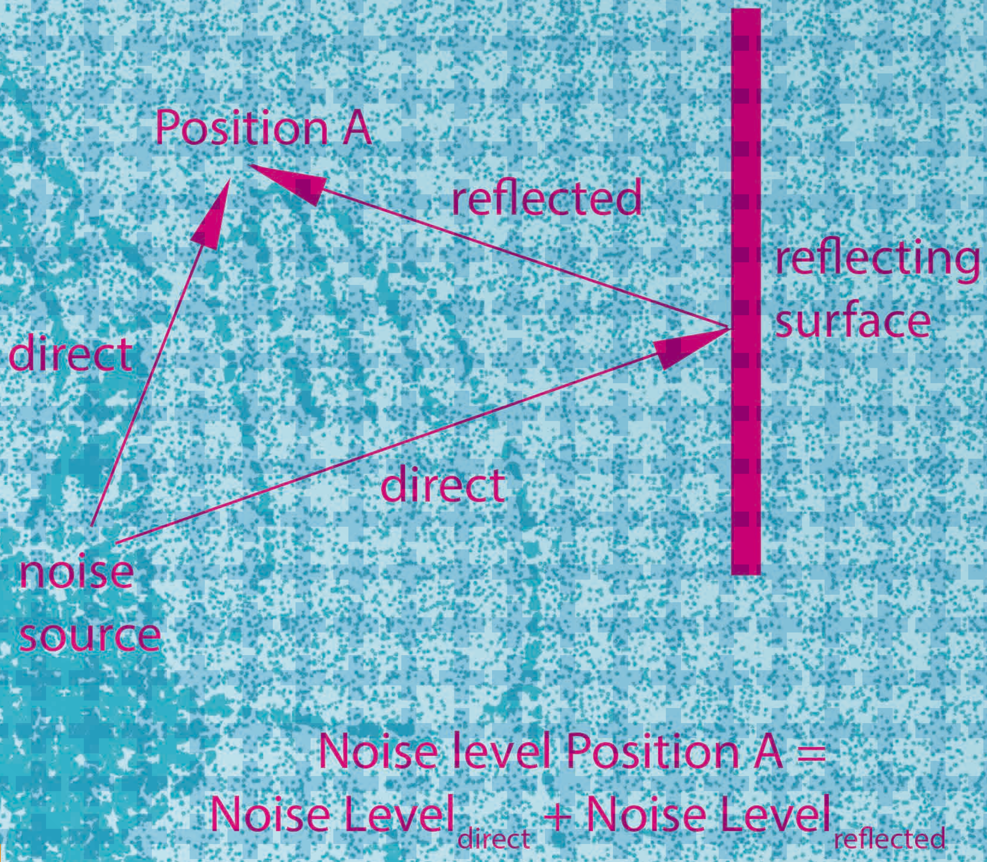
#16
2018

A+BE Architecture and the Built environment



Acoustically effective façades

Jochen Krimm

Acoustically effective façades design

Jochen Krimm
Delft University of Technology, Faculty of Architecture and the Built Environment, Department of Architectural Engineering + Technology

Architecture
and the
Built environment

abe.tudelft.nl

Design: Sirene Ontwerpers, Rotterdam

ISBN 978-94-6366-052-5
ISSN 2212-3202

Unless otherwise specified, all the photographs in this thesis were taken by the author. For the use of illustrations effort has been made to ask permission for the legal owners as far as possible. We apologize for those cases in which we did not succeed. These legal owners are kindly requested to contact the publisher.

Contents

List of Tables

List of Figures

Summary

The silhouettes of the great European metropolises are characterised by a high density of high-rise facades made of glass, metal or stone. On one hand this density stands for economic power and good employment values. On the other hand, the large sound-reflecting surfaces in the cities are responsible for an increase in sound pollution in their vicinity. They cause the most frequent inner-city sound source, traffic noise, to double in perceived intensity. Direct sound and reflected sound add up in the urban environment. This effect of sound level increase through reflection has been subject of acoustic research for some time. In architecture, however, the topic of noise reflection has been completely neglected. But it is exactly these concentration processes in the continuously growing metropolises that make architects face problems that they cannot solve with their own tools alone. For example, placing bedrooms in the quiet part of a building is only possible if there are quiet areas. But highly concentrated areas as a result of creating additional living space are often surrounded by 4 or more sound sources. Hereby, the noise originating from air traffic further aggravates the situation because this type of noise generally impacts the urban space from above. These developments require us to discuss the topic of the reflective properties of facades within the disciplines acoustics and architecture. The fundamental question was:

Is it possible to develop a design strategy that can be employed by architecture firms, and that enables them to develop facades for a quieter city in challenging urban situations?

To answer this question, both disciplines and their respective tools were studied.

In the scope of a literature research, the results of acoustic research related to the topic of reflection on urban surfaces were summarised and examined. The architectural relevance of the results of the individual researches was determined by use of the examined parameters.

Several case studies were conducted to record existing acoustic urban spaces with acoustic measuring methods. The on-site measurements were used to examine the possibility of generating architecturally relevant measurement values for the effect of facades in dependence of locally present sound sources.

The laboratory method of scaled acoustic measurement was not only examined to determine the transferability of the results from the on-site measurements to the model scale, but also the possibility of applying them in an architectural design process. Studies were executed on the design planning scales of 1:50 and 1:100.

Design studies were used to develop proposals for acoustically effective surfaces on a detailed scale as well. Another question was how and based on which parameters surfaces can be designed, and how they can be determined in terms of measurement technology.

The essence of the here conducted studies around the topic of implementing an intended acoustical effect of a façade construction is the development of a procedural guideline for future projects.

The results in short:

- The disciplines architecture and acoustics must develop new paths to be able to execute acoustically driven building projects in a mutually fertile collaboration. Building projects must be thought acoustically and architecturally by both parties.
- This requires a fundamental paradigm change in building acoustics. The transmission path of the sound energy must be considered from the exterior space to the exterior space and not, as until now, from the exterior space to the interior space.
- In order to plan the acoustic effect of a façade it is necessary to define a targeted acoustic quality for specific uses at specific locations in the exterior space.
- The effect of the noise sources defining the building site can only be determined in dependence of the position of the planned use.
- The acoustic values as the basis for acoustic façade planning can only be reliably determined with the help of a multi-channel measurement on-site.
- The impact of a façade area can only be described in a meaningful manner with individual sound level values per frequency band, in dependence of a specific planning-relevant angle of reflection.
- All known and available façade elements can be used as reflection changing elements to reduce the sound impact if they lie at a certain angle to the sound source and the planned exterior use.
- Applying suitable dimensioning of building elements such as lamellas or sills, for example, allows specifying a certain frequency range of the reflection change.
- The frequency range of the greatest reflection changing impact must be attuned to the sensitive range of the human ear to achieve the longest possible effective reflection change with an acoustically effective façade.
- An acoustic façade design can only be applied successfully if, at the same time it fulfils all other basic requirements of a façade construction such as tightness, transparency and light. Only then is it possible that the acoustic input leads to new, exciting façade constructions.

Samenvatting

De contouren van de grote Europese metropolen bestaan grotendeels uit wolkenkrabbergevels van glas, metaal of steen. Aan de ene kant staat deze hoge concentratie voor economisch kracht en veel werkplekken. Aan de andere kant zijn al deze grote reflecterende oppervlakten verantwoordelijk voor het toenemend geluidsniveau in hun directe omgeving. Het verkeer, de meest voorkomende binnenstedelijke bron van lawaai, wordt daardoor twee keer zo luid waargenomen. Direct geluid en gereflecteerd geluid worden bij elkaar opgeteld. In de akoestiek wordt er al gedurende langer tijd onderzoek gedaan naar dit effect van stijgende geluidsniveaus aan reflecterend oppervlaktes. In de bouw daarentegen is het onderwerp geluidsreflectie helemaal niet aan de orde. Maar juist de hoge concentratie in de groeiende metropolen stelt de bouw voor problemen die ze zelf niet kan oplossen.

Zo is het bijvoorbeeld alleen mogelijk de slaapkamers aan de rustige kant van gebouwen te situeren als er überhaupt een rustige kant is. In gebieden met hoge concentraties aan woonruimte, worden deze vaak omgeven door vier of meer geluidsbronnen. En in geval van luchtverkeer in metropoolregio's wordt de situatie nog versterkt, doordat het lawaai dan ook nog eens van boven komt.

