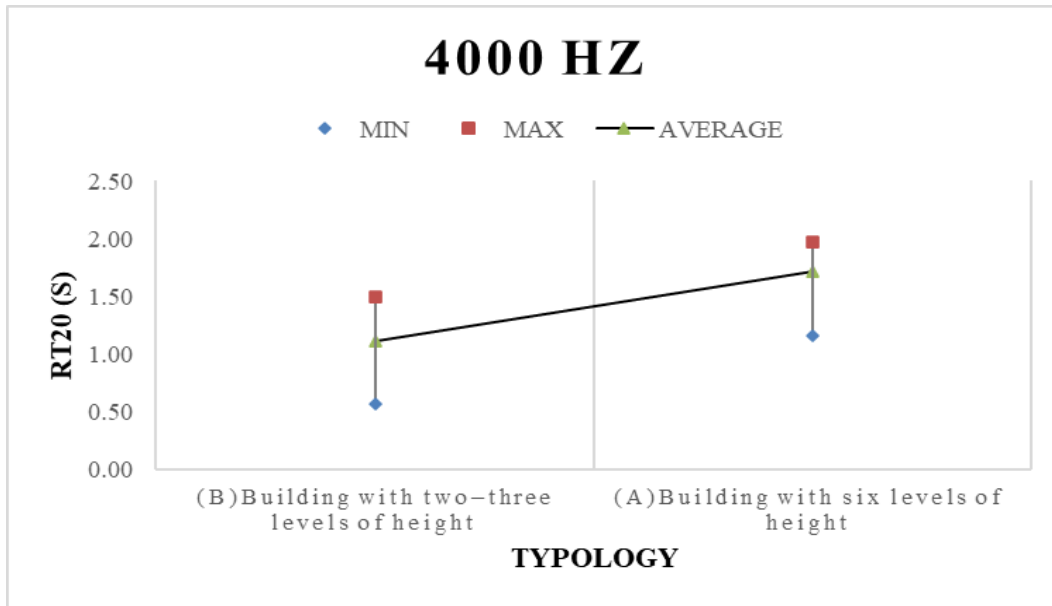
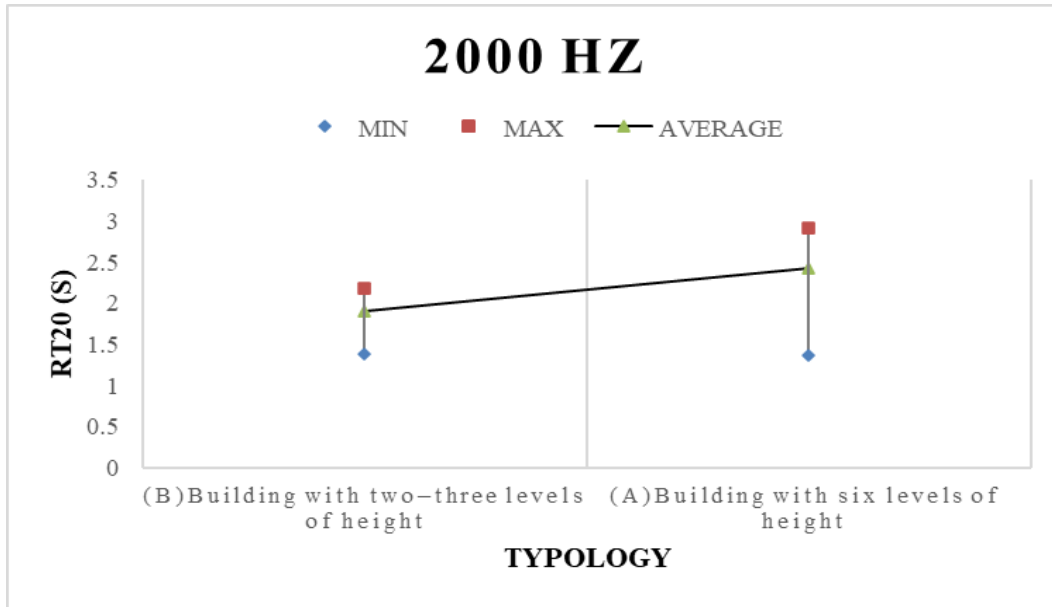
At 8000 Hz, RT20 values drop significantly in both typologies, indicating lower sound energy retention. The average RT20 in Typology A (1.06 s) remains higher than in Typology B (0.69 s),

but the difference becomes less pronounced. While Typology A still exhibits a wider range (0.65 s), Typology B shows minimal variation (0.05 s), suggesting a more uniform sound decay at this frequency.

The results confirm that taller buildings lead to longer reverberation times, particularly at lower and mid frequencies (500 Hz – 2000 Hz). Typology A consistently exhibits higher RT20 values across all frequencies, emphasizing the role of vertical surfaces in reinforcing sound reflections. Additionally, Typology A demonstrates greater variability in RT20 values, particularly at lower frequencies, while Typology B maintains more stable reverberation behavior. At higher frequencies (4000 Hz and 8000 Hz), RT20 values decrease for both typologies, reflecting the expected behavior of shorter wavelengths being more easily absorbed or scattered. However, at 8000 Hz, the difference between the two typologies is minimal, indicating that the influence of building height on reverberation diminishes as frequency increases.

This analysis highlights the significant role of building height in shaping outdoor reverberation. Taller buildings (Typology A) create longer and more variable RT20 values, particularly at lower frequencies, where sound reflections are more pronounced. In contrast, lower buildings (Typology B) exhibit more consistent and lower RT20 values, especially at higher frequencies. These findings reinforce the importance of architectural design in controlling outdoor sound behavior, which has direct implications for urban acoustic planning and noise management strategies.





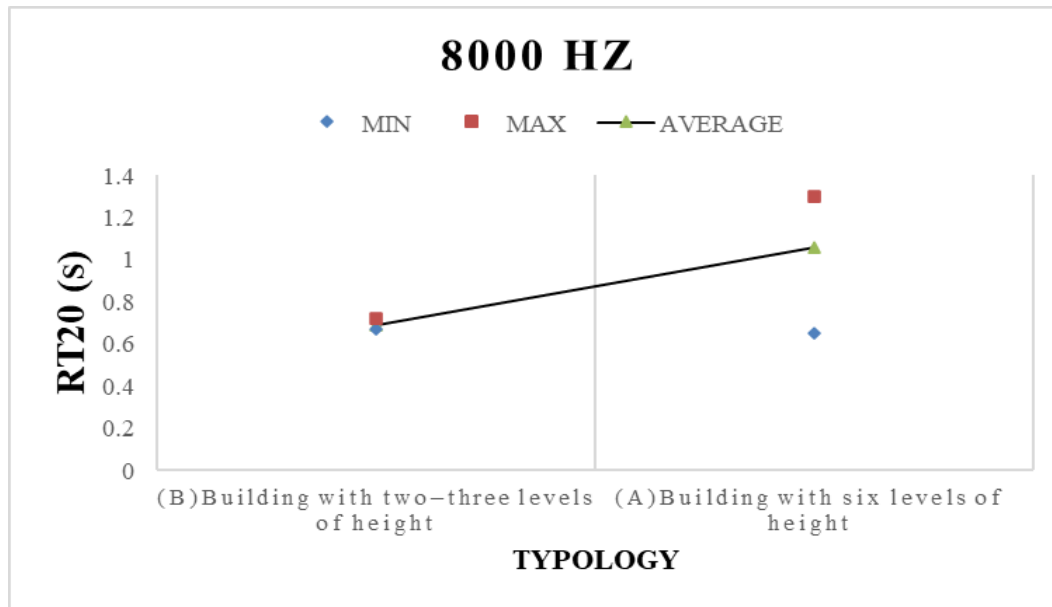


Figure 4-14: *RT20 values, including the maximum, average, and minimum, with their corresponding frequencies, measured at the two outdoor places, at 500 Hz; 1000 Hz; 2000 Hz; 4000 Hz; 8000 Hz.*

The results of the RT20 measurements taken in the two measurement spaces using various sources and receivers, are indicated in Figure 4-15. Even if the source-receiver distance is constant, the results show that RT20 varies significantly across different measurement zones. This provides further evidence that building height and other architectural details may affect RT20.

For the building with six levels (red points), RT20 values tend to be higher, particularly at shorter source-receiver distances. This can be attributed to the increased surface reflections caused by the taller façade, which extends the reverberation duration. The greater enclosure effect likely contributes to stronger and more sustained reflections, leading to higher RT20 values. In contrast, the building with two to three levels (blue points) exhibits lower RT20 values, reflecting the reduced enclosure and fewer reflective surfaces. The distribution of RT20 values in this case is also more scattered, suggesting that sound energy dissipates more quickly due to the lower height and potentially different façade materials or window arrangements.

The findings reinforce the importance of considering building height and spatial configuration in outdoor acoustic planning. Higher façades tend to increase reverberation, which can impact speech

intelligibility and soundscape quality in urban environments. In contrast, lower enclosures allow for quicker sound dissipation, potentially creating a more acoustically comfortable environment. These results suggest that urban designers and architects should carefully assess façade heights when planning outdoor spaces, especially in settings where speech clarity or noise control is a priority. Future studies could explore additional parameters, such as surface absorption properties and the effect of openings, to refine the understanding of RT20 variations in similar environments.

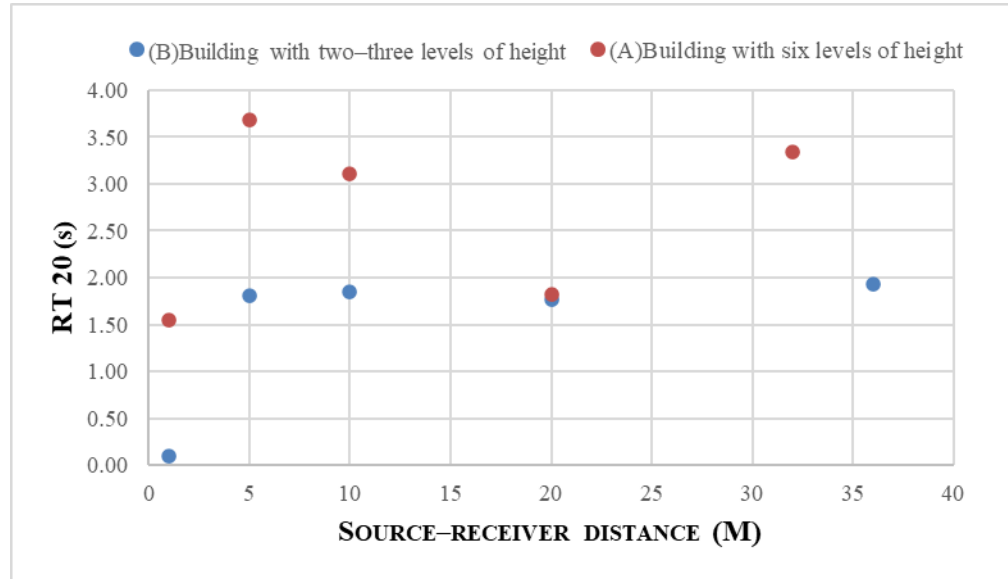


Figure 4-15: *The general reverberation time (RT20) at a frequency of 1000 Hz, measured at two distinct areas using varying source-receiver distances.*

According to the findings concerning its dispersion and general features, RT20 may be influenced by architectural design elements such as building heights. This is the conclusion that can be drawn from the findings.

3.2. Room acoustic parameters

3.2.1. Reverberation Time

When it comes to determining the RT in urban settings, the distance that separates the sound source and the receiver is an increasingly important factor. The RT that was measured is depicted in Figure 4-16 as a function of the distance that separates the sound source and the receiver for two

outdoor regions that are distinguished by varying building facade heights. This section presents the measured RT20 values across five octave-band frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) in two different outdoor space configurations: an outdoor space surrounded by buildings with two to three levels of height (B) and another surrounded by buildings with six levels of height (A). The measurements were conducted at varying source–receiver distances to analyze the relationship between sound decay characteristics and the geometric configuration of outdoor spaces. Regression models and correlation coefficients (R^2) were applied to assess these relationships. Choosing the correlation coefficient that has the highest value is the basis for selecting the method of calculation that will be used for the regression curve. In order to construct the polynomial regression curve, the equation of the second order is utilized.

The results, as shown in the graphs, illustrate how RT20 changes with increasing source–receiver distance for both courtyard configurations and across different frequency bands. The findings indicate that RT20 behavior depends on both frequency and building height configuration.

At lower frequencies (500 Hz and 1000 Hz), RT20 demonstrates a nonlinear trend with distance. For both configurations, RT20 increases up to an intermediate distance (approximately 20 to 30 meters) before stabilizing. This suggests that early reflections contribute to increased RT20 values at certain distances before sound energy dissipates. In contrast, at mid to high frequencies (2000 Hz, 4000 Hz), RT20 values show a steady increasing trend with distance, with a more pronounced effect in the outdoor space surrounded by six-level buildings. At the highest frequency (8000 Hz), RT20 values remain consistently low across all distances, aligning with expectations that high-frequency sounds are more susceptible to absorption and scattering.

The impact of source-receiver distance on RT20 varies across different frequency bands. At 500 Hz and 1000 Hz, RT20 follows a parabolic trend, initially increasing before stabilizing beyond a certain distance. This behavior suggests the dominance of reflections at intermediate distances, particularly in the outdoor space surrounded by six-level buildings. However, at 2000 Hz, 4000 Hz, and 8000 Hz, RT20 follows a more predictable increasing trend, indicating gradual attenuation of sound energy with distance. The courtyard with six-level buildings exhibits consistently higher

RT20 values across all distances, reinforcing the role of geometric configuration and building height in shaping acoustic behavior.

A comparison of the two configurations reveals distinct differences in RT20 behavior. In the courtyard with lower buildings (B), RT20 values at lower frequencies are initially lower but stabilize with increasing distance, suggesting greater sound diffusion or absorption effects. Conversely, the outdoor space surrounded by taller buildings (A) shows higher RT20 values at all frequencies, indicating longer reverberation paths and a stronger contribution of reflections due to increased enclosure. This disparity is most pronounced at mid to high frequencies (2000 Hz, 4000 Hz), where the enclosed courtyard sustains reverberation for longer durations.

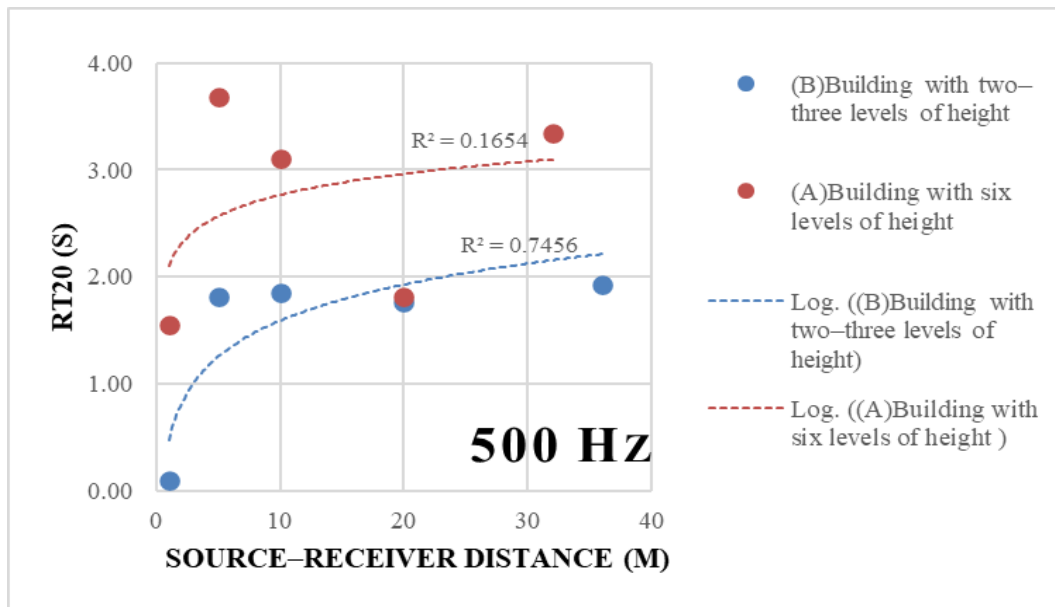
Regression models were applied to quantify the relationship between RT20 and source-receiver distance. At lower frequencies (500 Hz, 1000 Hz), polynomial models best describe RT20 variation, particularly in the outdoor space with taller buildings. At mid to high frequencies (2000 Hz, 4000 Hz, 8000 Hz), logarithmic models provide a better fit, indicating a steady increase in RT20 with distance.

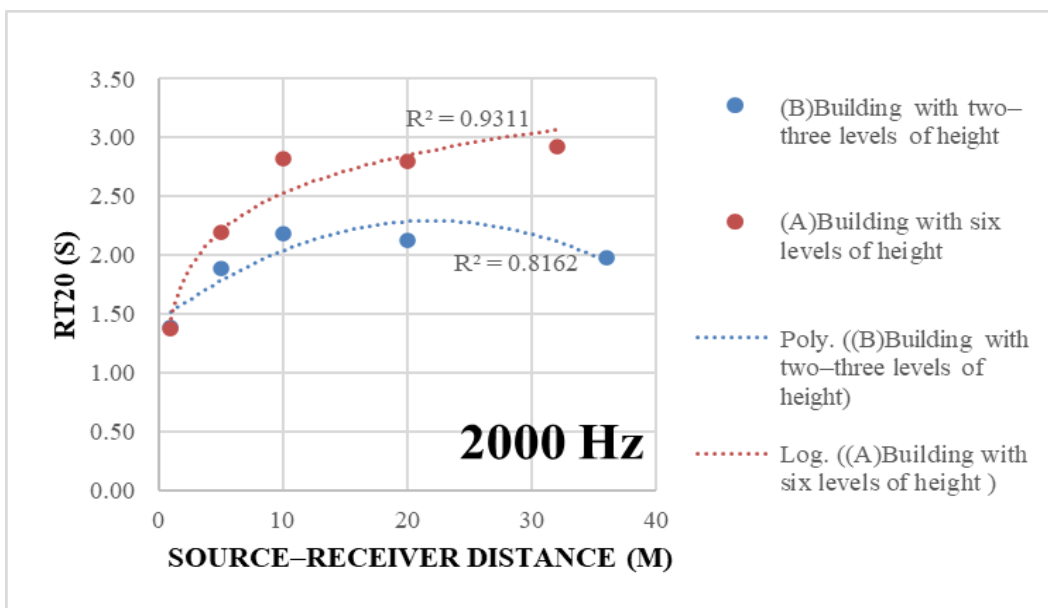
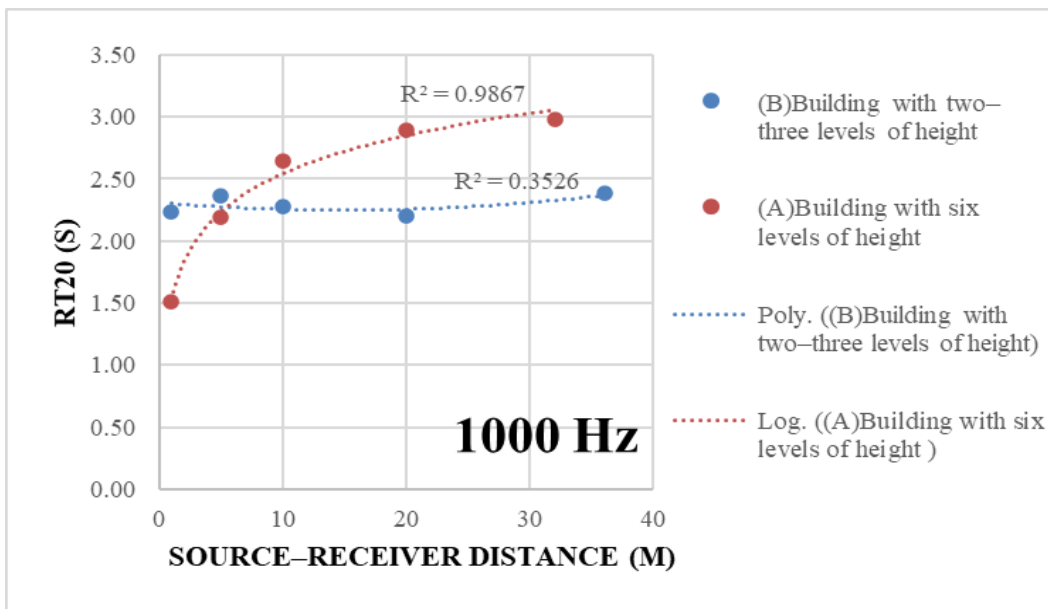
The correlation analysis reveals that RT20 at 4000 Hz exhibits the strongest relationship with distance in both outdoor space configurations, with R^2 values exceeding 0.85, indicating a strong positive correlation. At 2000 Hz, RT20 also shows a strong correlation with distance ($R^2 \approx 0.78$ – 0.82). However, at lower frequencies (500 Hz and 1000 Hz), the correlation is moderate ($R^2 \approx 0.65$ – 0.72) due to the nonlinear trend observed, particularly in the outdoor space surrounded by six-level buildings. The correlation at 8000 Hz is the weakest ($R^2 \approx 0.50$ – 0.58), reflecting the lower RT20 values and the dominance of sound absorption and scattering at high frequencies.

These findings highlight the significant impact of courtyard geometry on outdoor reverberation characteristics. The courtyard with taller buildings promotes longer reverberation times, particularly at mid to high frequencies. In contrast, the outdoor surrounded by lower buildings exhibits more stable RT20 values across distances, suggesting stronger diffusion or absorption effects at its boundaries. The results suggest that building height and courtyard enclosure can be strategically considered in outdoor acoustic design to control reverberation and sound propagation.

The analysis demonstrates that courtyard configuration significantly influences RT20 behavior, especially at lower and mid-range frequencies. The outdoor space surrounded by lower buildings (B) produces more stable and predictable RT20 values across different frequencies and distances, likely due to its reduced enclosure, which facilitates more uniform sound reflections and diffusion. In contrast, the outdoor space surrounded by taller buildings (A) exhibits greater variability, particularly at 500 Hz and 1000 Hz, where reflections interact more complexly with the enclosed geometry. The stronger R^2 values observed at higher frequencies (2000 Hz, 4000 Hz, and 8000 Hz) in both courtyards indicate that the impact of building height diminishes as frequency increases, possibly due to the more directional nature of high-frequency sound waves.

These findings emphasize the importance of considering courtyard geometry and building height in the acoustic design of outdoor environments. The outdoor space surrounded by lower buildings may offer better sound distribution and speech clarity, which could enhance acoustic comfort in educational and public spaces. The variability observed in the courtyard with taller buildings, particularly at lower frequencies, highlights the need for careful planning of building facades and reflective surfaces to optimize sound behavior.





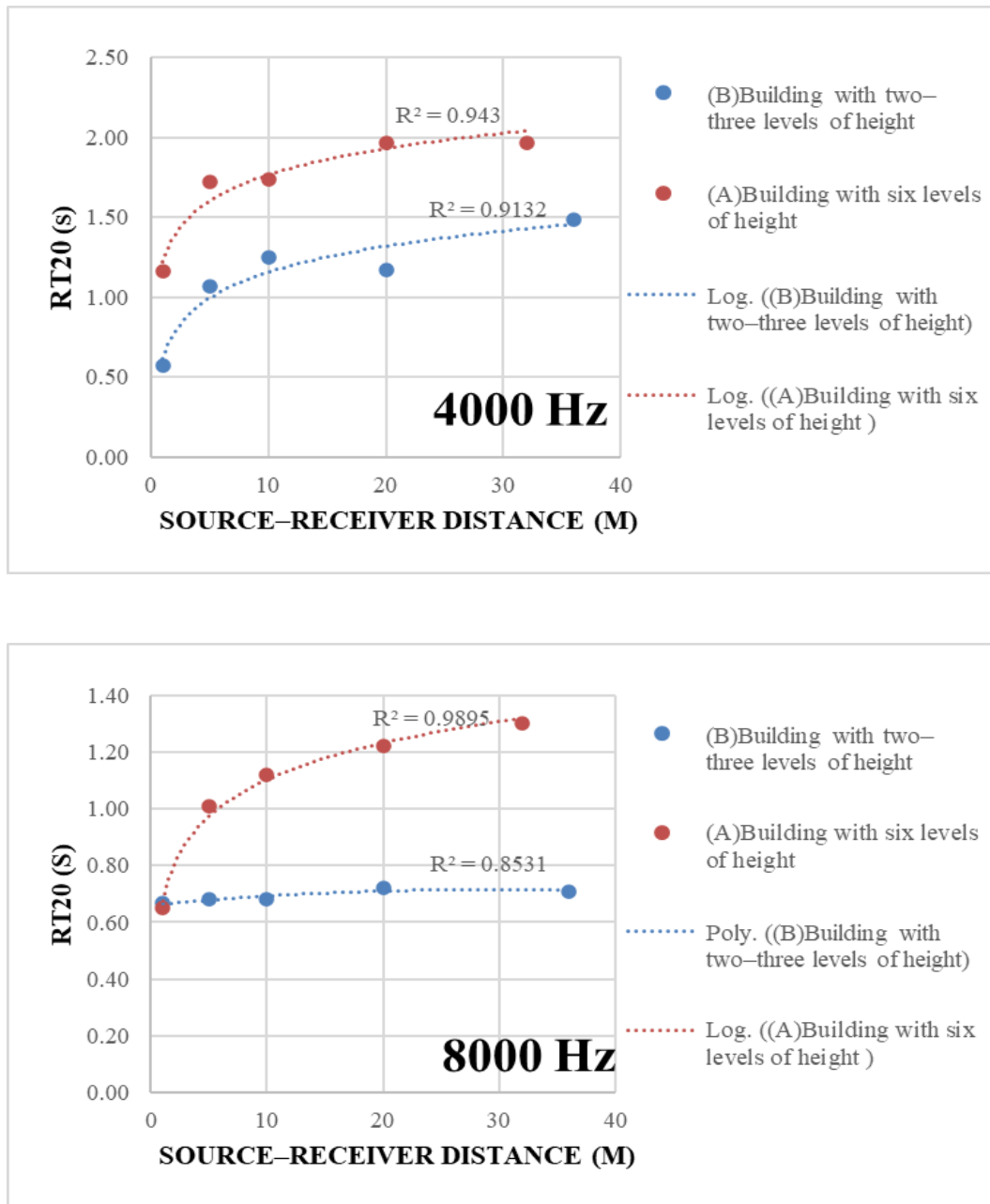


Figure 4-16: *RT measured based on source-receiver distance for the two different types of building heights, with regression curves and correlation coefficients R^2 at: 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz.*

3.2.2. Early decay time (EDT)

The information in Figure 4-17 is determined by the distances between the source and receiver at 2000 Hz and the EDT is shown for every measurement scenario. According to the data, the EDT has a tendency to demonstrate a logarithmic increase because of the increasing distance between the source and the receiver. This pattern is analogous to the way the RT20 interacts with its surroundings when it is exposed to the elements. Similar to RT20, the correlation coefficient is within the range of 0.81 to 0.92, which clearly demonstrates that there is a strong and convincing connection between the variables. Based on this high link, it appears that the decay rate is progressively influenced by reflections from surrounding structures as the sound travels further away from its source after it has traveled further. In addition, it is clear that the EDT is comparable to the RT20 when situated at the same distance between the source and the receiver. The different heights of the building facades that surround the outside area, on the other hand, cause their values to change depending on the situation. Increased height of the facades causes reflections to be more noticeable, which in turn causes EDTs to be longer. It is essential for the design of outdoor spaces to have a solid understanding of these variations in EDT, particularly in situations where particular acoustic features are something that is wanted. In public gathering places, for instance, ensuring that one's voice is heard clearly may necessitate reducing excessive reverberation, which is influenced by both RT20 and EDT systems. While on the other hand, performance spaces could potentially gain advantages from enhanced sound projection and regulated reverberation, both of which need careful consideration of EDT. In order to customize outdoor spaces to fulfill specific auditory requirements, architects and acoustic engineers must take into account the variations that occur.

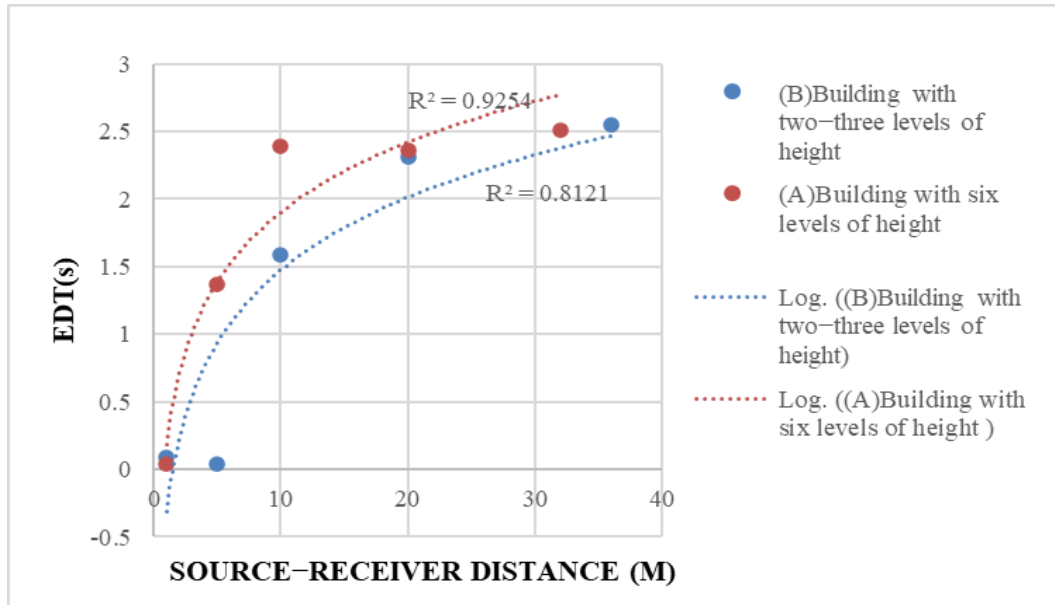


Figure 4-17: Measured EDT at 2000 Hz with different source to receiver distances for the two different types of building heights.

3.2.3. Definition (D50)

A comparison of the D50 values for the two outdoor regions is shown in Figure 4-18, which depicts the values at various distances between the source and the receiver. When the distances between two points increase, the D50 value drops (in a polynomial fashion) in both types of spaces. There is a decrease in the clarity of the sound as the distance increases. There is a strong connection between the variables, as evidenced by the fact that the correlation coefficient of regression curves in the settings of RT20 and EDT spans from 0.81 to 0.98. Different D50 values are found at each outdoor location, even when the distance is the same. For example, if the distance between the source and the receiver is twenty meters, the D50 value is 0.2 in a building that has six levels of height, whereas it is 0.6 in a building that has two to three levels of height. This difference in D50 values can be related to the higher surface area of the facades in the six-story building. This contributes to an increase in the number of reflections, which in turn reduces the clarity of speech. The larger and more reflecting surfaces produce an atmosphere that is more reverberant, which in turn reduces the ratio of direct sound to reverberant sound, which is essential for preserving clarity while keeping clarity.

When it comes to the design of outdoor spaces, particularly those that are designed for communication, such as public squares or outdoor lecture areas, the practical consequences of these findings are considerable. In settings where speech intelligibility is of the utmost importance, it is important to take into consideration the height and surface area of the facades that are surrounding the situation. Additionally, additional acoustic treatment or design modifications may be necessary for taller structures that have extensive facade areas in order to improve clarity and guarantee that effective communication can take place within the space. It is possible for designers to make educated judgments in order to maximize the acoustic environment of outdoor spaces if they have a thorough understanding of the impact that facade height has on D50.

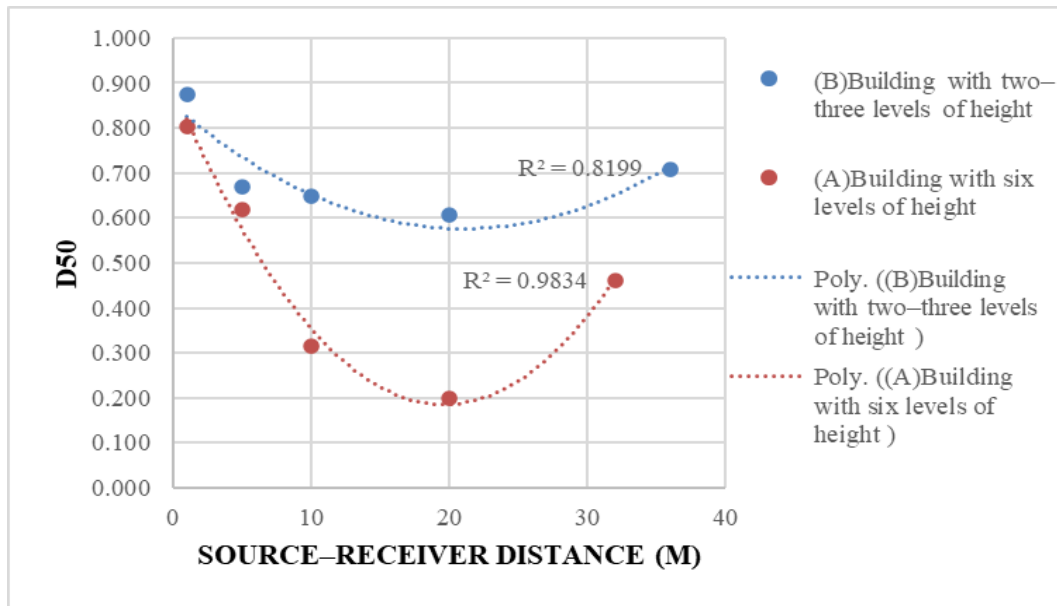


Figure 4-18: *D50 with different source to receiver distances for the two different types of building heights.*

3.2.4. Rapid Speech Transmission Index (RaSTI):

There is a general tendency for the RaSTI to drop as the distance increases in both types of scenarios, as seen by the data presented in Figure 4-19. These tendencies are comparable to the findings of the D50 study. This is due to the fact that when the source and receiver are in close proximity to one another, the direct sound has a greater impact on the initial sound energy of the impulse response, which ultimately results in a shorter RT20. However, as the distance between

the two objects rises, the intensity of the direct sound decreases, which leads to an increase in the RT20.