Dit soort ontwikkelingen maakt het noodzakelijk dat de disciplines akoestiek en bouwkunde zich met het onderwerp reflectiecapaciteit van gevels gaan bezighouden. De fundamentele vraag is:

Is het mogelijk om een ontwerpstrategie te ontwikkelen die bij architectenbureaus geïmplementeerd kan worden en die het mogelijk maakt om gevels te ontwikkelen die de stad rustiger maakt in dit soort moeilijke binnenstedelijke situaties?

Om een antwoord te vinden werden beiden disciplines en hun gereedschappen onderzocht.

In de literatuurstudie werden de resultaten van actueel onderzoek naar reflectie aan stedelijke oppervlaktes samengevat en gecontroleerd. Het bouwkundig belang van eerdere op zich zelf staande onderzoeksresultaten werd bepaald aan de hand van vastgestelde parameters.

In verschillende casestudy's werden de akoestiek van bestaande stedelijke ruimtes met akoestische meetmethodes in kaart gebracht. Deze metingen werden gebruikt om de impact van gevels afhankelijk van de geluidsbronnen te onderzoeken en bouwkunde-relevante specificaties op te stellen.

De laboratoriummethode om akoestische metingen te verschalen is niet alleen onderzocht om te bepalen óf de metingen op locatie naar modelschaal konden worden overgezet. Ook is onderzocht hóe deze verschaling in het architectonisch ontwerpproces kan worden toegepast. De studies werden uitgevoerd op de bouwkundige schalen 1:50 en 1:100.

Met de ontwerpstudies werden ook voorstellen ontwikkeld voor effectieve akoestische oppervlakten op detailschaal. Een vraag was, met welke parameters deze oppervlakten kunnen worden ontworpen en hoe deze zijn te bepalen aan de hand van de meettechniek. De belangrijkste reden voor dit onderzoek naar de implementatie van bedoelde akoestisch effecten bij het construeren van gevels is het ontwikkelen van een procedurele leidraad voor toekomstige projecten.

Een korte opsomming van de resultaten:

- De architectuur en de akoestiek moeten nieuwe routes ontwikkelen om gezamenlijk in staat te zijn bouwprojecten te realiseren waarbij beide disciplines elkaar versterken.
- Hiervoor moet fundamenteel op een andere manier gedacht worden in de bouwfysische akoestiek: de overdrachtsweg van de geluidsenergie moet daarbij worden beschouwd van buitenruimte naar buitenruimte en niet enkel van buiten naar binnen zoals nu gedaan wordt.
- Om de akoestische effecten van een gevel te kunnen plannen moeten de vereiste akoestisch kwaliteiten voor specifiek gebruik van specifieke plekken in de buitenruimte worden vastgesteld.
- Het effect van geluidsbronnen die op een bepaalde plek inwerken, kan alleen afhankelijk van de plek van het gepland gebruik bepaald worden.
- Geluidswaarden die als basis dienen voor een akoestisch gevelontwerp kunnen alleen met meerkanaalsmetingen ter plekke worden vastgesteld.
- De impact van een gevelvlak kan alleen betekenisvol worden beschreven met afzonderlijke geluidswaarden per frequentieband, afhankelijk van een voor het ontwerp relevante reflectiehoek.
- Zolang ze onder een bepaalde hoek liggen ten opzichte van geluidsbron en de geplande buitenruimte, kunnen alle beschikbare gevelelementen gebruikt worden om de reflectie te veranderen en zo de geluidsbelasting te beperken.

- De toepassing van bouwelementen met precies geschikte afmetingen, zoals bijvoorbeeld lamellen of dorpels, maakt het mogelijk om het frequentiegebied te bepalen waar de geluidsreflectie verandert.
- Het frequentiebereik waar de grootste reflectieve verandering optreedt, moet worden afgestemd op het gevoeligste gehoorgebied van het menselijk oor om de meest langdurig werkzame reflectieverandering te verkrijgen met een akoestisch effectieve gevel.
- Een akoestisch gevelontwerp kan alleen succesvol worden toegepast als het tegelijkertijd aan alle andere fundamentele eisen aan een gevelconstructie voldoet, zoals bijvoorbeeld dichtheid, transparantie en licht. Alleen dan is het mogelijk dat de akoestisch input leidt tot nieuwe spannende gevelconstructies.

Zusammenfassung

Die Silhouetten der großen Metropolen Europas werden charakterisiert durch eine hohe Dichte von Hochhausfassaden aus Glas, Metall oder Stein. Diese große Hochhausdichte steht auf der einen Seite für Wirtschaftskraft und Arbeitsplätze. Auf der anderen Seite sind diese großen schallharten Flächen im Stadtraum verantwortlich für zunehmende Lärmpegel in deren Umgebung. So ist die häufigste innerstädtische Lärmquelle, der Verkehrslärm, doppelt wahrnehmbar. Der Direktschall und der reflektierte Schall addieren sich im Stadtraum. Über diesen Effekt der Pegelerhöhung durch Reflexion an schallharten Oberflächen wird in der Akustik schon länger geforscht. In der Architektur hingegen kommt das Thema der Reflexion von Lärm noch nicht mal ansatzweise vor. Aber gerade die Verdichtungsprozesse in den stetig wachsenden Metropolen stellen die Architektur vor Aufgaben, die sie mit Hilfe ihrer eigenen Werkzeuge nicht lösen kann. So ist das Prinzip der Anordnung der Schlafräume auf der ruhigen Seite eines Gebäudes nur möglich, wenn es eine ruhige Seite gibt. Jedoch sind die Nachverdichtungsgebiete zur Schaffung von Wohnraum oft von vier oder mehr Quellen umgeben. Wobei die Lärmquelle des Flugverkehrs in Metropolregionen die Lage noch zusätzlich verschärft, da diese Lärmart generell von oben auf den Stadtraum einwirkt. Diese Entwicklungen machten es notwendig sich mit dem Thema der Reflexionsfähigkeit von Fassaden in den Disziplinen der Akustik und der Architektur zu beschäftigen. Die grundlegende Frage war:

Ist es möglich eine Entwurfsstrategie zu entwickeln, die in Architekturbüros durchgeführt werden kann und es möglich macht in herausfordernden städtebaulichen Situationen Fassaden für eine ruhigere Stadt zu entwickeln?

Um eine Antwort zu finden wurden beide Disziplinen und ihre Werkzeuge studiert.

In Rahmen einer Literaturrecherche wurden die Ergebnisse der akustischen Forschung zum Thema der Reflexion an städtischen Oberflächen zusammengefasst und untersucht. Die Ergebnisse der einzelnen Forschungen wurden anhand der untersuchten Parameter auf ihre architektonische Bedeutung hin bestimmt.

In mehreren Fallstudien wurde versucht eine Erfassung von bestehenden akustischen städtischen Räumen mit akustischen Messmethoden vorzunehmen. In den Vor-Ort-Messungen wurde die Möglichkeit der Erzeugung von architektonisch relevanten Messwerten für die Wirkung von Fassaden in Abhängigkeit der vor Ort vorhandenen Lärmquellen nachgegangen.

Mit der Labormethode der skalierten akustischen Messung wurde nicht nur die Übertragbarkeit der Erkenntnisse aus den vor Ort Messungen auf den Modellmaßstab untersucht, sondern auch die Möglichkeit einer Anwendung in einem architektonischen Gestaltungsprozess. Es wurden Untersuchungen in den gebäudeplanerischen Maßstäben 1:50 und 1:100 durchgeführt.

Um auch im Detailmaßstab Aussagen treffen zu können wurden in Designstudien Vorschläge für akustisch wirksame Oberflächen entwickelt. Es wurde der Frage nachgegangen wie und aufgrund welcher Parameter Oberflächen gestaltet werden können und wie diese messtechnisch bestimmt werden können.

Als Essenz aus den hier durchgeführten Studien mit dem Thema der Implementierung einer beabsichtigten akustischen Wirkung in einer Fassadenkonstruktion wurde eine Handlungsrichtlinie für zukünftige Projekte entwickelt.

Die Ergebnisse in Kurzform:

- Die Disziplinen der Architektur und der Akustik müssen neue Wege entwickeln um akustisch gesteuerte Bauprojekte in einer wechselseitigen fruchtbaren Zusammenarbeit durchführen zu können. Bauprojekte müssen von beiden sowohl akustisch als auch architektonisch gedacht werden.
- Ein grundlegender Paradigmenwechsel in der baulichen Akustik ist hierzu nötig. Der Übertragungsweg der Schallenergie muss betrachtet werden vom Außenraum zum Außenraum hin und nicht wie bisher vom Außenraum zum Innenraum hin.
- Um akustisch mit der Wirkung einer Fassade planen zu können, ist es notwendig für bestimmte Nutzungen an bestimmten Stellen im Außenraum eine beabsichtigte akustische Qualität zu definieren.
- Die, das Baugrundstück bestimmenden Lärmquellen, lassen sich nur in Abhängigkeit der Lage der geplanten Nutzungen auf ihren Effekt hin bestimmen.
- Die akustischen Werte als Grundlage einer akustischen Fassadenplanung lassen sich nur mit Hilfe einer Mehrkanalmessung vor Ort zuverlässig bestimmen.
- Die Wirkung einer Fassadenfläche kann nur aussagekräftig beschrieben werden durch einzelne Pegelwerte je Frequenzband, in Abhängigkeit eines bestimmten, in der Planung relevanten Reflexionswinkels.
- Alle bekannten und verfügbaren Elemente einer Fassade können, wenn sie in einem bestimmten Winkel zur Schallquelle und der geplanten Außennutzung angeordnet werden, als reflexionsverändernde Elemente zur Reduzierung des Lärmpegels genutzt werden.
- Durch eine geeignete Dimensionierung von den Bauteilen, wie zum Beispiel Lamellen oder Simsbänder, lässt sich ein bestimmter Frequenzbereich der Reflexionsveränderung bestimmen.

- Um eine möglichst langfristig wirksame Reflexionsveränderung mit einer akustisch wirksamen Fassade zu erhalten ist es notwendig den Frequenzbereich der größten reflexionsveränderten Wirkung auf die empfindlichen Bereiche des menschlichen Gehörs abzustimmen.
- Ein akustisches Fassadendesign kann nur erfolgreich eingesetzt werden, wenn es gleichzeitig alle anderen grundlegenden Anforderungen an eine Fassadenkonstruktion, wie etwa Dichtigkeit, Transparenz und Licht erfüllt. Erst dann ist es möglich, dass der akustische Input zu neuen spannenden Fassadenkonstruktionen führt.

1 Introduction

Today's urban centres of major cities in metropolitan regions such as Frankfurt Rhine-Main or Rotterdam The Hague Metropolitan Area, for example, are comprised of high-rises built out of glass, stone and metal façades. On the one hand these high-rise clusters act as landmarks for prosperity and success, representing the attractiveness of the on-going movement into the cities. On the other hand, the façades of high-rises with hard reflective acoustical properties are responsible for increasing noise levels in the vicinity of these buildings. The sound energy emitted from traffic noise sources, e.g. cars, trains or airplanes, is reflected on the hard reflective façades, which redirect the sound energy back to the city ground. The basic acoustic mechanism is shown in Figure 1.1.

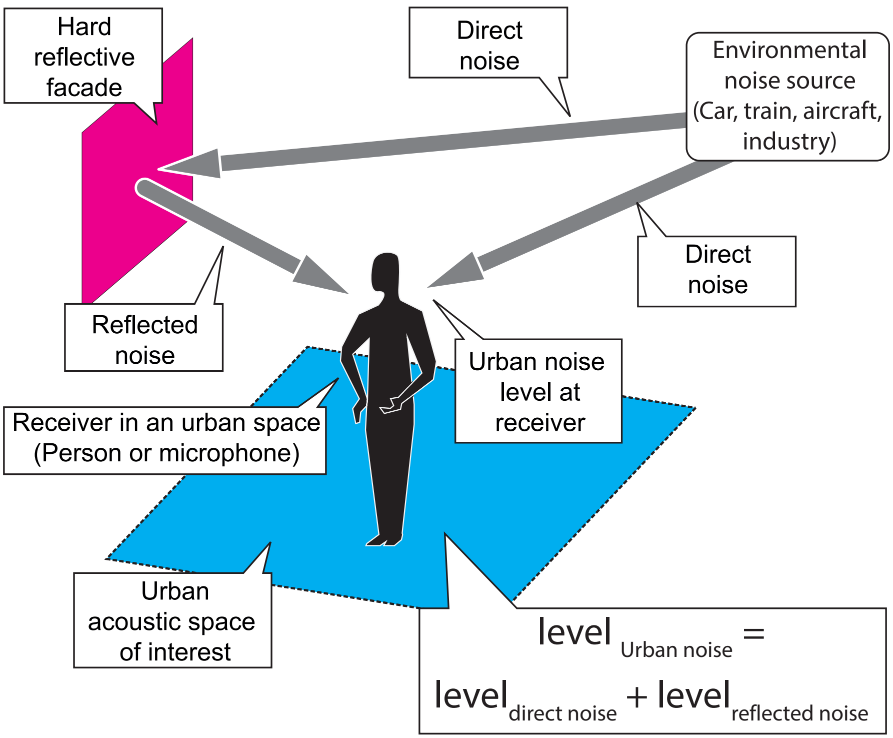


FIGURE 1.1 The basic spatial setup of an urban acoustic space and its comprising elements.

The perceivable and measurable higher noise levels in urban spaces with hard reflective surfaces offer lower amenity qualities compared to urban spaces without hard reflective surfaces. The need for extended transportation capacities in growing cities causes more traffic on the streets and thus intensifies the effect of increased noise levels. Furthermore, the migration to the cities goes in conjunction with a statistically reported growing number of people affected by noise, as new citizens are moving from the blank areas of noise maps to the well-documented metropolitan areas. Although the negative impact of high noise levels on health and general sense of wellbeing are beyond controversy it is often ignored in the process of urban re-densification. In order to cover the demand for new households, former industrial areas close to highly frequented traffic arteries were converted into spaces for living. In these conversion areas, the omnidirectional arrangement of noise sources such as airborne noise or car traffic noise and their reflection on the façades leads neither to urban arrangements with silent indoor areas nor to comfortable quiet areas outdoor. The statistical evaluation of noise maps from 2012 conducted by the UBA showed that 68 % of the population in Germany is affected by one or up to five noise sources. 65 % thereof are affected by two or more noise sources (Myck, 2015). The percentage of the population in relation to the number of noise sources is shown in Figure 1.2.

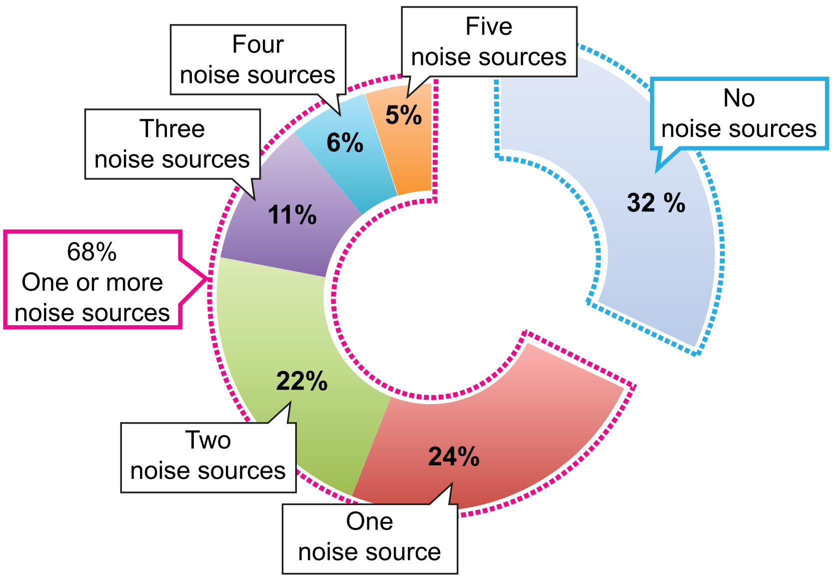


FIGURE 1.2 Results of the statistical noise map evaluation from 2012, drawing based on data from the German Federal Office for Environmental Affairs (Myck, 2015).