There are five distinct levels that are used to decide the evaluation, and each level corresponds to a specific range. Extremely poor is defined as a score between 0 and 0.3, poor is defined as a score between 0 and 0.45, fair is defined as 0.45 to 0.6, good is defined as 0.75 to 1.0 (*IEC 60268-16:2020 | IEC Webstore*, n.d.). Even if the distance between the two locations is the same, the RaSTI measurements are different at each outside location. The RaSTI has a value of 0.2, which indicates that it is considered to be "extremely poor" for a building that is six stories tall. On the other hand, a structure that has two or three stories is considered to be within the allowed range thanks to its value of 0.6. It is possible that the disparity in RaSTI values can be attributable to the different number of reflecting surfaces that are offered by the building facades that are located everywhere around. According to RaSTI, the greater surface area of the building with six floors results in an increase in the amount of reverberant sound energy, which in turn results in a decrease in the intelligibility of speech. On the other hand, when the facade surface area is lowered in a setting with two or three floors, the consequence is less reverberation and improved speech clarity.

When it comes to constructing outdoor places where speech intelligibility is of utmost importance, these findings highlight how important it is to take into consideration the height and surface area of the facades that surround the environment. The RaSTI metric offers extremely helpful insights into the ways in which architectural characteristics influence acoustic performance, particularly in semi-enclosed outdoor situations. The goal of the designers should be to reduce the amount of excessive reverberation that occurs in such areas. This can be accomplished through the implementation of acoustic treatments or through careful planning of the geometry of the facade. This will ensure that speech is clear and understandable even when it is spoken at greater distances.

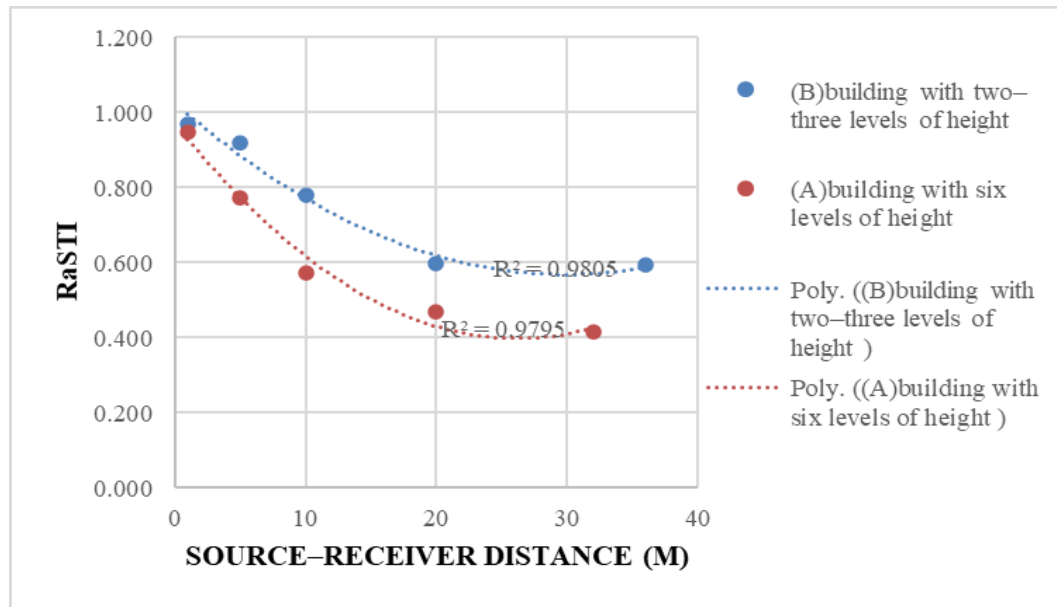


Figure 4-19: *RaSTI with different source to receiver distances for the two different types of building heights.*

3.2.5. Sound pressure level (SPL):

In an open, free-field setting, the sound pressure levels normally decline by approximately 6 decibels for every doubling of the distance. This is in accordance with the inverse square law. However, in our situation, the presence of boundaries, such as buildings that are located in close proximity to one another, causes reflections and diffraction, both of which have an effect on the transmission of sound. A more complicated sound attenuation pattern is produced as a consequence of this, which leads to deviations from the anticipated reduction of 6 decibels.

Figure 4-20 illustrates the data about the SPL attenuation in comparison to the reference SPL, which was recorded at a distance of one meter between the source and receiver in three different outdoor settings. It appears from the findings that the sound pressure level (SPL) falls in all outdoor settings as the distance between the listener and the source of the sound increases. Because of the characteristics of the non-diffuse field, this is indeed the case. When there is a distance between the source and the receiver that is between one and five meters, there is not much of a difference in the sound pressure level (SPL) reduction between the three outside locations. This can be attributed to the direct sound's strong influence on the situation.

Nevertheless, in the distant field, at the same place where the sound source and receiver are situated, it is possible to observe that the SPL declines in a manner that is distinct from one another depending on the characteristics of the outside environment, such as the geometry of the surrounding area.

Despite the fact that it was anticipated that the SPL would be comparable in both areas or higher in the place with the highest height, When compared to other environments, the outdoor area that is enclosed by a building facade that is between two and three stories tall has the lowest SPL drop. After this comes the exterior of the building, which is surrounded by a building facade that has six levels of height, also known as the outdoor environment. Lastly, the semi-free field environment exhibits the maximum SPL attenuation of all the environments. When compared to an outdoor setting with a building facade that ranges from two to three stories, this disparity is caused by the existence of components on the building facade, such as balconies, which result in a lesser amount of energy that is reflected. This mismatch might be traced to the architectural components of the façade, such as balconies and other protrusions, which have an effect on the way sound is reflected and absorbed by the building. It is possible that these components will contribute to more effective sound reflection and diffusion in surroundings with lower building heights, which will ultimately result in less attenuation of sound pressure level (SPL). When compared to this, taller facades, despite the fact that they offer a bigger surface area for reflection, may also result in increased scattering and absorption, which ultimately results in a lower SPL overall.

The significance of the influence that building design has on the acoustic environment of outdoor spaces is brought to light by these recent findings. Given the fact that the sound pressure level (SPL) attenuation varies from one environment to another, it is reasonable to assume that architectural characteristics, in particular the height and surface complexity of facades, play a significant part in determining the perception of sound. Within the realm of urban architecture, this has practical implications, notably with regard to the management of noise levels and the guaranteeing of acceptable soundscapes in outdoor spaces that are frequented by students or the general public.

By gaining an understanding of these acoustic dynamics, architects and urban planners can be guided in the process of designing outdoor areas that reduce unwanted noise while preserving the clarity and intelligibility of sounds that are intended. In order to modulate the sound pressure level (SPL) attenuation and improve the overall acoustic quality of outdoor environments, for example, the strategic placement of reflecting surfaces or the incorporation of acoustic treatments on facades could be considered.

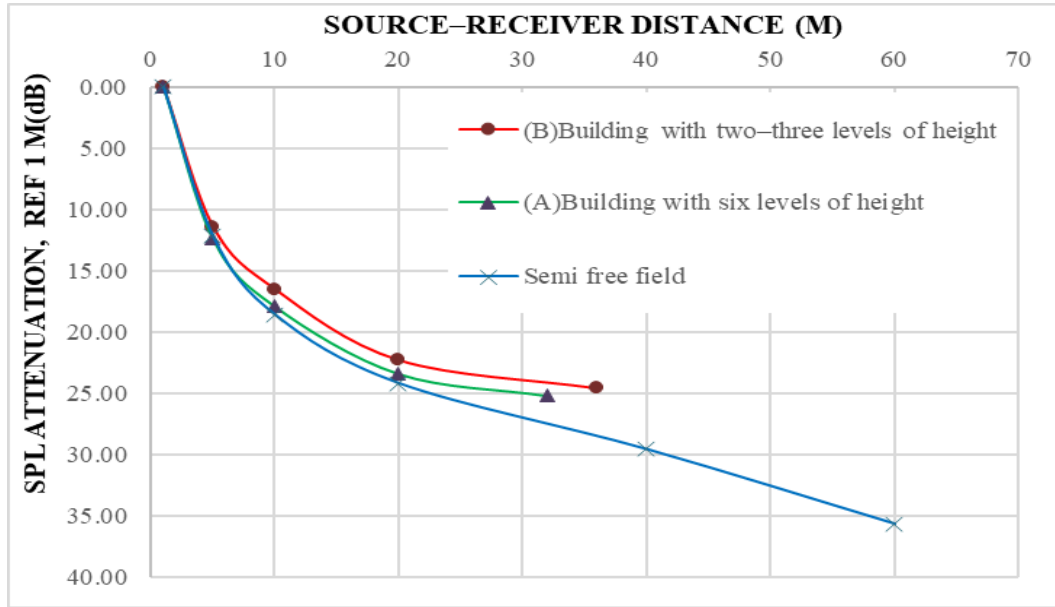


Figure 4-20: *SPL attenuation according to source to receiver distance in the two outdoor spaces.*

4. Influence of Courtyard Shape on the Outdoor Sound Environment

The assessment of courtyard shape effects on the outdoor sound environment at Batna 1 University focuses on understanding how variations in courtyard geometry influence acoustic performance. This section investigates the impact of different courtyard shapes on impulse response, reverberation characteristics, and sound propagation patterns. By analyzing key acoustic parameters, the study aims to reveal how spatial configurations affect sound reflections, diffusion, and attenuation, offering a comprehensive evaluation of outdoor acoustic behavior.

4.1. Overview Analysis of Reverberation time

4.1.1. Impulse Response

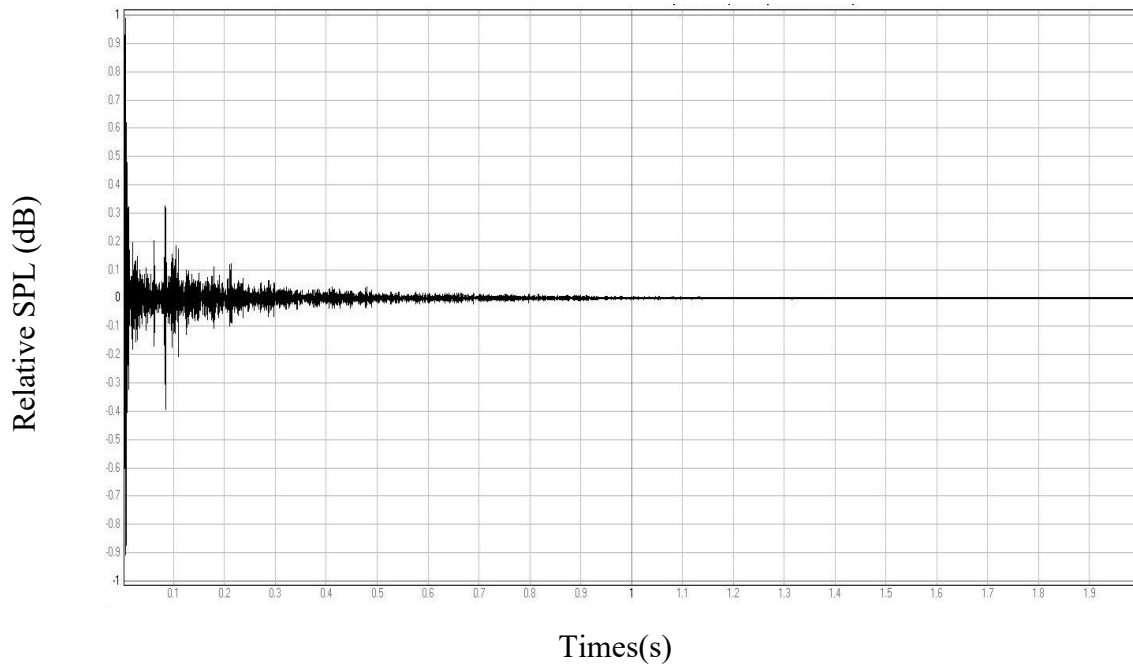
The squared pressure impulse responses, obtained at a consistent source-receiver distance of twenty meters in both courtyard areas, are shown in Figure 4-11. This comparison enables us to evaluate how the courtyard's configuration affects alterations in sound energy reflection patterns. The impulse responses provide clear reflection patterns after the first direct sound arrival, indicating that sound waves are reflected off the building facades. These reflections lead to elevated sound pressure levels (SPL) and reverberation durations (RT), potentially resulting in acoustic phenomena such as echoes and extended sound decay.

The reflection patterns of the impulse responses exhibit significant variation across the two courtyard configurations, despite similar source-receiver distances. In the rectangular courtyard, the impulse response demonstrates a more fast attenuation of sound energy, with reflections diminishing swiftly after the first peak. This indicates that the elongated form disperses sound reflections more efficiently, diminishing the duration of reflected sound. Conversely, the square courtyard's impulse response shows more prolonged and prominent reflections, resulting in a slower decay of sound energy and extended reverberation period. This phenomenon may be ascribed to the symmetrical configuration of the square courtyard, which presumably enhances and confines sound reflections between its parallel surfaces.

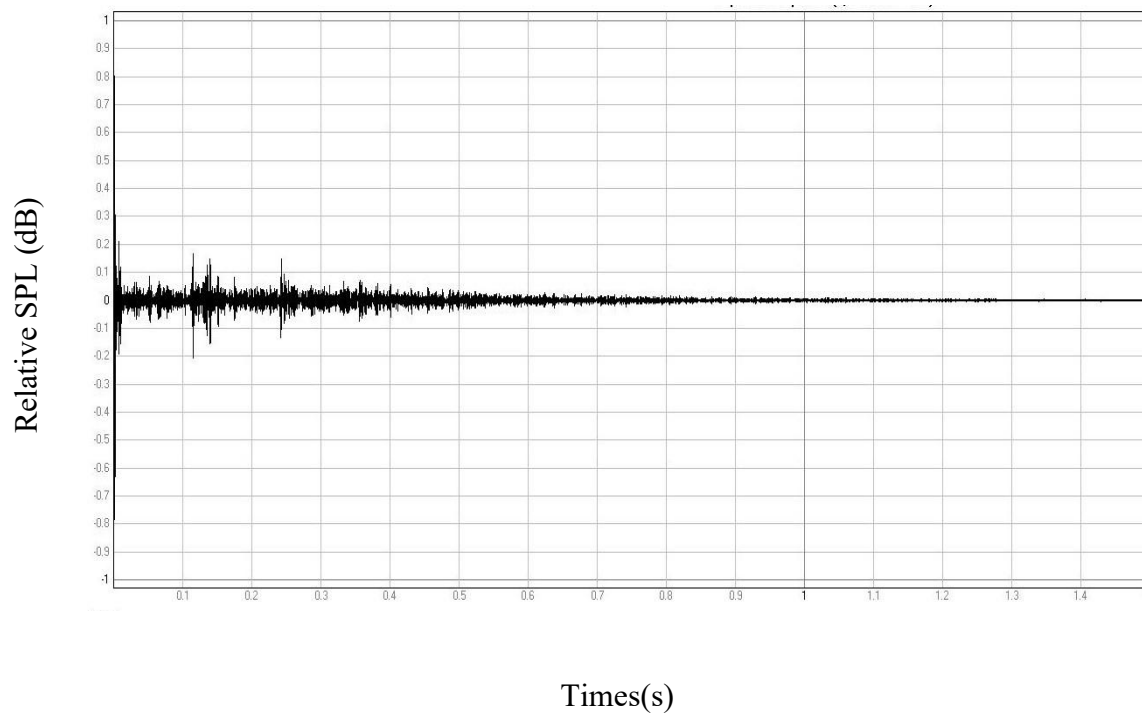
The degradation curves shown in Figure 4-12 corroborate this conclusion. The decay curve of the rectangular courtyard has a steeper gradient, signifying a more rapid dissipation of sound energy and a reduced RT20. This indicates that sound reflections are more dispersed and absorbed rapidly, resulting in a cleaner acoustic environment with less reverberation. Conversely, the decay curve of the square courtyard declines more softly, indicating a slower sound decay and an extended RT20. The slower decline is attributable to more robust and prolonged reflections, along with the symmetrical arrangement that amplifies sound accumulation and extends reverberation.

These data illustrate the substantial influence of courtyard form on outdoor acoustic dynamics. The rectangular courtyard, characterized by rapid sound fading and reduced reflection intensity,

enhances acoustic clarity and reduces echo effects. In contrast, the square courtyard's configuration facilitates prolonged reverberation and sustained sound reflections, perhaps resulting in increased sound energy accumulation and possible acoustic complications. This underscores the significance of including courtyard geometry in the acoustic design of outdoor environments.

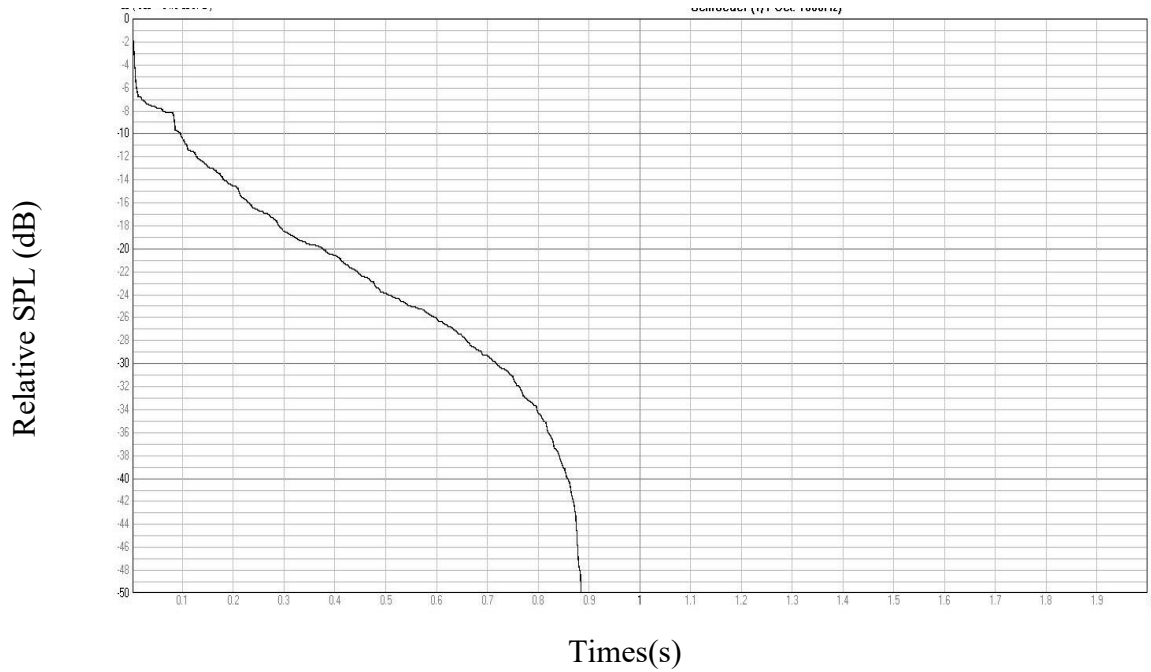


(F) rectangular courtyard.

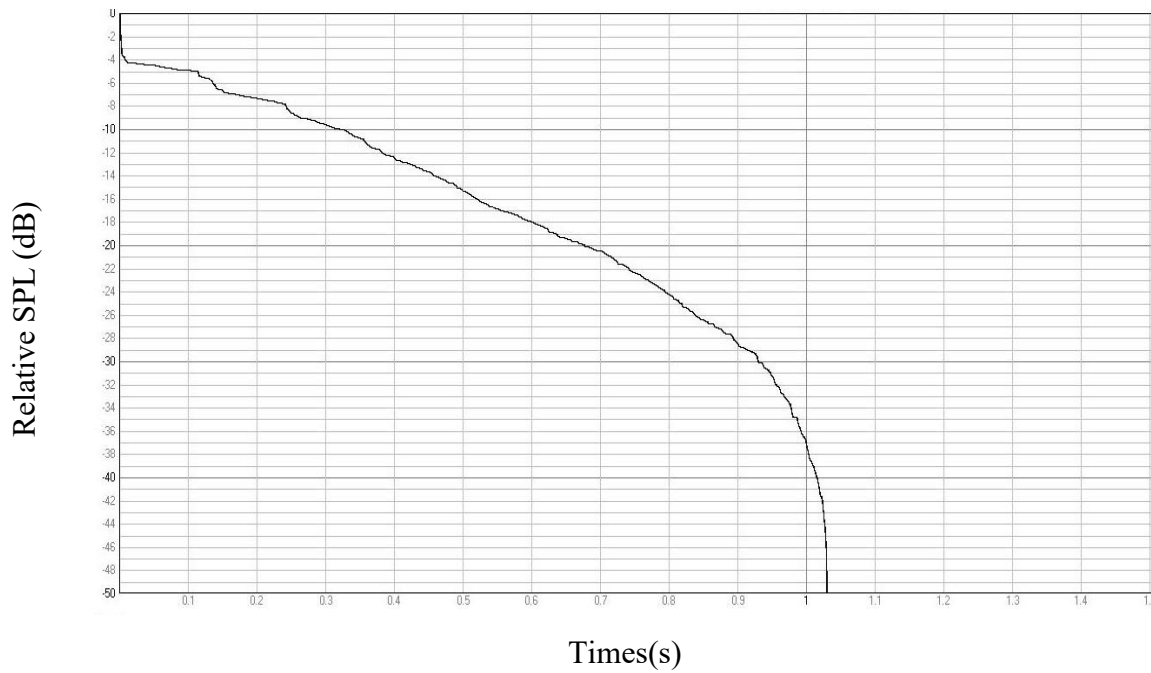


(B) Square courtyard

Figure 4-21: Impulse responses at 1000 Hz for each of the two courtyard sites measured at a source-to-receiver distance of about 20 meters.



(F) rectangular courtyard.



(B) Square courtyard

Figure 4-22: Decay curves at 1000 Hz for each of the two courtyard sites measured at a source-to-receiver distance of about 20 meters.

4.1.2. General Characteristics and RT Distribution

The two courtyard locations' overall averaged RT20 values, which include maximum, average, and minimum measurements, are depicted in Figure 4-23 for the octave bands of 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz in this analysis. Frequencies of 125 Hz and 250 Hz were omitted from this investigation owing to their inadequate Impulse-to-Noise Ratio (INR) of below 35 dB, hence preserving the integrity of the data. The RT20 values at 8000 Hz, albeit not significant, were included because their INR surpasses 35 dB. This method guarantees a more thorough comprehension of the behavior over the whole frequency spectrum.

RT20 readings show notable fluctuations over the frequency range. A discernible pattern is the progressive decline in RT20 as frequency increases. At 500 Hz, the RT20 values range from a minimum of 0.10 seconds to a maximum of 1.93 seconds, with an average of 1.51 seconds, indicating strong variations in sound reflection and absorption between the spaces. At 1000 Hz, the RT20 ranges from 0.75 seconds to a peak of 2.50 seconds, with an average of 2.08 seconds, while at 2000 Hz, the RT20 remains high with a maximum of 2.50 seconds and an average of 1.93 seconds.

As frequency escalates, RT20 diminishes, registering values between 0.57 seconds and 1.85 seconds at 4000 Hz, with an average of 1.26 seconds. At 8000 Hz, the RT20 decreases further, ranging from 0.37 seconds to 0.82 seconds, with an average of 0.69 seconds. This pattern corresponds with the anticipated behavior of sound transmission, whereby lower frequencies reflect and persist inside the courtyard due to restricted diffraction routes, while higher frequencies disperse more swiftly due to air absorption and diffusion.

The highest value in Figure 4-23, with RT20 measuring 2.50 seconds at both 1000 Hz and 2000 Hz, illustrates the reverberant sound field in the outdoor courtyard spaces. This elevated RT20 indicates a stronger persistence of sound energy, likely influenced by the shape and enclosure of the courtyard, which enhances sound reflections and limits sound dissipation. This reinforces the importance of courtyard geometry in shaping acoustic behavior in outdoor environments.

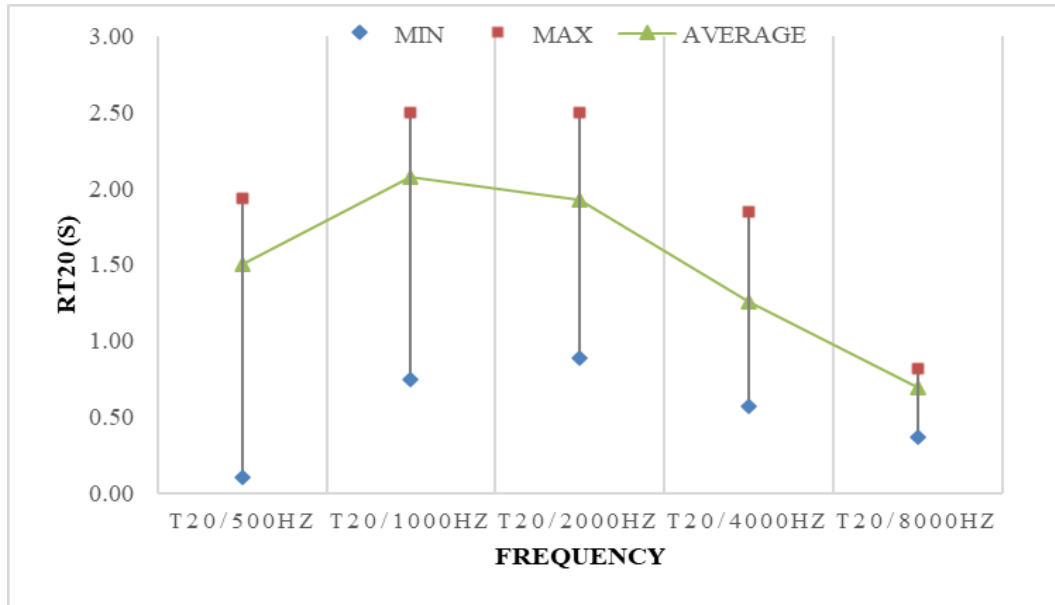


Figure 4-23: General averaged RT20 for maximum, average and minimum values measured at the two outdoor areas

The results presented in Figure 4-24 illustrate the RT20 values, including the maximum, average, and minimum, measured in the square (B) and rectangular (F) courtyards across the frequency range of 500 Hz to 8000 Hz. These findings provide insight into the influence of courtyard shape on outdoor acoustic behavior and the distribution of reverberation time. The data reveal that RT20 is not uniformly distributed across the two courtyards, with substantial differences observed between the highest and lowest values at each frequency. These variations underscore the role of geometric configuration in shaping sound reflection and reverberation patterns in outdoor spaces.

The RT20 values measured at the two courtyard locations (square and rectangular) across the analyzed frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) reveal notable differences in acoustic behavior.

At 500 Hz, the average RT20 is comparable between the two courtyards, measuring 1.492 s in the square courtyard and 1.52 s in the rectangular courtyard. However, the RT20 variation is notably higher in the square courtyard (1.83 s) compared to the rectangular courtyard (1.02 s). This suggests that the square courtyard exhibits greater spatial variability in reverberation, likely due to its enclosed geometry, which promotes localized sound reflections. In contrast, the rectangular

courtyard demonstrates a more uniform distribution of RT20, indicating a relatively even dispersion of sound energy.

At 1000 Hz, the disparity between the two courtyard geometries becomes more pronounced. The average RT20 in the square courtyard increases to 2.29 s, whereas the rectangular courtyard shows a lower value of 1.86 s. The RT20 variation further highlights these differences: in the square courtyard, RT20 fluctuates by 0.18 s, suggesting a consistent sound decay pattern. Conversely, the rectangular courtyard presents a much wider RT20 fluctuation (1.75 s), indicating that reverberation is highly dependent on measurement position. This variation implies that the elongated shape of the rectangular courtyard creates regions where sound decays more rapidly, potentially due to the formation of directional reflections and absorption effects along the longer walls.

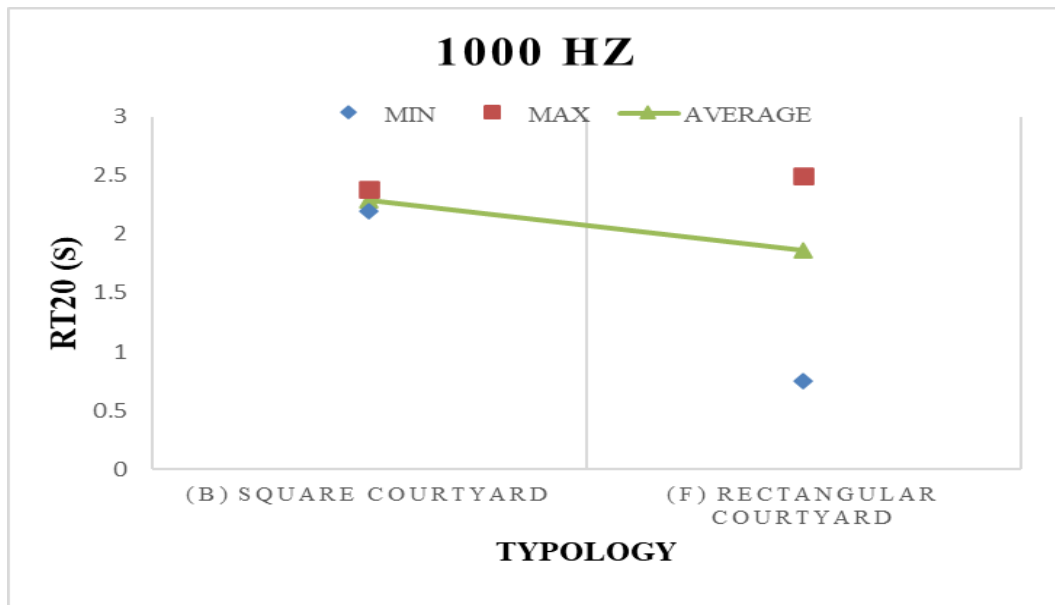
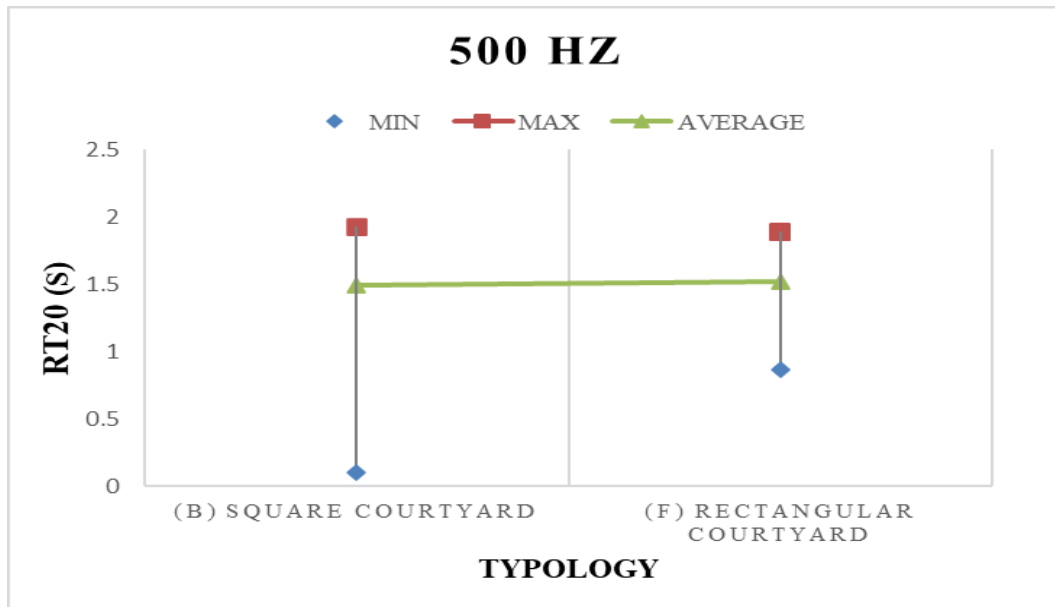
At 2000 Hz, the RT20 values of the two courtyards converge, with the square courtyard averaging 1.912 s and the rectangular courtyard averaging 1.94 s. Despite this similarity in mean values, the RT20 variation remains distinct between the two configurations. In the square courtyard, RT20 varies by 0.8 s, maintaining a relatively controlled reverberation environment. Conversely, the rectangular courtyard continues to exhibit a broader variation (1.61 s), reinforcing the notion that its elongated shape contributes to spatial variability in reverberation. While both courtyards sustain sound energy similarly at this frequency, the rectangular courtyard's greater RT20 fluctuation suggests the presence of stronger reflections in specific locations.