In order to define requirements for urban re-densification and the need for silent areas inside and outside of buildings, further design parameters have to be introduced. The façade should no longer be treated as a shelter for the inside only. Beyond its basic functions such as transparency, daylight control, thermal insulation, energy production and water tightness, a façade can also provide an acoustical comfort space outside the building. Engineers and architects cannot modify environmental noise sources, but can influence the impact of buildings on the surrounding urban space by controlling the reflection of noise emissions on urban surfaces. This research introduces an acoustic point of view. The acoustical impact of environmental noise sources on a building was investigated focussing on measurable effects outside the building. For a building design, the acoustical performance of a building should be considered for three cases of sound paths. Up to now only two cases of sound paths are considered in a building project. An evaluation of the sound path from the inside to the inside determines the quality of the room acoustics. The evaluation of the sound path from the outside to the inside or vice versa determines the sound insulation properties of a façade design. The proposal of an acoustically driven façade design process incorporates a change of view on the acoustics. In contrast to the standard practice in building acoustics where the sound energy path is evaluated focussing on the inside, here, the sound energy path is considered from the outside to the outside. The three cases of sound paths are shown in Figure 1.3.

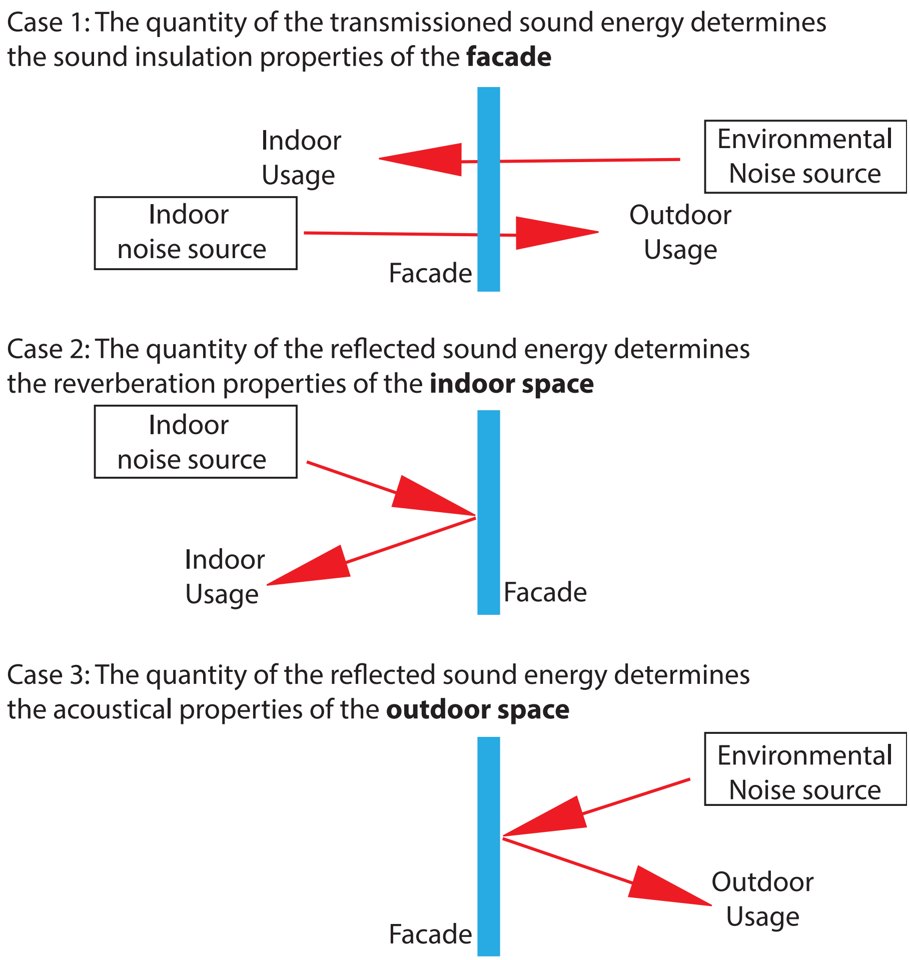


FIGURE 1.3 Three cases of an acoustical investigation in a façade design project.

2 Current status of acoustic urbanism and its relevance

§ 2.1 Societal relevance

In today's European society the growing need for mobility leads to increasing perceivable traffic noise levels in major cities and, thus, an increasing percentage of inhabitants is impaired by city noise levels. The increasing impact of environmental noise on the health status of a city population is evident in several studies conducted throughout the last years. The results of the WHO study „Burden of disease from environmental noise“ from 2011 have been presented as a number of lost healthy life years (WHO, 2011). The number of lost healthy life years in relation to specific environmental impacts was calculated by linking population statistics with the output of medical studies on specific diseases. For example, available medical studies on ischaemic heart diseases were analysed and summarized in relation to environmental noise. Based on this evaluation of medical statistical data the authors of the WHO study are coming to the conclusion that in the western countries of the European Union 60,000 healthy life years were lost to ischaemic heart diseases caused by environmental noise. For the overall effect of noise annoyance, the number of 645,000 lost healthy life years was calculated (WHO, 2011: 102). Based on this study, environmental noise became number two on the list of health risks in the EU. Beyond this fact, the medical studies included in the WHO study have shown that there is a relationship between noise impact and high blood pressure diseases. (WHO, 2011: 23). The relation is shown in Figure 2.1.

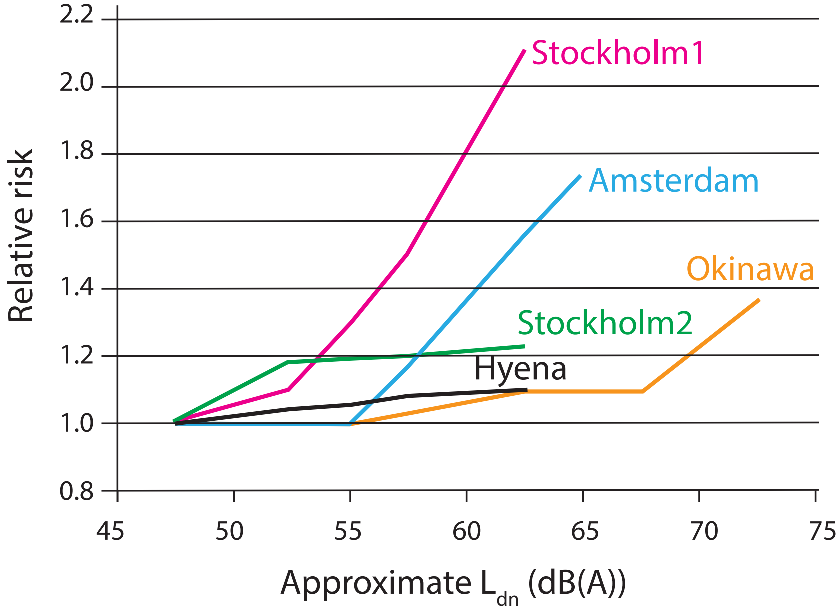


FIGURE 2.1 The relationship between the incidence of high blood pressure and aircraft noise levels. Graphic based on the work of Babisch (Babisch & Kamp, 2009).

In further studies, Babisch et al. were investigating this relationship in detail. They came to the conclusion that the impact of environmental noise is linked to heart disease but the role of the main factors of noise level and noise annoyance remains unclear with regard to their weighting and interaction (Babisch et al., 2013).

In the framework of the more recent NORAH study from 2015 the relationship between high blood pressure and noise levels was investigated in a sub study. In the NORAH study multiple research and survey methods were included for monitoring the noise related effects in the Rhine Main Area. The NORAH blood pressure study could not verify a direct connection between noise levels and higher blood pressure levels (Eikmann et al., 2015). Thus, the interaction of noise annoyance and higher noise levels remains unclear regarding their impact on the population. But it remains clear in all studies that there is a link between noise and diseases.

The specific long-term study design of the NORAH study delivered remarkable results, not only on the relationship between noise and a risk of disease, it also delivered a broad insight into the impact on cognitive processes. In the „child study" the relationship between noise exposure and reading abilities among 1,243 second grade pupils in primary schools was investigated. The data shows a link between higher noise level exposure and lower reading abilities (Klatte, Bergström, Spilski, Mayer & Meis 2014).

As the NORAH study took place in the Rhine Main area before and after the opening of a new runway at Frankfurt Airport, a comparison of the psychological quality of life before and after the opening of the runways was feasible. In 2011, the introduction of the new runway North West and the required new flight routes resulted in a greater coverage of residential areas by aircraft noise. This lead to an increasing noise annoyance among the residents of the whole Rhine Main area. To describe the noise annoyance, the psychological quality of life was quantified in a survey. The results of the psychological quality of life study show that the noise annoyance decreases over time. After the first year of the runaway being active, in 2013 the psychological quality of life rate was below the values reported before the opening in 2011 (Schreckenberg, Faulbaum, Guski, Ninke, Peschel, Spilski, & Wothge, 2015). The highest values were reported for 2012. This was the first full year of the runway North West being active. Refer to Figure 2.2.

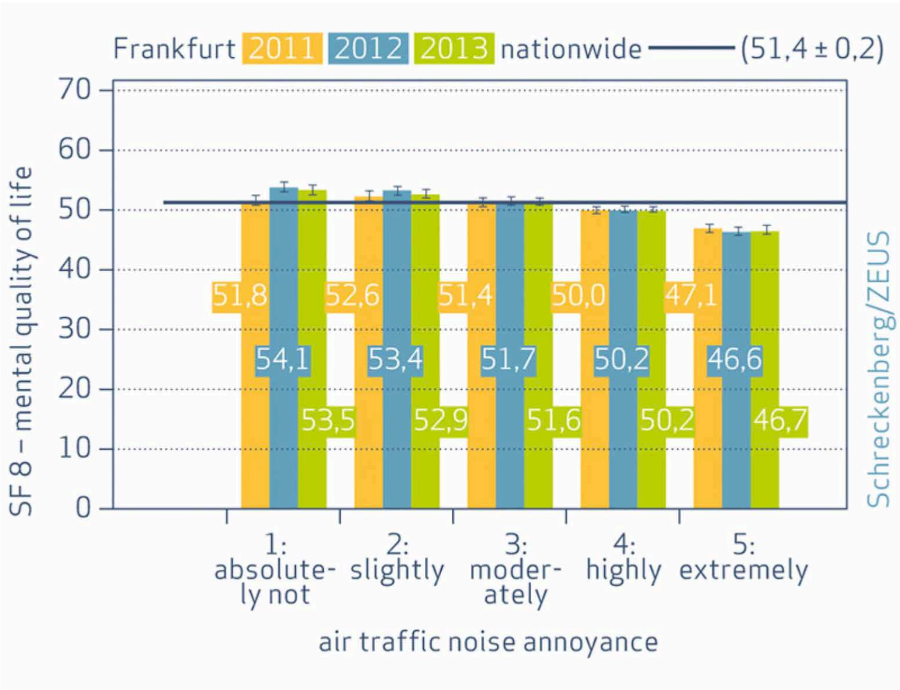
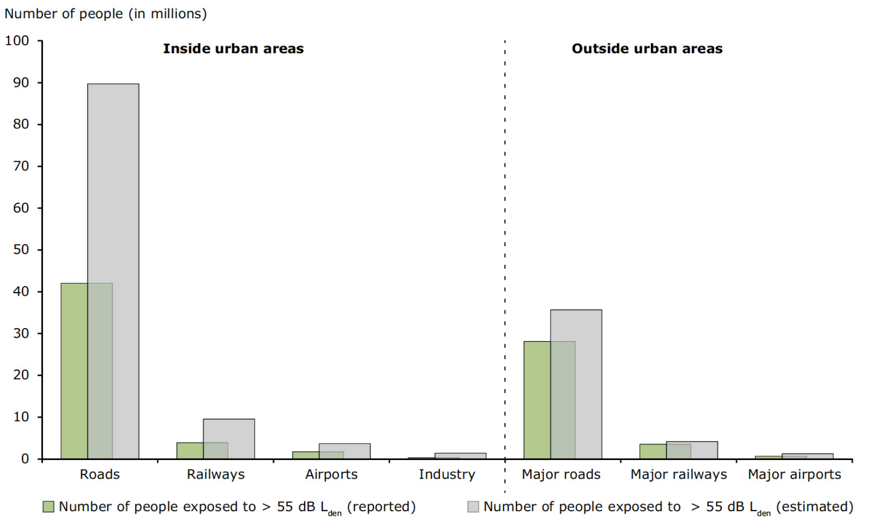


FIGURE 2.2 Bar graph of the NORAH study depicting the reported psychological quality of life in the years 2011, 2012 and 2013.

The report of the European Environmental Agency (EEA) „Noise in Europe 2014" documents the recent status of environmental noise with regard to the environmental noise sources of road traffic, railway traffic, air traffic and industrial noise. In order to quantify the noise annoyance in EEA member countries this report documents the statistically reported number of affected people as well as an estimated number of people. The calculated number of noise affected people is reported by the statistics of the EU regulated noise mapping process. Taking the limitations of the noise mapping into account generates the estimated values. The column graphs in Figure 2.3 depict that more than 40,000,000 people are exposed to noise levels above 55 dB L_{den} within urban areas. The estimated value is 90,000,000 people in Europe being exposed to noise levels above 55 dB L_{den} (European Environmental Agency [EEA], 2014).



(²) Urban areas are described in the END as 'agglomerations', meaning the part of the territory, delimited by the Member State, having a population in excess of 100 000 persons and a population density such that the Member State considers it to be an urbanised area. Noise mapping outside urban areas is restricted to major infrastructure.
(³) 55 dB L_{den} is the EU threshold for excess exposure, indicating a weighted average during the day, evening and night.

FIGURE 2.3 Number of noise exposed people in urban and rural areas. Based on (EEA, 2014).

The estimated exposure value within urban areas is more than twice as much, as some characteristics of the noise mapping do not represent the daily practice in urban agglomerations. The estimated value is based on the assumption that many people are not included in the statistics because of the limited coverage of the noise map procedure. Furthermore, the statistics of the noise mapping only count inhabitants.

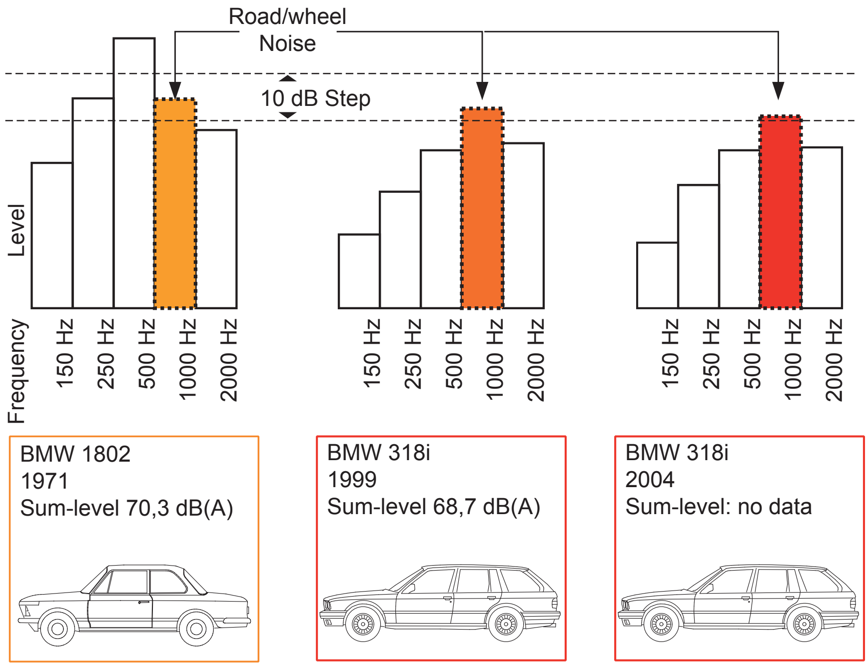
The temporarily present people, for example commuters or tourists are not represented in the noise map data. The graphs further depict that the noise exposure is a serious problem for urban areas. The estimated value for within urban areas is approximately three times higher than for outside urban areas.

Taking all these studies into account it is beyond controversy that the detected unhealthy effects are directly linked to the quality and quantity of noise sources.

However, the rising number of harmed people in the statistics cannot be solely linked to a growing number of noise sources. The reported growing number of noise-annoyed people in the official statistics is also linked to the rural depopulation. The on-going process of migration to the cities reported by the statistics provided by PBL Netherlands Environmental Assessment Agency is similar to an exchange of opposed acoustic environments (Nabielek K. et al., 2016).