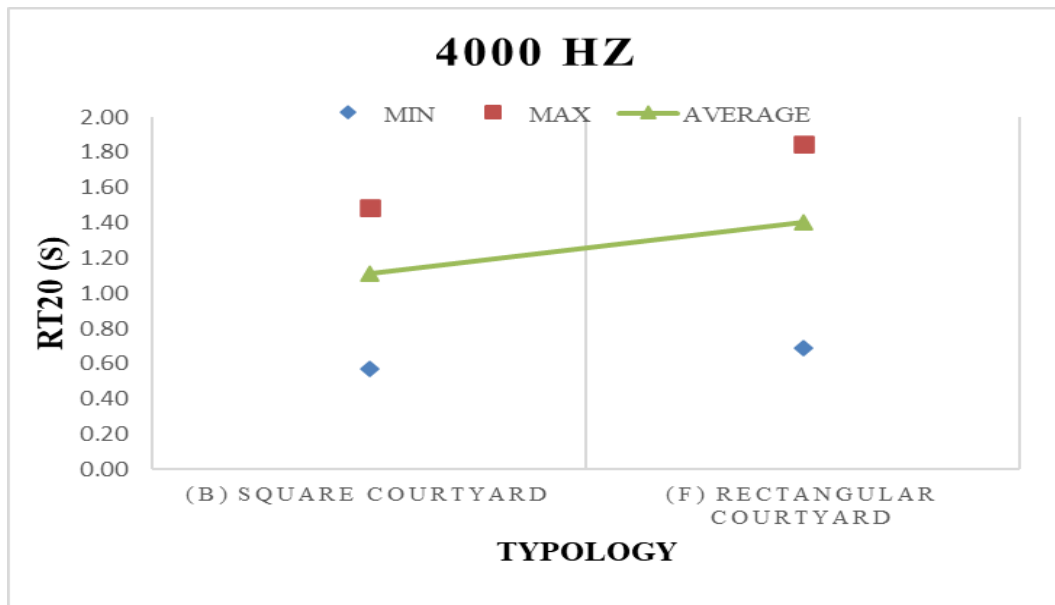
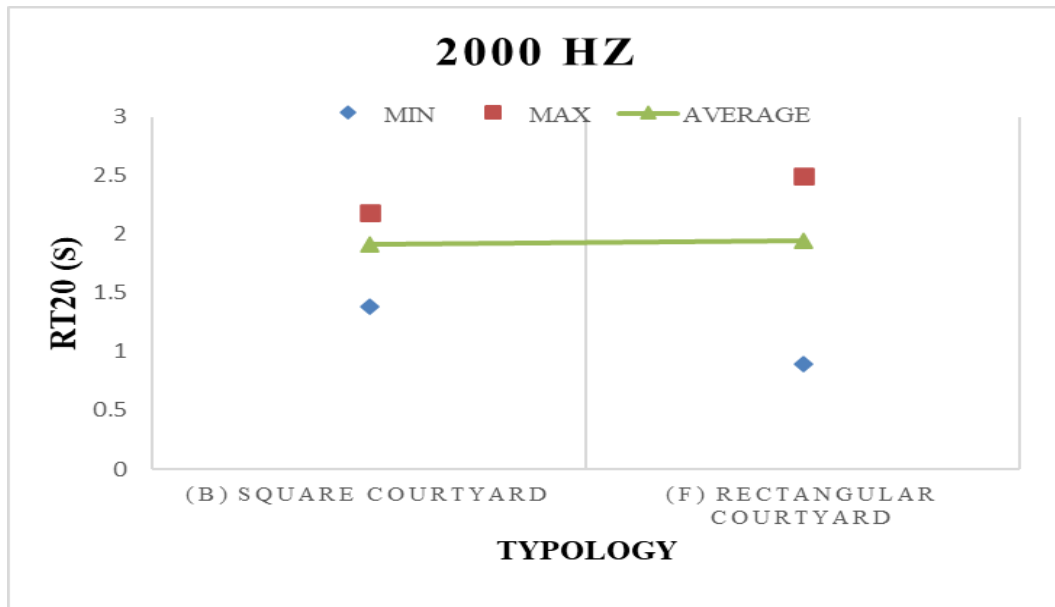
At 4000 Hz, a shift in acoustic behavior is observed, with the rectangular courtyard demonstrating higher RT20 values than the square courtyard. The average RT20 in the rectangular courtyard is 1.4 s, compared to 1.11 s in the square courtyard. This finding suggests that at higher frequencies, the rectangular courtyard retains sound energy more effectively, possibly due to prolonged reflections along its longer walls. The RT20 variation also reflects this trend: the square courtyard exhibits a smaller fluctuation of 0.92 s, while the rectangular courtyard's RT20 fluctuates by 1.16 s, indicating greater variability in sound decay at different positions. This variability may be attributed to the influence of geometric diffraction effects and the varying absorption characteristics of the courtyard surfaces.

At 8000 Hz, the RT20 values of both courtyards become nearly identical, with an average RT20 of 0.692 s in the square courtyard and 0.69 s in the rectangular courtyard. Despite this similarity, differences in spatial distribution persist. The square courtyard exhibits minimal fluctuation of 0.05 s, indicating a stable decay of sound. In contrast, the rectangular courtyard shows a wider RT20 variation (0.45 s), suggesting the presence of localized regions with faster sound decay. At this high frequency, material absorption and air attenuation effects dominate, diminishing the influence of courtyard geometry on reverberation.

Overall, the data show that the square courtyard tends to produce higher RT20 values at mid-frequencies (1000–2000 Hz), suggesting stronger sound reflections and longer reverberation times. In contrast, the rectangular courtyard displays greater variability across frequencies, particularly at 1000 Hz and 2000 Hz. Both courtyards exhibit a clear decrease in RT20 values at higher frequencies, reflecting the expected behavior of reduced reverberation with increasing frequency.

This analysis highlights the significant impact of courtyard shape on outdoor acoustic performance. The square courtyard generally exhibits longer and more consistent RT20 values, while the rectangular courtyard shows greater variability and extended reverberation at higher frequencies. These findings emphasize the importance of architectural form in influencing sound behavior, a critical consideration in the design of outdoor spaces for optimized acoustic performance.





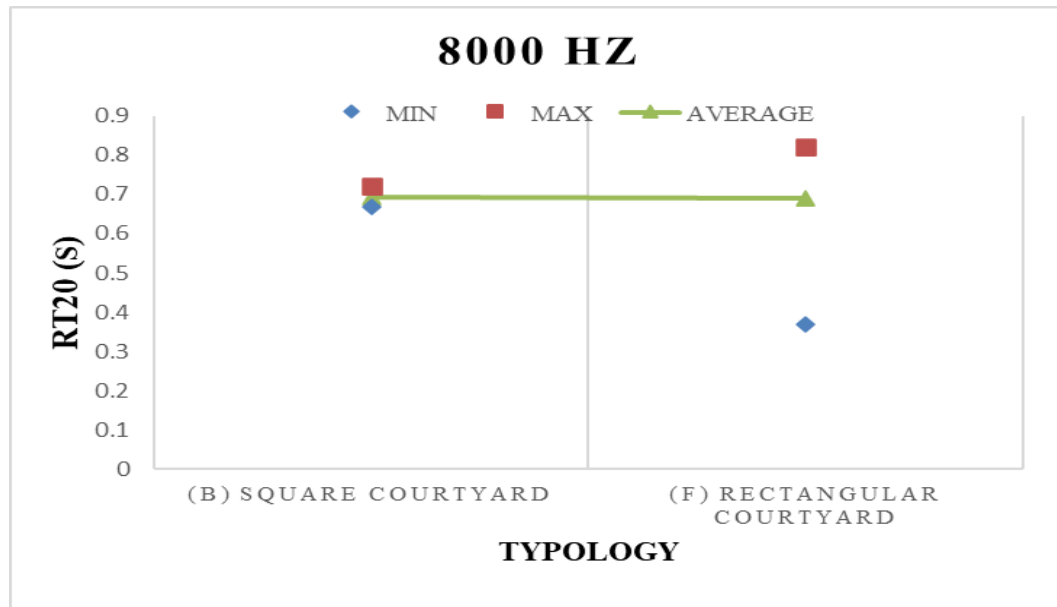


Figure 4-24: *RT20 values, including the maximum, average, and minimum, with their corresponding frequencies, measured at the two courtyard places, at 500 Hz; 1000 Hz; 2000 Hz; 4000 Hz; 8000 Hz.*

The general reverberation time (RT20) at a frequency of 1000 Hz, measured across varying source-receiver distances in two distinct courtyard configurations: a square courtyard (B) and a rectangular courtyard (F) were presented in Figure 4-25. The results highlight significant differences in RT20 behavior, emphasizing the role of courtyard geometry in shaping acoustic performance.

The square courtyard (B) exhibits higher and more stable RT20 values, mostly ranging between 2.0 and 2.5 seconds, regardless of source-receiver distance. This consistency suggests a more balanced distribution of sound reflections due to the symmetrical layout of the space. In contrast, the rectangular courtyard (F) shows greater variation in RT20, particularly at shorter distances (0–20 m), where values fluctuate between 0.5 and 2.0 seconds. This variability indicates faster sound decay and less uniform reflection patterns, likely resulting from the elongated form of the courtyard.

Even if the source-receiver distance is constant, the results show that RT20 varies significantly across the two measurement spaces. This further reinforces the impact of courtyard shape on

acoustic behavior, with differences in geometric configuration leading to distinct sound reflection and dissipation patterns.

Moreover, while distance has little impact on RT20 in the square courtyard, the rectangular courtyard only stabilizes beyond 40 m, suggesting that sound behavior becomes more predictable at longer source-receiver separations. These findings confirm that courtyard shape significantly influences outdoor acoustic characteristics, with more enclosed and symmetrical spaces retaining sound energy longer, while elongated forms facilitate faster sound dissipation.

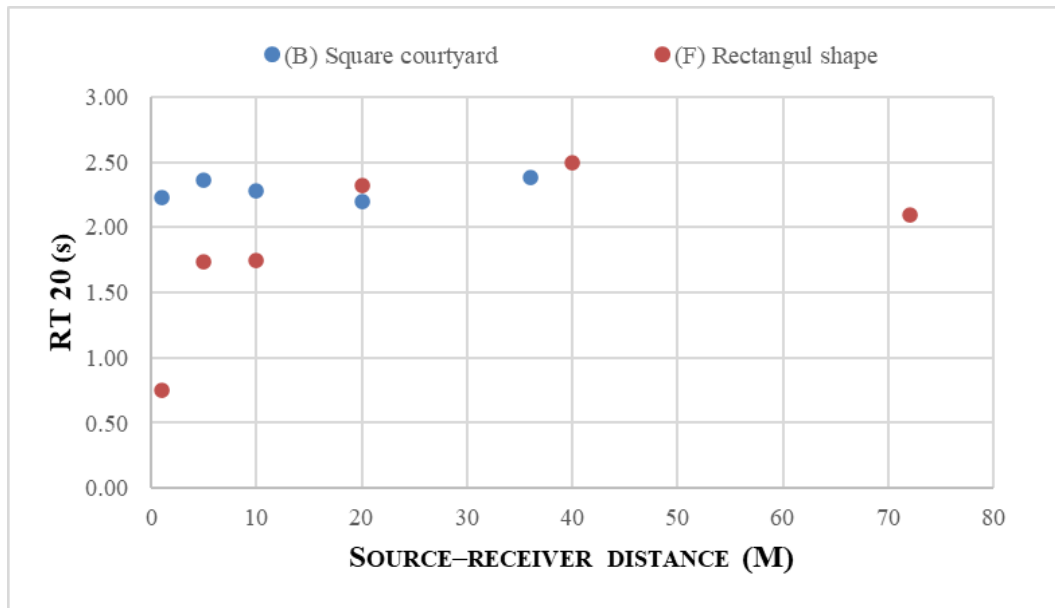


Figure 4-25: *The general reverberation time (RT20) at a frequency of 1000 Hz, measured at two distinct courtyard using varying source-receiver distances.*

The findings indicate that RT20 behavior is closely influenced by architectural design elements, with courtyard shape emerging as a critical factor in determining sound dispersion and overall acoustic performance. The variation in RT20 values observed between the square and rectangular courtyards suggests that geometric configuration directly impacts sound reflection, energy retention, and dissipation. In more symmetrical and enclosed spaces like the square courtyard, sound tends to persist longer and exhibit more stable reverberation times, while elongated forms, such as the rectangular courtyard, lead to faster sound decay and greater variability. These results highlight the importance of considering architectural morphology when assessing outdoor

acoustic environments, as design choices can significantly shape acoustic behavior and sound quality.

4.2. Room acoustic parameters

4.2.1. Reverberation Time

This section presents the measured RT20 values across five octave-band frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) in two different courtyard shapes: a nearly square courtyard (B) and a rectangular courtyard (F). The measurements were taken at varying source–receiver distances to investigate the relationship between the sound decay characteristics and the geometric configuration of outdoor spaces. Regression curves and correlation coefficients (R^2) were used to assess the strength of these relationships.

The results, as shown in Figures 4-26, illustrate how RT20 changes with increasing source–receiver distance for both courtyard shapes and across the different frequency bands. The results indicate that RT20 exhibits different behaviors depending on the frequency and the geometric configuration of the courtyard.

At lower frequencies, particularly 500 Hz and 1000 Hz, RT20 shows a nonlinear variation with distance. In both courtyards, RT20 increases up to an intermediate distance of approximately 20 to 30 meters before decreasing. This trend suggests that strong early reflections contribute to higher RT20 values at these distances before sound energy dissipates. In contrast, at mid to high frequencies (2000 Hz, 4000 Hz), RT20 values are lower, and a more stable increasing trend with distance is observed, especially in the rectangular courtyard. At the highest frequency of 8000 Hz, RT20 values remain consistently low across all distances, which aligns with the expectation that high-frequency sounds are more susceptible to absorption and scattering.

The effect of source-receiver distance on RT20 varies across frequencies. At 500 Hz and 1000 Hz, RT20 follows a parabolic trend, initially increasing before decreasing beyond a certain distance. This behavior indicates the dominance of reflections at intermediate distances, particularly in the rectangular courtyard. However, at 2000 Hz, 4000 Hz, and 8000 Hz, RT20 follows a more

predictable increasing trend, suggesting a gradual attenuation of sound energy as distance increases. The rectangular courtyard consistently exhibits higher RT20 values across all distances, reinforcing the role of geometric configuration in shaping acoustic behavior.

Comparing the two courtyard configurations, distinct differences in RT20 behavior emerge. In the square courtyard, RT20 at lower frequencies is initially higher at shorter distances but decreases more rapidly with increasing distance. This suggests stronger diffusion or absorption effects. Conversely, in the rectangular courtyard, RT20 values remain higher across all frequencies, suggesting longer reverberation paths and a greater contribution of reflections due to the elongated shape. The disparity between the two courtyards is most pronounced at mid to high frequencies (2000 Hz, 4000 Hz), where the rectangular courtyard sustains reverberation for longer durations.

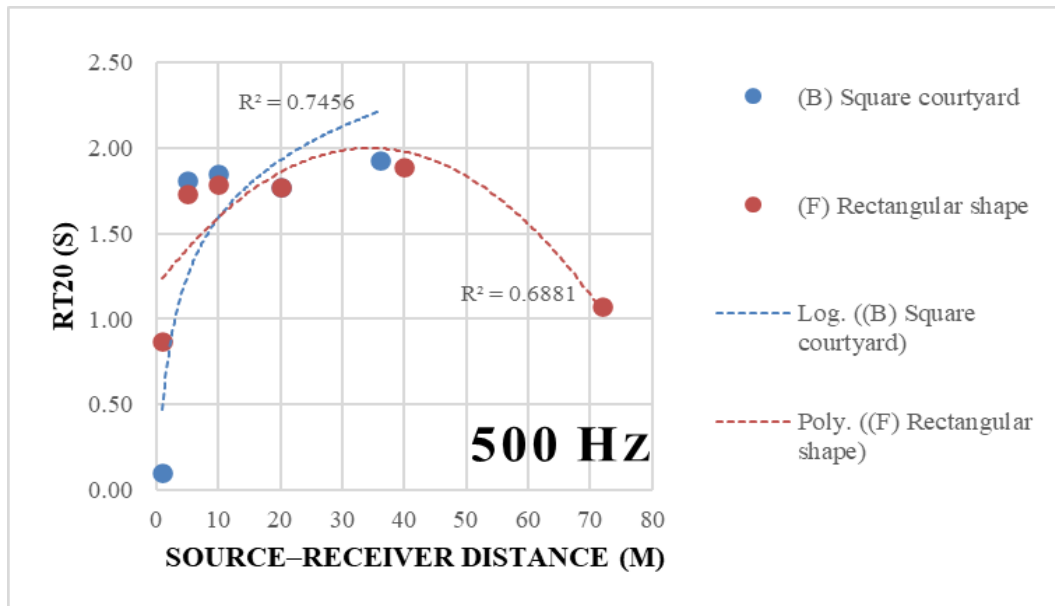
To quantify the relationship between RT20 and source-receiver distance, regression models were applied to the data. The results indicate that at lower frequencies (500 Hz, 1000 Hz), polynomial models best describe RT20 variation, particularly in the rectangular courtyard. At mid to high frequencies (2000 Hz, 4000 Hz, 8000 Hz), logarithmic models provide a better fit, demonstrating a steady increase in RT20 with distance. The highest correlation between RT20 and distance was observed at 4000 Hz, where the R^2 values were the strongest.

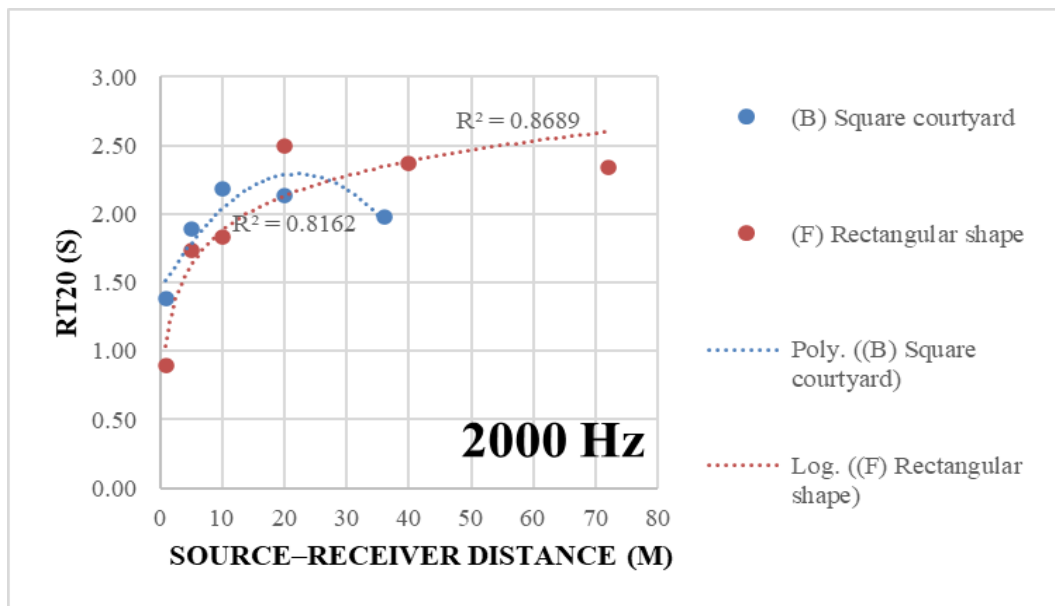
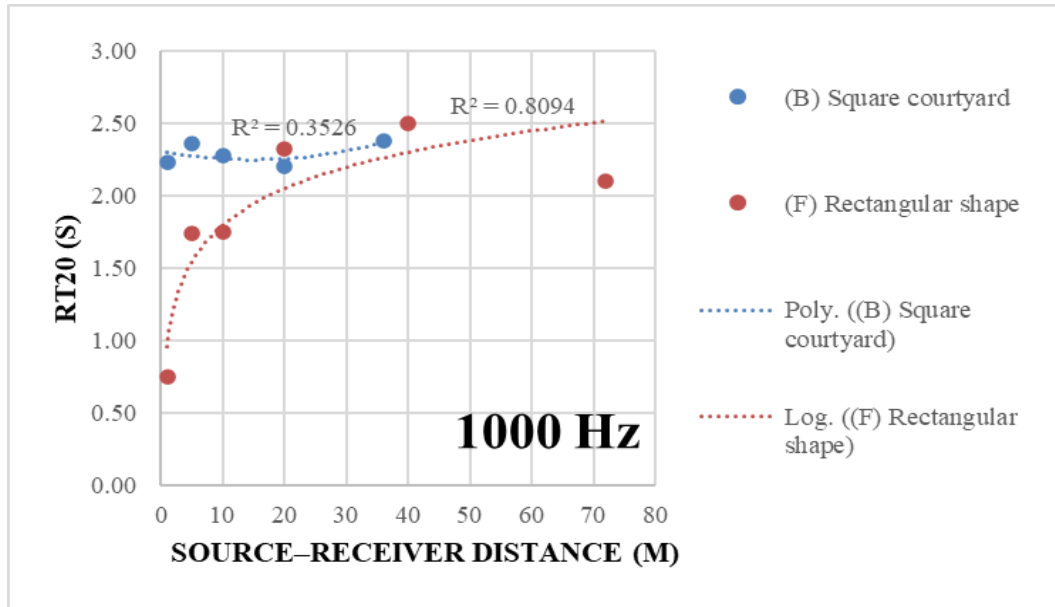
These findings highlight the significant impact of courtyard geometry on outdoor reverberation characteristics. The rectangular courtyard, due to its elongated shape, promotes longer reverberation times, particularly at mid to high frequencies. In contrast, the square courtyard exhibits a more rapid RT20 decay at greater distances, indicating stronger diffusion or absorption effects at its boundaries. The results suggest that courtyard geometry can be strategically used in outdoor acoustic design to control reverberation and sound propagation.

The analysis clearly shows that courtyard shape significantly influences RT20 behavior, particularly at lower and mid-range frequencies. The square courtyard (B) generally produces more consistent and predictable RT20 values across different frequencies and distances. This can be attributed to its more symmetrical layout, which likely facilitates more uniform sound reflections and distribution. In contrast, the rectangular courtyard (F) shows more variability,

especially at 500 Hz and 1000 Hz, where sound reflections appear to interact more complexly with the elongated geometry. The stronger R^2 values observed at higher frequencies (2000 Hz, 4000 Hz, and 8000 Hz) in both courtyards indicate that the impact of courtyard shape diminishes as frequency increases, possibly due to the more directional nature of high-frequency sound waves.

These findings underscore the importance of considering courtyard shape when designing outdoor environments in educational settings. The square courtyard's more balanced acoustic behavior suggests it may offer better sound distribution and clarity, which could enhance speech intelligibility and comfort in outdoor gathering spaces. The variability observed in the rectangular courtyard, particularly at lower frequencies, highlights the need for careful planning of building facades and reflective surfaces to manage sound behavior more effectively.





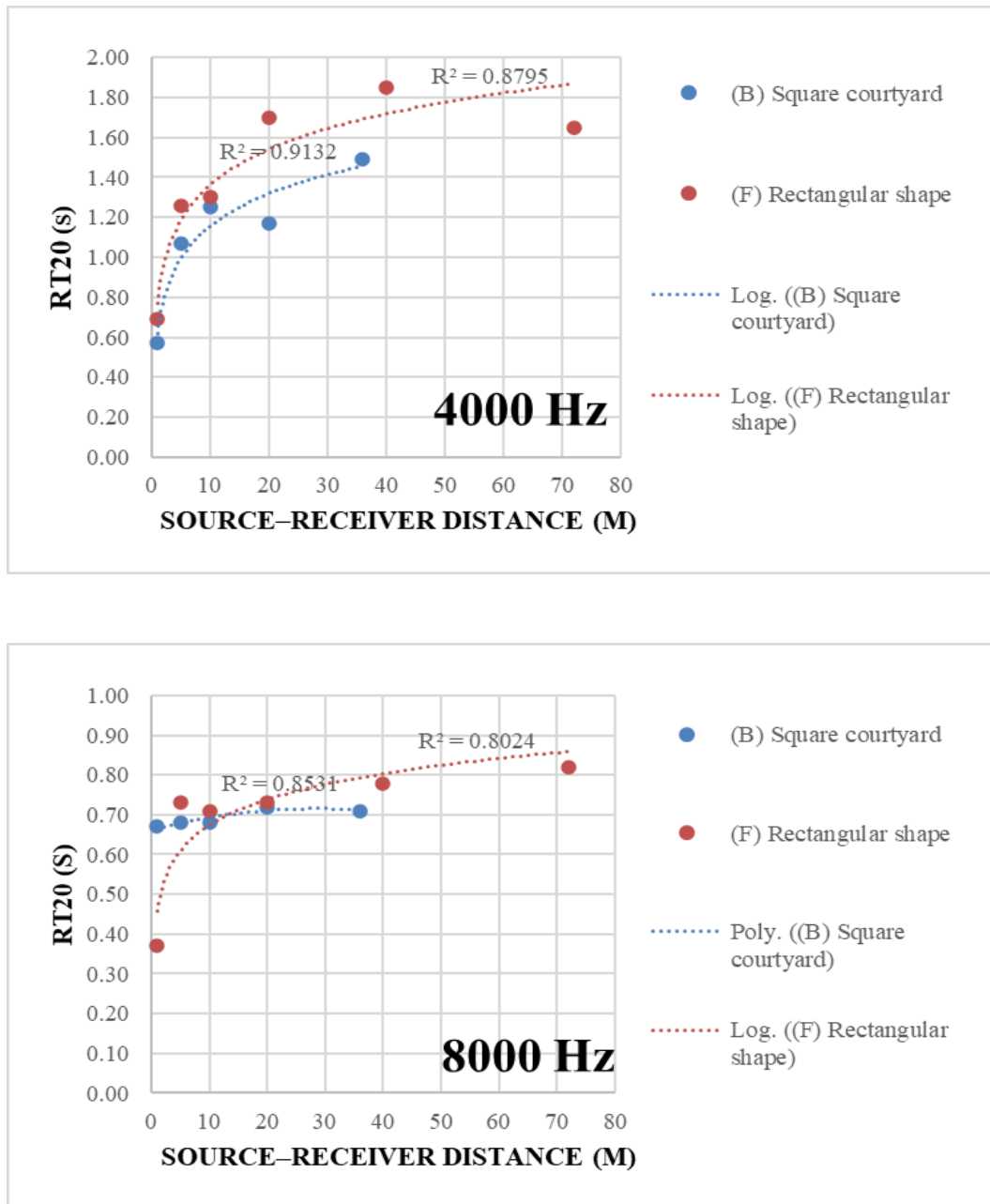


Figure 4-26: *RT measured based on source–receiver distance for the two different types of courtyard shape, with regression curves and correlation coefficients R2 at: 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz.*

4.2.2. Early decay time (EDT)

The analysis of Early Decay Time (EDT) based on source–receiver distance provides valuable insights into the acoustic behavior of two distinct outdoor courtyard configurations: the square-shaped courtyard (B) and the rectangular courtyard (F). This section presents the measured EDT values across five octave-band frequencies (500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) and explores how courtyard geometry influences sound decay characteristics. To evaluate the relationship between EDT and source–receiver distance, polynomial regression curves and their corresponding R^2 values were used. Figure 4.27 presents the measured EDT at 500 Hz for different source-to-receiver distances in the two courtyard configurations with different building heights, illustrating the impact of architectural form on sound decay behavior.

The differences in EDT behavior between the two courtyard shapes become particularly evident. In the square-shaped courtyard (B), EDT values rise sharply at shorter distances, peaking at approximately 2.0 s when the source–receiver distance reaches around 30 m. Beyond this point, EDT gradually decreases, reflecting the diminishing influence of early sound reflections as distance increases. The polynomial regression curve for this configuration shows a strong fit to the data, with an R^2 value of 0.9194, indicating a high correlation between source–receiver distance and EDT. In contrast, the rectangular courtyard (F) displays a more gradual increase in EDT, reaching its peak at a distance of approximately 50 m before tapering off. This more extended rise and fall suggest a complex interaction between sound reflections and the courtyard's elongated geometry, with an R^2 value of 0.8945 reflecting a slightly more variable relationship between distance and EDT.

The observed differences between the two courtyards highlight the impact of architectural configuration on early sound reflections. The square courtyard exhibits a more pronounced peak in EDT at shorter distances, likely due to the concentrated distribution of reflective surfaces, which results in stronger and more immediate early reflections. This behavior suggests that sound energy builds up and decays more quickly in this configuration. On the other hand, the rectangular courtyard shows a more gradual progression of EDT, probably due to the increased distance

between opposing facades, which delays and diffuses early reflections and leads to a slower accumulation of reflected sound energy.

These findings emphasize the importance of courtyard shape in determining early sound decay, which directly influences speech clarity and perceived acoustic comfort in outdoor environments. The stronger and more immediate reflections in the square courtyard may enhance speech intelligibility at closer ranges, while the more diffused reflections in the rectangular courtyard could lead to greater variability in acoustic conditions over larger distances.

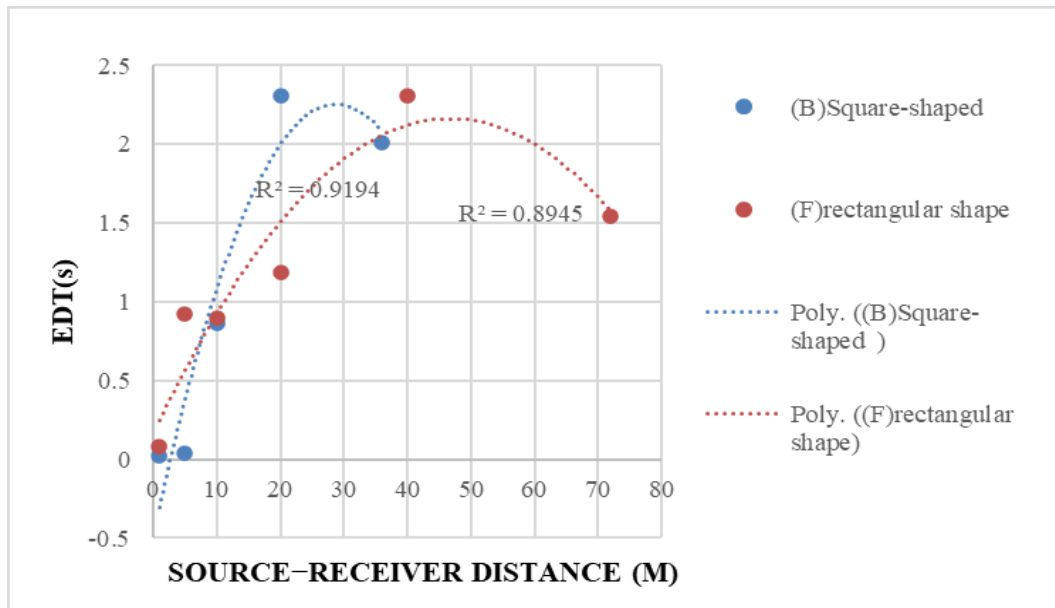


Figure 4-27: Measured EDT at 500 Hz with different source to receiver distances for the two different types of building heights.

4.2.3. Definition (D50)

The D50 parameter, also known as the Speech Transmission Index for the first 50 ms, is a key measure of speech intelligibility in an acoustic environment. It quantifies the ratio of early sound energy arriving within the first 50 milliseconds of the impulse response to the total sound energy. Expressed as a percentage, D50 values closer to 1 (or 100%) indicate clearer and more intelligible sound, as early reflections enhance direct sound perception. Lower D50 values suggest increased reverberation and delayed reflections, leading to poorer speech clarity.

In the context of this study, Figure 4-28 presents the variation of D50 with source–receiver distance for the square-shaped courtyard (B) and the rectangular courtyard (F). In both configurations, D50 decreases as the source–receiver distance increases, reflecting the diminishing influence of early reflections over greater distances. The square-shaped courtyard shows higher D50 values at shorter distances, maintaining relatively good speech intelligibility closer to the sound source. As the distance increases, the decrease in D50 is more pronounced, but the polynomial regression curve fits well with an R^2 value of 0.8199.

In contrast, the rectangular courtyard (F) displays lower initial D50 values and a more gradual decline. This behavior suggests that the elongated layout of the courtyard results in more dispersed and delayed early reflections, reducing the clarity of direct sound. The polynomial regression curve for this configuration shows a slightly lower R^2 value of 0.7819, indicating a more variable relationship between D50 and distance.

These findings underscore the impact of courtyard shape on speech intelligibility in outdoor environments. The square courtyard's higher and more stable D50 values at shorter distances suggest better acoustic conditions for communication, whereas the rectangular courtyard's lower D50 values highlight potential challenges in maintaining speech clarity, especially over longer distances. Future studies could further explore how architectural elements like façade materials and building heights affect the distribution of early sound reflections and, consequently, D50 behavior.

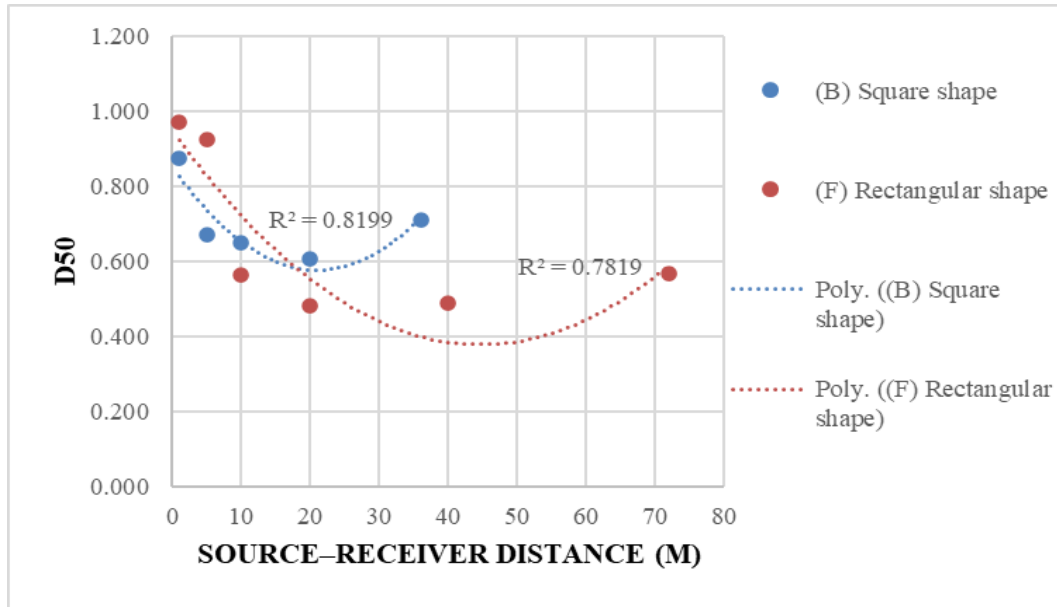


Figure 4-28: *D50 with different source to receiver distances for the two different types of courtyard shape.*

4.2.4. Rapid Speech Transmission Index (RaSTI)

The Rapid Speech Transmission Index (RaSTI) is a widely used metric for evaluating speech intelligibility in acoustic environments. It measures how clearly speech information is transmitted from the source to the receiver by assessing the modulation of the sound signal. RaSTI values range from 0 to 1, where higher values indicate better speech intelligibility. According to the IEC 60268-16:2020 standard, RaSTI is classified into five distinct levels: "Extremely poor" (0 to 0.3), "Poor" (0 to 0.45), "Fair" (0.45 to 0.6), "Good" (0.6 to 0.75), and "Excellent" (0.75 to 1.0).