The acoustical environment of a rural area is typically comprised of one or two noise sources, whereas the acoustical environment of a typical urban area is comprised of up to five noise sources. As the European Noise Directive (END) regulated that noise map statistics are only mandatory for cities of more than 200,000 inhabitants, the rural depopulation contributes to a growing number of people stressed by noise in the available statistical data (European Parliament and the Council of the European Union [EU], 2002). The lack of a noise mapping calculation of roads below a number of 8000 cars a day also distorts the statistical overview by excluding the countryside from the statistical records.

The negative effects for people moving to places comprised of multiple noise sources are intensified by technical limits of the noise emitting transportation systems. The achievable noise reduction in the development of noise abatement solutions is affected by its immanent physical limits. The road traffic noise is determined by two system immanent borders, which prohibit a successful introduction of meaningful noise reduction measures. Considering that the road wheel noise above a driving speed of 50 km/h mainly contributes to the resulting road traffic noise level, only an overall exchange of tires or paving can obtain a perceivable noise level reduction. Figure 2.4 shows the development of car noise over the timespan of 33 years. The road wheel noise remains at a constant level.



Bargraph drawing based on ATZ 6/2004,Volume 106, p 564, figure 2 and Vieweg Handbuch Kraftfahrtzeugtechnik, 6. edition 2011, p 77

FIGURE 2.4 Development of road wheel noise, emission comparison between a 1971 model, a 1999 model and a 2004 model (Biermann W., Beckmann T., Wech L., Meier R).

In Germany, for example, there is no feasible option to change 62.600,000 cars from conventional tires to more silent ones in a reasonable time period. Considering the practical impossibility to change 350,000 km of standard road paving in Germany into silent road surfaces, the time period for a perceptible change of traffic noise has to be extended on the scale of decades. The widely used argument of electric cars as a noise reducing factor has no significant impact either, because the road wheel noise of an electric vehicle is very similar to a conventional combustion engine driven car above a driving speed of 50 km/h. With the number of 34,022 e-mobiles and 165,405 hybrid cars running on German roads in the year 2016, the electro mobility indicates rather no effect on a change of a noise level emitted by 62,600,000 conventional vehicles. The Federal Motor Transport Authority (KBA) provided the statistical data regarding the car traffic in Germany (Federal Motor Transport Authority, 2017).

These considerations and study results demonstrate that there is a need to obtain control on environmental noise. One of the major determining factors will be the production of less noise emitting vehicles or attractive public transport systems. The major determining factors have to be developed by the industry as well as by society.

Traffic development and urban development in this context have a big impact on the constitution of tolerable environmental noise settings but, as of today, they are no comparable considerations in architectural or building engineering tasks.

§ 2.2 Architectural relevance

Keeping track of the development in urban agglomerations highlighted the fact that in the field of architecture there is no solution for the rising number of noise stressed people.

Some efforts were made to come up with solutions for buildings in relation to one strong noise source. Among others the research conducted by L. Nijs and F. Kranendonk „Akoestisch optimaleoriëntering van bouwmassa's nabij verkeerswegen" (Nijs & Kranendonk, 1979) and „Reclaiming land from urban traffic noise impact zones" by Arc de Ruiter can be mentioned (de Ruiter, 2004). The research of Martijn Lugten „re-sil(i)ence, design patterns for an aircraft noise abating spatial environment" from 2014 focussed on aircraft noise and the urban plot (Lugten, 2014). Among others, these researches only represent a small part of urban settings in metropolitan regions. Thus, they provide solutions for only a part of the noise problem, and they are not linked to on-going developments in metropolitan regions. Here, more and more urban situations are comprised of two or more noise sources around one receiver.

The following examples from the metropolitan region Rhine Main show that the redensification process of urban areas triggers this development. In order to provide more residential living spaces, office or industrial buildings were converted into spaces for living. Three exemplarily examples located in the city of Frankfurt/Main are shown in Figure 2.5 and Figure 2.6. In these examples two or more noise sources can be detected at one receiver point. Figure 2.5 shows the development area „Lyoner Strasse". Here, abandoned office buildings are going to be converted into apartment buildings. According to the business optimized urban planning from 1962, the former called „Office Town Niederrad" is situated in short distance to all important traffic infrastructures such as airport, train station and motorway. The result is a projected conversion area for 3000 apartments surrounded by up to three or more heavy noise sources: the aircrafts approaching Frankfurt Airport, the motorway A5 and the railroad tracks.

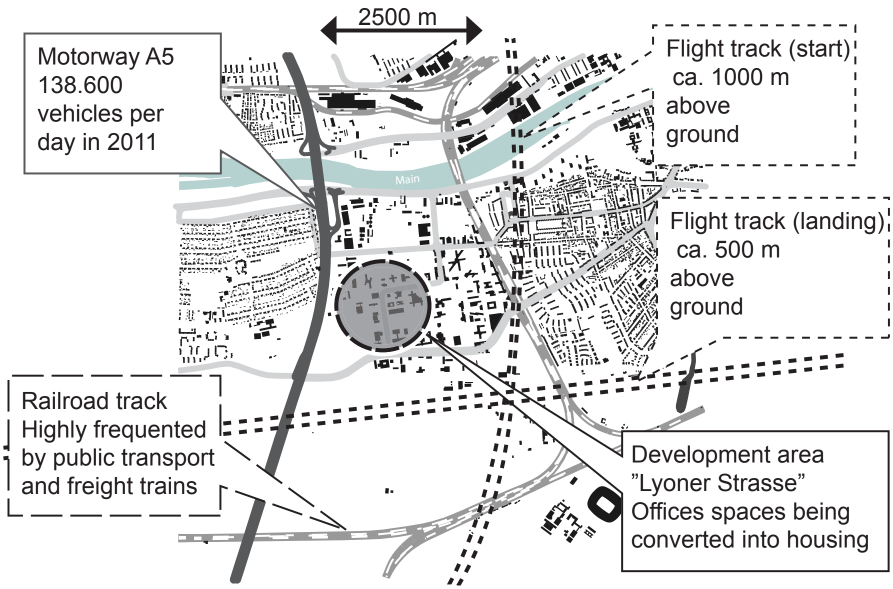


FIGURE 2.5 The situation around the conversion project area of „Lyoner Strasse" in Frankfurt/Main. Drawing based on maps provided by Stadtplanungsamt Frankfurt 2015.

Another redensification strategy is the replacement of workshops located in the courtyards of apartment buildings. Figure 2.6 shows two conversion areas of former industrial or workshop usage. The new housing areas in Frankfurt/Main Sachsenhausen are located very close to the main railroad tracks to Frankfurt main station. The nearby flight path with aircrafts flying at 600 m above ground contributes even more high noise levels to the urban acoustic space there. This noise source - receiver setting results in perceivable noise levels outdoors or indoors far above the minimum comfort levels of 55 dB.

In addition to these developments, the tools that were used for building in such noisy areas until now, are outdated. The architectural tool of arranging rooms in a floor plan regarding their silence requirements is no longer practicable. In an environment with noise sources emitting sound energy to all cardinal points around a residential area, a bed room, for example, can no longer be arranged at the silent face of a building if there is no longer a silent face available. These noise sources interfering from many directions have to be in the focus of urban designs with the aim to develop a new set of architectural tools concerning the transformed situation in dense cities.

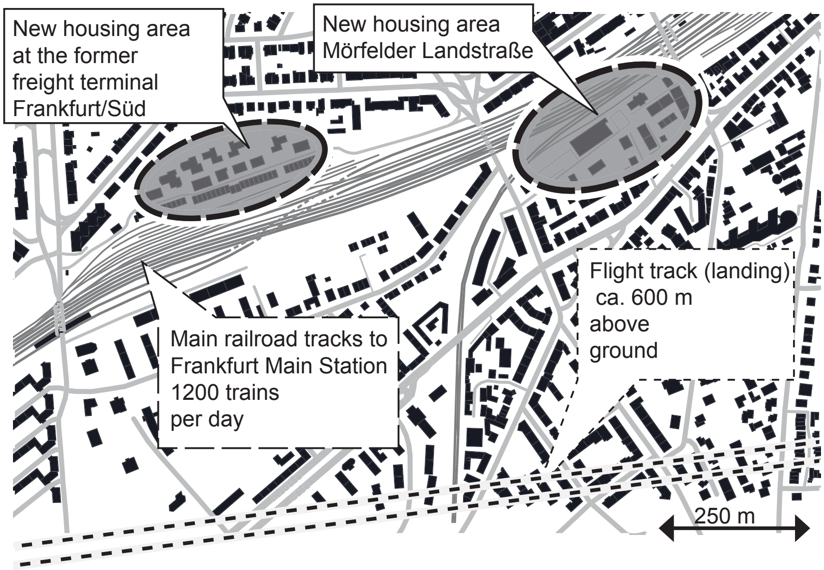


FIGURE 2.6 New housing areas in Frankfurt/Main close to the railroad tracks and flight paths. Drawing based on maps provided by Stadtplanungsamt Frankfurt 2015.

Other developments amplify the level of traffic noise in our city centres. The EU guided noise mapping of major cities shows that noisy city centres are mostly comprised of high-rises with large façade surfaces. For economic reasons, the building industry kept building more and more high-rises and even more glass façades, because of their rental space saving type of construction.

The high-rise development in New York is on the same track. More and more hard reflective façades were introduced in the gaps of the existing historical high-rise structure. One example is the Tribeca tower by Architects Herzog & de Meuron. Eight storey buildings surround the 250 m tall glass apartment tower (Alexico group, 2017).

The rapid growthof hard reflective façades inside urban areas in the area of Frankfurt/ Main is depicted in Figure 2.7. Over the 37 years spanning time period between the two pictures, the Frankfurt city high-rise cluster has grown continuously to its current size. And it is still growing. Five new high-rise building with a height above 100 m are projected for the area of the high-rise cluster in the centre of Frankfurt/Main (Wutzke, 2017).

FIGURE 2.7 A comparison of the high-rise cluster at the Taunusanlage in Frankfurt/Main in the years 1985 and 2017. The Helaba high rise with its rigid elevator core can be seen in the centre of both pictures. Picture on top: copyright Stadtarchiv Frankfurt am Main.

This redensification is also visible in realised refurbishment or replacement building projects. The Skyper high-rise project is presented exemplarily for this development in Figure 2.8. A formerly structured façade from the seventies with stone covered stringcourses is substituted by even more space covering glass façades comprised of huge, storey-high glass elements.

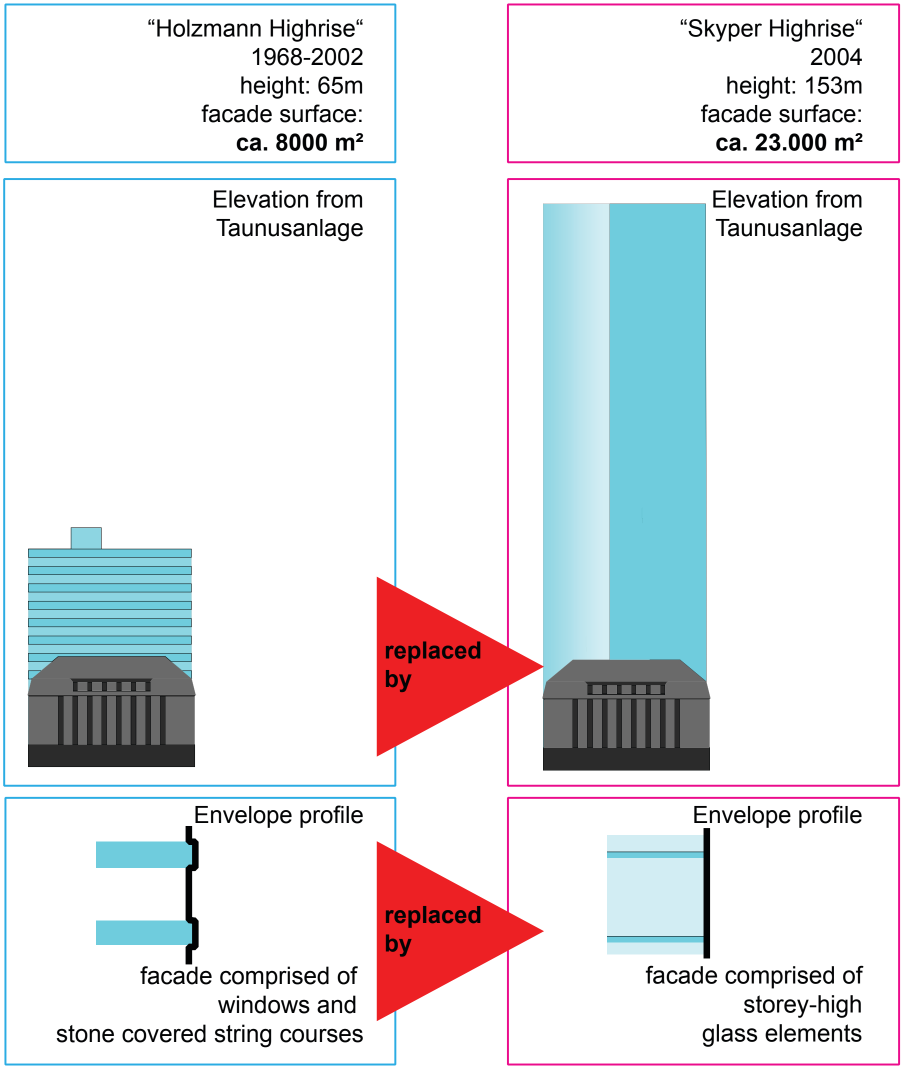


FIGURE 2.8 Example of a high-rise development

When analysing these developments regarding the introduction of new high-rises, it becomes evident that the design practice is not up to par with regard to environmental noise determining factors. The ongoing developments are forcing the urge to introduce façades with a defined acoustical effect on the urban space.

Architects and engineers must keep track of the actual developments in society in order to control the impact of environmental noise with the building façade.

Up to now, in Germany, for example, no regulation or code exists that can be applied, taking the acoustical effect of reflecting noise into the urban space into account. This research does not aim at introducing additional codes and regulations for the building industry, but at a better understanding of the impact of a building on the urban acoustic space.

§ 2.3 The urban acoustic space and architectural means / Scientific relevance

Throughout the last 50 years multiple research was conducted on the topic of noise impact on urban spaces covering several aspects.

The influence of a façade on an urban acoustic space was investigated and determined in relation to the prediction of resulting noise levels. In the early investigations of urban spaces, the focus lay on the range of acoustic signals in street canyons and on the speech intelligibility over distance. In 1965, Wiener, Malme and Gogos conducted a research focussed on the range of acoustic signals in an urban setting (Wiener, Malme & Gogos, 1965). Lyon investigated the influence of multiple reflections and their influence on the sound propagation in an urban space. Among others he recommended the scaled model measuring technique as a promising tool for a precise sound propagation in three dimensions (Lyon,Pande & Kinney, 1971; Lyon, 1974). Bullen and Fricke introduced the scattering on façades to their sound propagation model (Bullen & Fricke, 1976). In 2001, Picaut and Simon proved that a given structured façade with its reflection abilities could be replaced by pure geometry Picaut & Simon, 2001). Van Renterghem and Botteldooren are treating the green façade or green roofs in a suburban housing setup with different simulation and measurement methods (Van Renterghem & Botteldoren, 2008; 2009; 2011). In the research of Schiff, Hornikx and Forssén, the concept of noise transmission between shielded canyons was simulated with numerical and measurement methods (Hornikx & Forssén, 2008; Schiff, Hornikx & Forssén, 2010). These research projects investigated acoustics and related methods, but not the architectural aspect thereof. The scale of the urban situations in these researches is linked to smaller rather than major cities and their high-rises. Furthermore, nearly all researched simulation methods except the scaled model measurement remain in two dimensions. From this research a lot of proposals for investigating urban spaces with various simulation or measurements methods can be derived. Only in few cases recommendations for a façade design were made based on the achieved results. Thus, until now the impact of urbanisation and the influence of the façade on an urban soundscape were neither considered seriously as architectural design parameters nor translated into an architectural language for designing façades. This was not to be expected, since the discipline of architecture should be in charge of translating the acoustical results into architectural solutions.

In order to establish a relationship between the field of acoustics and architecture, the underlying spatial settings, the dimensionality and the results of the studies were investigated. The aim of this literature study was to establish a connection between architectural and acoustical research topics. As the focus for the selection of the researches was on built structures, building additions or material properties on various scales, this selection of 70 articles does not represent every research on urban acoustics. For this literature study 70 articles touching the topic of façades in relation to urban space and noise spreading were evaluated regarding the following architectural parameters.