In this study, Figure 4-29 illustrates the variation of RaSTI with increasing source–receiver distance for the two courtyard configurations: the square-shaped courtyard (B) and the rectangular courtyard (F). Both shapes show a noticeable decline in RaSTI values as distance increases, reflecting the weakening of direct sound and the increasing influence of delayed reflections and sound diffusion. For the square-shaped courtyard (B), RaSTI values start high, maintaining good speech intelligibility at shorter distances. The polynomial regression curve fits well with an R^2 value of 0.9805, indicating a strong correlation between distance and RaSTI performance. In contrast, the rectangular courtyard (F) shows a faster decline in RaSTI values, suggesting a quicker

loss of speech clarity over distance. The regression curve for this configuration also fits well, with an R^2 value of 0.9665, though it highlights greater variability in speech transmission.

These results emphasize the role of courtyard geometry in shaping acoustic performance. The square courtyard offers better speech intelligibility at closer ranges, while the rectangular courtyard's elongated layout leads to more dispersed sound reflections, reducing clarity over longer distances. This insight is crucial for the architectural design of outdoor spaces intended for communication, where optimizing sound transmission can significantly enhance user experience.

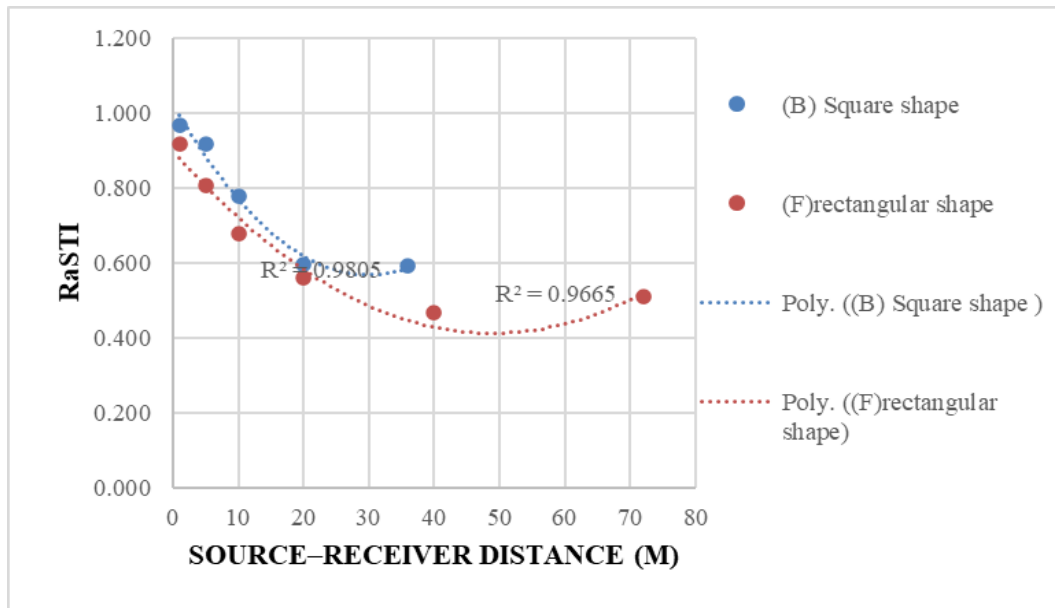


Figure 4-29: *RaSTI with different source to receiver distances for the two different types of courtyard shape.*

4.2.5. Sound pressure level (SPL)

Sound Pressure Level (SPL) attenuation is a key parameter in evaluating sound propagation and its behavior over distance in outdoor environments. The findings of SPL attenuation were analyzed by comparing the observations to the semi-free-field attenuation model, which indicates that sound pressure levels generally diminish by around 6 dB for every doubling of distance from the source in an unobstructed setting. This comparison provided a reference baseline for evaluating the

impact of adjacent building façades and courtyard layouts on sound propagation in the examined outdoor areas.

Figure 4-30 illustrates the SPL attenuation as a function of source–receiver distance for the two courtyard configurations: the square-shaped courtyard (B) and the rectangular courtyard (F). The results are compared with the expected attenuation in a semi-free field environment.

In both courtyard configurations, SPL decreases as the distance from the source increases. However, the rate of attenuation differs between the two cases. The square courtyard (B) exhibits a slightly steeper decline in SPL at shorter distances, which can be attributed to the presence of surrounding reflective surfaces that initially reinforce sound levels before contributing to energy loss. The rectangular courtyard (F), in contrast, shows a more gradual decrease in SPL over longer distances, suggesting that its elongated shape allows for extended sound propagation with reduced early reflections. The study found that while taller buildings generally lead to greater SPL attenuation, façade details such as balconies and protruding elements significantly influenced sound propagation. These architectural features created additional reflections, sustaining sound energy and, in some cases, reducing SPL attenuation in the six-level courtyard compared to the lower courtyard. Diffraction, interference, and surface material properties also played a role in modifying expected attenuation trends. These findings highlight the complexity of sound behavior in real architectural environments, emphasizing the need to consider façade geometry and surface treatments in acoustic design.

Compared to the semi-free field scenario, both courtyard configurations exhibit less attenuation at greater distances, indicating that the surrounding built environment influences sound propagation by providing reflections that partially compensate for free-field energy loss. These findings highlight the impact of architectural geometry on SPL attenuation, which is crucial for optimizing soundscapes in urban outdoor spaces.

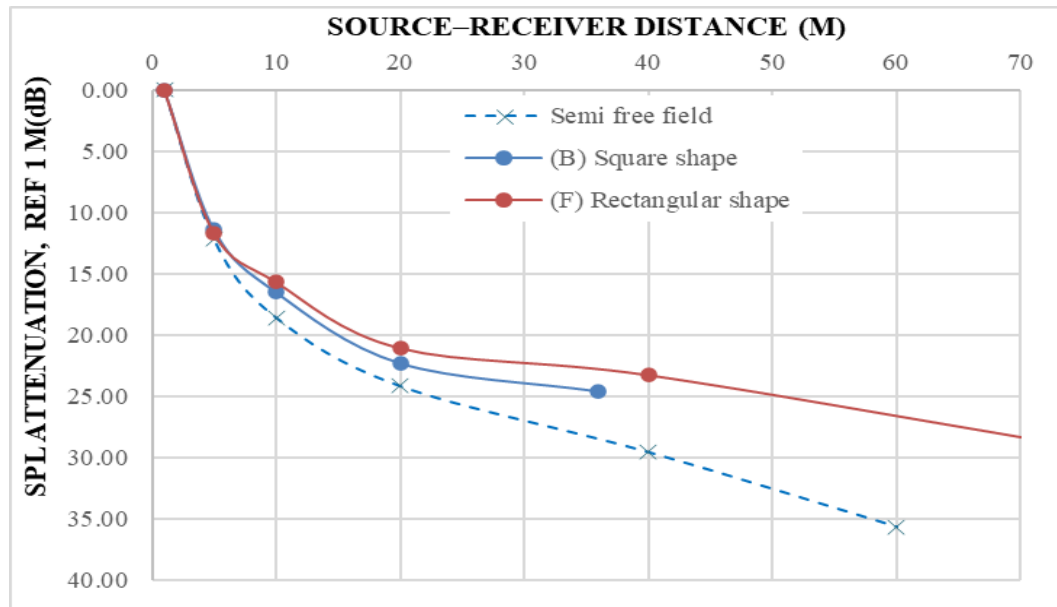


Figure 4-30: *SPL attenuation according to source to receiver distance in the two-courtyard shape.*

5. Conclusion

This study investigated the influence of building layout, façade height, and courtyard geometry on the outdoor acoustic environment at Batna 1 University. Through an in-depth analysis of key acoustic metrics—including Reverberation Time (RT20), Early Decay Time (EDT), Sound Pressure Level (SPL) attenuation, Definition (D50), and the Rapid Speech Transmission Index (RaSTI)—the findings provide a comprehensive understanding of how different architectural configurations shape sound propagation, reflections, and intelligibility in enclosed outdoor spaces.

The results demonstrated that building layout significantly affects the distribution of acoustic energy. Among the different configurations analyzed—square, U-shaped, L-shaped, and linear—the square and U-shaped courtyards exhibited the highest RT20 values, particularly at mid-range frequencies (1000 Hz–2000 Hz), due to their enclosed geometry trapping sound energy. The linear and L-shaped courtyards facilitated faster sound decay, exhibiting lower RT20 values and more stable SPL attenuation, making them more suitable for environments requiring better speech intelligibility. The impulse response analysis confirmed that U-shaped and square layouts resulted

in stronger reflections, leading to prolonged reverberation, while the linear configuration exhibited the lowest RT20 values, demonstrating efficient sound dissipation.

In terms of speech intelligibility, the D50 and RaSTI values were highest in linear courtyards, indicating improved clarity due to reduced reverberation and stronger direct sound dominance. Conversely, square and U-shaped courtyards had lower D50 and RaSTI values, suggesting a decline in speech clarity due to prolonged reverberation. The SPL attenuation analysis further revealed that linear courtyards experienced a more gradual decrease in SPL over distance, whereas square and U-shaped spaces showed fluctuating SPL trends, influenced by the increased reflections within their enclosed boundaries.

The study also examined the role of façade height in shaping acoustic behavior. The results showed that higher façades (six levels) led to significantly increased RT20 values, particularly at low and mid frequencies (500 Hz–2000 Hz), due to stronger reflections. In contrast, lower façades (two to three levels) facilitated faster sound decay, resulting in lower RT20 values across all frequency bands. The impulse response data confirmed that spaces surrounded by taller buildings exhibited stronger secondary reflections, which extended reverberation duration.

For speech intelligibility, the results showed that D50 and RaSTI values were significantly lower in areas enclosed by higher façades, confirming that excessive reverberation negatively impacts clarity. The early decay time (EDT) values were also higher in six-level façades, meaning that sound energy persisted longer before decaying, reinforcing the prolonged reverberation observed in the RT20 results. For SPL attenuation, Despite the expectation that taller buildings would lead to greater SPL attenuation, the study found that certain façade details, such as balconies and protruding elements, influenced reflection patterns. In some cases, the presence of these elements in the six-level courtyard resulted in less SPL attenuation than in the lower courtyard, as the surfaces provided additional reflections that sustained sound energy. This highlights the complexity of sound propagation in real architectural environments, where façade geometry and surface treatments can alter expected attenuation trends.

The influence of courtyard geometry was further explored by comparing square and rectangular courtyard configurations. The results revealed that the square courtyard exhibited longer RT20 values at mid frequencies (1000 Hz–2000 Hz) due to its enclosed shape promoting stronger reflections. The rectangular courtyard, in contrast, demonstrated faster sound decay, especially at low frequencies (500 Hz–1000 Hz), indicating more efficient sound diffusion. At higher frequencies (4000 Hz–8000 Hz), RT20 values decreased in both courtyard shapes, aligning with the expected behavior where high-frequency sounds are more easily absorbed and scattered. The square courtyard had more consistent RT20 values across measurement points, while the rectangular courtyard exhibited greater variability, likely due to localized sound reflections along its elongated walls.

The EDT values followed a similar pattern, where the square courtyard showed higher EDT at shorter distances, reinforcing the idea that sound energy remained trapped within the space. In contrast, the rectangular courtyard exhibited a slower increase in EDT with distance, indicating more gradual sound decay. The D50 and RaSTI values were generally higher in the rectangular courtyard, suggesting improved speech clarity compared to the square courtyard, where prolonged reverberation reduced intelligibility. The SPL attenuation analysis revealed that the rectangular courtyard experienced a more gradual SPL reduction, while the square courtyard exhibited fluctuations in SPL levels due to varying reflection intensities.

These findings highlight the need for strategic design considerations to optimize outdoor acoustic performance. In environments where speech intelligibility and noise control are priorities, such as university courtyards and public spaces, open spatial configurations (such as linear or L-shaped layouts) and lower façade heights may be preferable to minimize excessive reverberation. Conversely, enclosed courtyards and taller façades may be beneficial for reducing external noise intrusion but should incorporate sound-absorbing materials or diffusive surfaces to prevent prolonged reverberation.

While this study provides significant insights into the effects of building layout, façade height, and courtyard geometry, further research is needed to refine acoustic optimization strategies. Future investigations should explore the influence of different façade materials, surface

treatments, and absorptive properties to better understand their role in controlling outdoor sound behavior. Additionally, environmental factors such as wind, humidity, and temperature variations should be examined to assess their impact on sound propagation. Furthermore, integrating psychoacoustic assessments and user perception studies could offer a more comprehensive evaluation of acoustic comfort in outdoor university settings.

In conclusion, this research underscores the strong relationship between urban morphology and outdoor acoustic performance. The findings emphasize that building layout, façade height, and courtyard shape collectively influence sound propagation, attenuation, and intelligibility in open spaces. These insights are crucial for architects, urban planners, and acoustic designers aiming to create well-balanced soundscapes that enhance speech clarity, reduce noise disturbances, and improve user comfort. By considering spatial configurations, façade treatments, and sound reflection control, future designs can optimize outdoor acoustic environments, ensuring they support their intended functions while maintaining a comfortable auditory experience.

General conclusion

General conclusion

1. General conclusion

Serene urban outdoor environments play a crucial role in promoting feelings of tranquility and well-being, offering numerous benefits such as reduced anxiety, enhanced cognitive performance, and therapeutic experiences. However, these environments are often disrupted by noise pollution, which has become a major environmental issue due to rapid urbanization and the expansion of construction and transportation sectors. This disruption negatively impacts human health, communication, and leisure activities, creating both immediate and long-term adverse effects.

University campuses, as dynamic urban microcosms, reflect the broader urban configuration in terms of climatic, physical, natural, social, and above all, acoustic characteristics and specificities. Their physical layout, architectural forms, and material choices mirror the urban fabric of the surrounding city, influencing how sound propagates and is perceived in outdoor spaces. Climatic factors such as temperature, wind patterns, and humidity further shape acoustic behavior, affecting sound attenuation and reverberation. Natural elements, like vegetation and open spaces, contribute to sound absorption and diffusion, playing a key role in the overall acoustic environment. Social dynamics, including the density of student populations and the diversity of activities taking place on campus, create varying noise levels and soundscapes. These combined elements make university campuses a microcosm of the broader urban environment, where the interaction between built and natural factors shapes the acoustic comfort and quality of outdoor spaces.

Given their dual role as educational and social spaces, university campuses are particularly sensitive to acoustic conditions. They face challenges in maintaining serene environments essential for students' academic success and well-being. Architectural structures shape acoustic behavior, influencing key parameters such as Reverberation Time (RT) and Sound Pressure Level (SPL), which ultimately impact outdoor comfort. The built environment's configuration plays a crucial role in defining these acoustic characteristics, where thoughtful design can significantly enhance aural comfort. In the context of Algerian urban settings, research has highlighted how urban form affects noise distribution and soundscape quality, emphasizing the importance of spatial planning in educational environments.

Acoustic comfort, therefore, becomes vital in supporting students' well-being, concentration, and overall academic performance. In outdoor spaces where students gather for leisure, study, and informal learning, excessive noise can disrupt these activities, leading to stress, reduced cognitive efficiency, and hindered communication. By examining the relationship between building configurations and outdoor acoustic behavior, this research provides valuable insights into how thoughtful architectural design can mitigate noise pollution and enhance the quality of open spaces, making these findings applicable not only to Batna city but also to similar urban contexts.

The acoustic quality of outdoor urban environments is a fundamental aspect of urban design, influencing well-being, communication, and overall environmental comfort. In rapidly urbanizing cities like Batna, the expansion of construction and transportation networks intensifies noise pollution, making it essential to explore how architectural design can mitigate these effects.

This research aimed to investigate the impact of building morphology on the outdoor sound environment, focusing on how layout and façade design of building influence key acoustic parameters. Given the increasing challenges posed by noise pollution in urban environments, understanding how built forms shape sound propagation is essential for creating comfortable and functional outdoor spaces. This study's focus on the University of Batna 1 offers a relevant case given its urban setting and diverse architectural forms. The campus's enclosed courtyards, surrounded by multi-story buildings with varying façade designs and different arrangement buildings, present a unique opportunity to analyze how building height, materiality, and layout shape the outdoor acoustic environment. Through this investigation, the research contributes not only to advancing knowledge in architectural acoustics but also to developing design strategies that promote more serene and effective educational environments.

To achieve these aims, the research follows a structured workflow designed to build a comprehensive understanding of the relationship between building morphology and outdoor acoustic environments.

Chapter 1 provided a comprehensive review of approaches and methodologies for assessing outdoor acoustic environments within the built environment. It highlighted two primary

approaches: soundscape and noise control. The soundscape approach focuses on enhancing the acoustic experience by shaping positive sound elements, contributing to a richer urban atmosphere. In contrast, the noise control approach aims to mitigate harmful noise pollution, protecting health and well-being. Both approaches offer complementary perspectives for managing urban sound environments.

The chapter also reviewed key methodologies for assessing outdoor sound environments. Field measurements provide accurate, context-specific data on sound propagation influenced by environmental factors. Scale-model experiments enable controlled exploration of variables like architectural elements and layout configurations, though they are limited in replicating large-scale complexities. Computer prediction techniques offer advanced simulation capabilities, modeling sound propagation under varied design scenarios. Emerging technologies such as AI, machine learning, and noise mapping enhance data analysis and noise control strategies, presenting innovative opportunities for urban acoustic planning.

Chapter 2 examined the complex nature of noise in urban outdoor environments, exploring noise sources, propagation, and impacts. It reviewed key acoustic parameters, including reverberation time (RT20), early decay time (EDT), definition index (D50), rapid speech transmission index (RaSTI), and sound pressure level (SPL), providing a framework for evaluating sound quality. The chapter emphasized the influence of urban morphology on sound propagation, particularly building layouts, façade designs, and courtyard shapes, demonstrating their impact on sound attenuation, reverberation, and speech intelligibility. The discussion included noise pollution in Algerian cities like Biskra, Guelma, and Annaba, highlighting the role of spatial configurations in shaping noise distribution. It also addressed the acoustic environment in university settings, emphasizing the need for acoustically comfortable outdoor spaces to support student concentration and well-being.

Chapter 3 outlined the methodological framework adopted to investigate the impact of building morphology on outdoor acoustic environments. The study employed a structured approach, including case study selection, standardized measurement techniques, and controlled environmental conditions, ensuring reliable and accurate data collection. The methodology

integrated impulse response measurements, SPL attenuation analysis, and speech intelligibility assessment, offering a comprehensive evaluation of acoustic behavior in enclosed outdoor spaces. Using standardized protocols, such as a starter clapper for reverberation time measurements and white noise for SPL analysis, enhanced the study's reproducibility. Comparative analysis of case study sites with distinct morphological characteristics provided insights into how architectural configurations influence acoustic performance. By detailing each research stage, Chapter 3 established a solid foundation for analyzing and discussing results in subsequent chapters, setting the stage for understanding acoustic variations across different spatial configurations and their implications for outdoor sound environments.

Furthermore, in this chapter also addressed the consistency of measurement techniques and the importance of controlled environmental conditions in ensuring reliable data. By comparing acoustic parameters across sites, the study provided a nuanced understanding of how spatial design impacts outdoor sound environments, emphasizing the need for thoughtful architectural planning to optimize acoustic comfort. The measurement methodology using a starter clapper demonstrated reliable reproducibility of RT20 above 500 Hz, confirming its suitability for assessing outdoor acoustic environments. The signal-to-noise ratio (S/N) and the Impulse-to-Noise Ratio (INR) were sufficient to ensure accurate RT20 measurements across various source-receiver distances. Specifically, the INR values exceeded the recommended threshold, ensuring that background noise did not compromise measurement reliability. Additionally, the measured data can serve as a reference for validating acoustic simulations, particularly in evaluating the accuracy of computational models for predicting sound propagation in outdoor spaces. These findings validate the robustness of our approach, indicating that it can be effectively applied to analyze sound propagation and reverberation characteristics in outdoor spaces, even in complex urban environments. Furthermore, the methodology provides a solid foundation for future studies exploring the acoustic effects of different architectural configurations through both empirical measurements and simulation-based analyses.

Chapter 4 provides a comprehensive analysis of the influence of building layout, façade design and courtyard shape on the outdoor sound environment at Batna 1 University, focusing on key acoustic parameters such as reverberation time (RT20), early decay time (EDT), impulse response,

and sound pressure level (SPL) attenuation. The findings reveal that variations in spatial configuration and architectural morphology significantly affect sound reflections, energy distribution, and propagation patterns in outdoor spaces. By systematically evaluating these acoustic parameters, the study sheds light on the complex interactions between built environment features and sound behavior in open-air settings. The analysis of building layouts demonstrated that different configurations—U-shaped, square-shaped, linear, and L-shaped—produce distinct acoustic behaviors. Specifically, more enclosed layouts, such as U-shaped and square forms, tend to prolong reverberation due to increased sound reflections from surrounding facades, while more open configurations exhibit faster sound decay and lower RT20 values. The relationship between RT20 and EDT was shown to vary across octave bands, highlighting the frequency-dependent nature of sound propagation in outdoor environments. This nuanced analysis reveals that architectural forms play a pivotal role in shaping the acoustic landscape, influencing both the spatial and temporal distribution of sound energy.

Similarly, the investigation of façade design emphasized the critical role of façade height in shaping acoustic characteristics. Spaces surrounded by taller buildings exhibited longer reverberation times and more pronounced sound energy reflections. The impulse response analysis further illustrated how varying façade heights contribute to differential sound reflection patterns, creating distinct acoustic environments even within the same outdoor context. The correlation between source-receiver distance and acoustic parameters further underscored the influence of architectural enclosures on outdoor sound behavior, demonstrating how physical dimensions and spatial arrangement directly impact sound decay and reverberation. This study demonstrated that while taller buildings generally contribute to greater SPL attenuation, unexpected variations can occur due to architectural details. Façade elements such as balconies and protrusions introduced additional reflections, sustaining sound energy and, in some cases, reducing attenuation in the six-level courtyard compared to the lower one. Furthermore, diffraction, interference, and surface material properties influenced sound propagation, occasionally leading to deviations from expected trends. These findings highlight the complexity of acoustic behavior in real architectural environments, emphasizing the need to consider façade geometry and surface treatments in outdoor soundscape design. Future research could further explore these effects using both empirical measurements and simulation-based analyses to refine predictive models.

In addition to building layouts and façade characteristics, courtyard shape plays a crucial role in shaping outdoor acoustic environments by influencing reverberation characteristics, speech intelligibility, and sound propagation patterns. The findings indicate that lower frequencies tend to persist longer due to limited diffraction pathways, while higher frequencies dissipate more rapidly. More enclosed courtyard shapes generally exhibit higher and more stable reverberation times at mid-frequencies, suggesting stronger reflections and prolonged reverberation, whereas elongated configurations show greater variability, particularly at shorter source-receiver distances. Beyond reverberation, key acoustic parameters such as Early Decay Time (EDT), Definition (D50), Rapid Speech Transmission Index (RaSTI), and Sound Pressure Level (SPL) attenuation demonstrate distinct differences across courtyard configurations. More enclosed courtyards tend to support better speech intelligibility at shorter distances due to stronger early reflections, while elongated courtyards show greater fluctuation in these parameters, indicating more dispersed reflections and reduced clarity. Additionally, SPL attenuation patterns suggest that enclosed courtyards distribute sound more evenly, while elongated spaces may exhibit directional effects and potential sound trapping. These findings underscore the role of architectural form in shaping acoustic environments and inform strategies for optimizing outdoor sound performance.

In addition to building layouts and façade characteristics, courtyard shape plays a crucial role in shaping outdoor acoustic environments by influencing reverberation characteristics, speech intelligibility, and sound propagation patterns. The analysis of RT20 distribution reveals that lower frequencies persist longer due to limited diffraction routes, while higher frequencies dissipate more rapidly. The square courtyard exhibits higher and more stable RT20 values at mid-frequencies (1000–2000 Hz), suggesting stronger reflections and prolonged reverberation, whereas the rectangular courtyard shows greater variability, particularly at shorter source-receiver distances, due to its elongated form. Beyond reverberation, key room acoustic parameters such as EDT, D50, RaSTI, and SPL demonstrate distinct differences between the two courtyard configurations. The square courtyard maintains higher D50 and RaSTI values at shorter distances, supporting better speech intelligibility, while the rectangular courtyard exhibits greater fluctuation in these parameters, indicating dispersed early reflections and reduced clarity. Furthermore, SPL attenuation patterns suggest that the square courtyard distributes sound more evenly, while the rectangular courtyard shows directional effects and potential sound trapping.

These results contribute to a deeper understanding of how urban morphology impacts the acoustic environment of outdoor university spaces. The findings not only reinforce the importance of architectural design in controlling sound propagation but also provide a foundation for future research aimed at optimizing acoustic comfort in open environments. By addressing the relationship between building configuration and acoustic performance, this study offers valuable insights for urban planners and architects seeking to enhance the quality of outdoor spaces through informed design strategies. Furthermore, the study underscores the need for localized research, particularly in Algerian contexts, where limited studies have focused on the impact of building morphology on outdoor sound environments. This gap in the literature highlights the significance of this work and the potential for future investigations to build upon these findings, exploring additional architectural variables and environmental conditions to refine and expand our understanding of outdoor acoustic performance.

The study's novelty lies in addressing the lack of research on this topic in Algeria and providing valuable insights for urban acoustic planning and architectural design. By offering a structured methodological framework and highlighting the importance of standardized measurement techniques, this research contributes to the broader understanding of outdoor sound environments and paves the way for future studies focusing on different urban contexts and morphological typologies.

2. Contribution and Practical recommendations

This research makes a significant contribution to the field of architectural acoustics, particularly within the Algerian context. By providing robust empirical data on the influence of building morphology on outdoor sound behavior, it offers valuable insights for architects, urban planners, and policymakers. The study's findings lay the foundation for developing practical guidelines aimed at creating acoustically comfortable educational environments, with potential applications in similar institutional settings.

The significance of this research is reflected in three key dimensions:

- **Theoretical Advancement:** This study deepens and enriches existing knowledge on the complex relationship between urban morphology and outdoor acoustic environments, expanding the understanding of how architectural forms shape sound behavior.
- **Methodological Framework:** It establishes a systematic and structured approach to measuring and analyzing acoustic parameters in outdoor spaces, ensuring the reliability and reproducibility of results.
- **Contextual Relevance:** By addressing the notable lack of research on outdoor acoustics in Algerian urban settings, this study provides localized insights that can inform future urban planning and architectural practices, making a crucial step toward context-sensitive design solutions.

Moreover, the study underscores the importance of integrating acoustic considerations into the early stages of architectural and urban design processes. To translate these findings into actionable strategies, the following design recommendations are proposed for optimizing outdoor acoustic environments in educational settings:

Courtyard Geometry and Sound Distribution

- **Optimize Courtyard Shape for Balanced Reverberation**
 - Square courtyards should incorporate sound-absorbing materials on façades to reduce excessive reverberation and improve speech clarity.
 - Rectangular courtyards naturally support better sound dissipation but benefit from strategically placed reflective surfaces to enhance sound distribution for speech intelligibility.
 - Hybrid courtyard designs (partially open layouts) can balance sound retention and dissipation, ensuring optimal acoustic comfort.

Building Layout and Façade Heights

- **Control Building Height for Sound Distribution**
 - Favor lower building heights (2-3 stories) over taller facades (6 stories) to minimize excessive reflections and reverberation in enclosed outdoor spaces.

- In high-rise façades, incorporate diffusive elements such as balconies, perforated panels, or vegetation to break up strong reflections and prevent excessive sound buildup.
- Utilize stepped or terraced building heights to create gradual sound diffusion and avoid concentrated reflection zones.
- **Optimize Layouts to Reduce Reflection Hotspots**
 - Avoid compact and symmetrical building layouts, such as square or U-shaped configurations, as they can lead to excessive reflections.
 - Prefer semi-enclosed layouts with varied façade orientations over those with long, continuous facades to ensure even sound attenuation.
 - Encourage irregular or staggered layouts to disperse sound energy more evenly and minimize focal points of sound reflection.
 - Use L-shaped or linear outdoor spaces where clear speech transmission is essential, as they reduce excessive reflections.

Façade Articulation and Material Selection

- **Enhance Sound Absorption and Diffusion**
 - Integrate façade articulation techniques such as balconies, protrusions, or angled surfaces to diffuse sound and mitigate reflections on speech intelligibility.
 - Employ porous or textured façade materials (e.g., perforated panels, absorptive cladding) to reduce excessive reverberation in enclosed courtyards.
 - Use a balanced combination of reflective and absorptive materials to control sound projection and prevent excessive reverberation.
 - Incorporate green walls, trees, or planted surfaces to provide natural absorption and diffusion of sound waves, particularly in dense urban areas.

Outdoor Space Configuration

- **Optimize Acoustic Performance with Landscaping and Structural Elements**

- Establish guidelines on the optimal dimensions and proportions of courtyards and other outdoor spaces to minimize the impact of building height on reverberation time (RT) and sound pressure level (SPL) attenuation.
- Utilize vegetation barriers, low-height noise walls, or semi-open roofing structures (e.g., pergolas with absorptive panels) to balance sound containment and dissipation.
- Position canopies or partial overhead structures to control direct sound reflections and improve speech clarity in gathering areas.
- Use low-height barriers or angled walls to reduce echo effects in highly reverberant courtyards.

Urban Noise Control Measures and Acoustic Simulations

- **Mitigate External Noise Sources**
 - Implement zoning strategies by placing noisy activities (e.g., traffic zones, sports areas) away from quiet learning or discussion spaces.
 - Utilize vegetation barriers or low-height noise walls to mitigate external noise intrusion from roads and surrounding urban areas.
- **Conduct Acoustic Simulations for Design Optimization**
 - Perform acoustic modeling before finalizing designs to predict reverberation behavior and SPL attenuation in different configurations.
 - Adjust building orientations and courtyard openings based on simulation results to optimize outdoor acoustic conditions.

3. Limitations of the Study

While this study provides valuable insights into the effects of building façades on outdoor acoustic performance, several limitations must be acknowledged, particularly in the Algerian context. One key limitation is that the research was conducted within a specific university setting in Algeria, characterized by distinct architectural features and spatial configurations. As a result, the findings may not be fully generalizable to other Algerian urban environments, which exhibit diverse

morphological patterns influenced by historical, climatic, and socio-economic factors. Expanding the study to include different cities and building typologies across Algeria would provide a broader perspective on outdoor acoustic behavior in the region.

Another limitation is that measurements were performed exclusively during the winter season to ensure consistency and minimize variations in weather conditions. However, Algeria experiences significant seasonal and climatic differences, with high temperatures and dry conditions in summer, and cooler, more humid conditions in winter. These environmental factors can influence sound propagation, absorption, and decay, affecting the overall acoustic performance of outdoor spaces. Future research should include long-term measurements across different seasons to capture the full range of climatic influences on outdoor sound environments.

Additionally, this study primarily focused on RT20 and SPL attenuation as key acoustic parameters, without integrating psychoacoustic assessments related to human perception of soundscapes in Algerian public spaces. Given the high levels of noise pollution in many Algerian cities, particularly from road traffic, markets, and informal urban activities, further research should incorporate subjective evaluations to better understand the impact of noise on public comfort and well-being. This could help inform urban planning strategies aimed at improving acoustic quality in open spaces.

Another constraint of this study is the reliance on in-situ measurements, which, while providing real-world acoustic data, are inherently subject to external noise variability and measurement uncertainties. In the Algerian context, where urban noise sources are often unpredictable due to informal street activities, varying traffic patterns, and unregulated construction work, external disturbances may have influenced the results. The use of computational simulations, such as geometric acoustics models or AI-driven noise mapping techniques, could complement field measurements and allow for controlled scenario testing under different urban conditions.

Finally, while this study examined the impact of building morphology, it did not extensively consider the role of vegetation, ground surfaces, and urban design elements in shaping outdoor acoustics. In many Algerian cities, green spaces are limited, and the use of sound-absorbing

materials in urban planning is often overlooked. Investigating how vegetation, pavement materials, and urban furniture influence outdoor soundscapes in Algeria could provide valuable insights for designing more acoustically comfortable public spaces.

4. Future Research Directions

Future studies should explore the influence of diverse urban morphologies on outdoor acoustic performance, considering variations in building height, street layouts, and open-space configurations. Investigating different building typologies and façade designs would contribute to a broader understanding of sound propagation and reverberation in various architectural contexts. Additionally, interdisciplinary research combining architectural design, acoustics, and environmental psychology could provide deeper insights into how built environments shape human perception and acoustic comfort.

Long-term monitoring of sound behavior across different seasons, times of day, and varying atmospheric conditions (such as temperature, humidity, and wind speed) would further enhance the robustness and applicability of the findings. Such studies would allow for a more accurate assessment of the dynamic nature of outdoor acoustic environments and their response to changing climatic factors.

Future research could also expand on these results by incorporating more diverse architectural forms and materials, particularly investigating how different façade materials, surface textures, and construction techniques influence sound reflection and absorption. Examining the role of vegetation, such as green walls, trees, and grass cover, in mitigating noise and enhancing acoustic comfort would be another important avenue of study.

Moreover, extending the frequency range of analysis and measuring RT20 under different climatic conditions could provide a more comprehensive understanding of sound behavior in enclosed outdoor environments. Exploring advanced computational modeling techniques, such as finite element analysis (FEA) and computational fluid dynamics (CFD), could complement field measurements and offer predictive insights into sound behavior in complex urban settings.

Finally, integrating outdoor acoustic studies with smart city initiatives—such as real-time sound monitoring, adaptive urban planning, and noise mitigation strategies—could bridge the gap between research and practical urban design applications, ultimately contributing to the development of more acoustically sustainable and user-friendly outdoor spaces.

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