Building height

Every study is based on a spatial arrangement that represents a model situation or an existing urban setting. In the first step the number of storeys of the buildings were analysed. If there was only information on the building height provided, the building height was divided by an average storey height of 3.2m. The resulting value was rounded to achieve an integral value. In the case of different building heights in one study, the maximum value for the number of storeys was taken.

Scale of the intervention

This represents the size of the object, which caused the change in the investigated spatial setup. In some of the investigated studies introducing a different setting of buildings caused the change of noise levels. This represents the urban planning scope. The building planning scope is represented by the introduction of façades with specific geometries or material properties. The addition of elements such as balconies, for example, are also part of the building planning scope.

Measured, calculated or simulated noise level reductions

The reported mean levels for a possible level reduction according to a change in the spatial setup or the introduction of material with absorbing properties.

Dimensionality

In the studies the chosen spatial setup was investigated with various calculation or simulation methods. Some of these methods represent a three-dimensional approach, others remain in a two-dimensional, section-wise approach. This divides the research in two groups: The group of the three-dimensional approach (3D) and the two-dimensional approach (2D). A typical 3D approach in urban acoustics is the scaled measurement method. For the group of the 2D approach, the problem occurs of transferring the acoustical findings from 2D into the 3D world. The gap between a 2D and a 3D approach has to be bridged. The following example illustrates the gap between a 2D approach and a 3D building project in reality. Figure 2.9 shows a section through an urban canyon with a façade shapes based on the work of Echevarria Sanchez from 2016 (Sanchez, Rentergehem & Botteldoren, 2016).

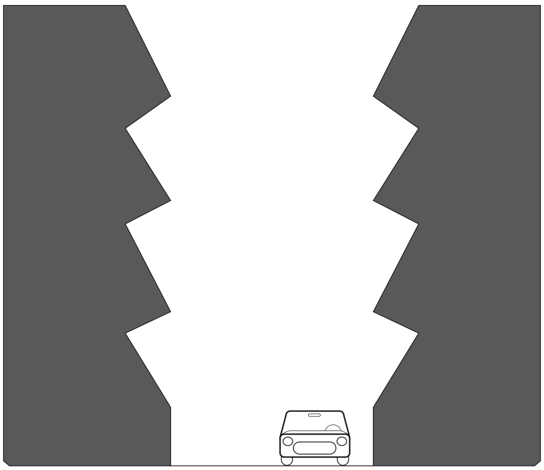


FIGURE 2.9 Urban canyon with façade shapes based on the work of Echevarria Sanchez from 2016

Simulations of these 2D façade shapes calculated a level reduction of 9 dB. But the simulation for the section of the urban canyon is only valid in 3D under specific conditions. The elongation of the intended building has to be infinite or at least very long. The section has to be similar for the whole length of the building. The 3-dimensional appearance of such a building is shown in Figure 2.10.

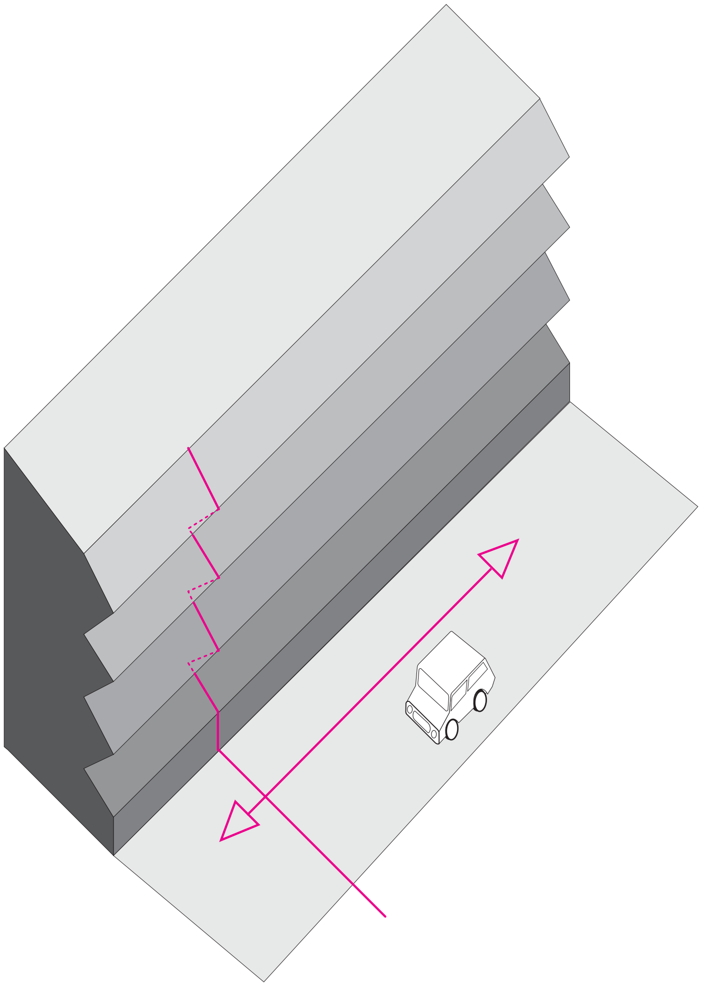


FIGURE 2.10 Perspective view of a long building with a constant section

In the daily practice of architects and engineers these types of building are not represented. In new projects or in façade refurbishment projects only a part of a building block is under development by one contractor. Thus, from the intended ideal infinite building only a part remains for the introduction of an acoustically effective façade. The realistic situation is shown in Figure 2.11.

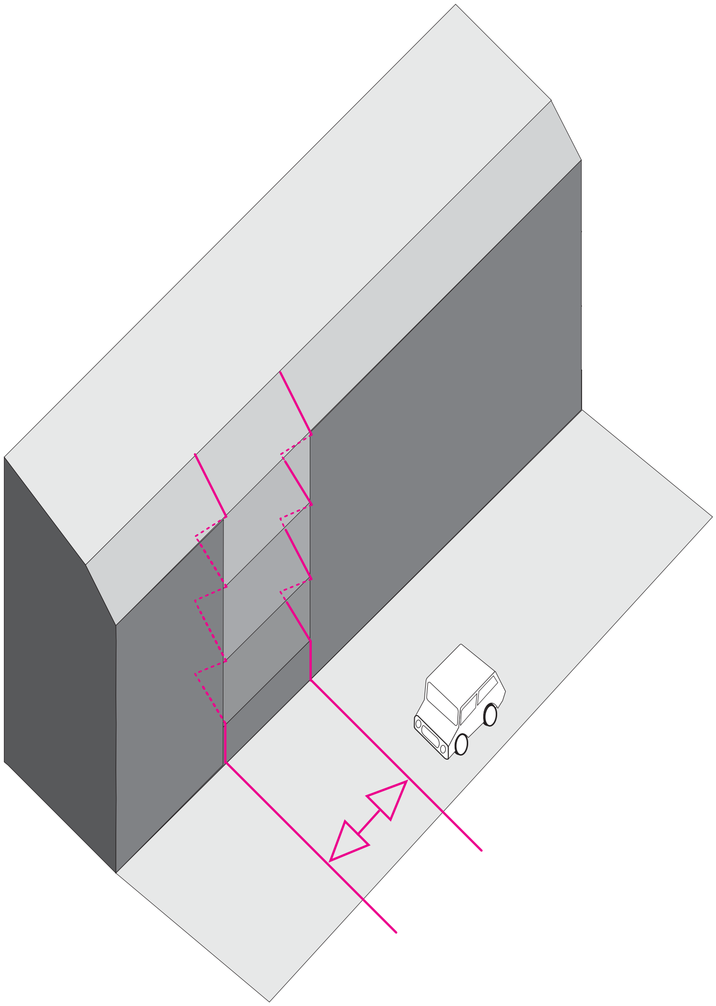


FIGURE 2.11 Realistic situation of part of a building block being in the planning scope of a project.

But what is the impact on the intended acoustical effect if only a part of the building block is available for an acoustic intervention? J. Kang postulates that a 2-dimensional approach is important anyway as it could reveal trends regarding the quality of the effect (Kang, 1999). Being faced with the urge for realisation, the question is whether a trend in 2D also occurs in 3D.

Results:

The bar graphs in Figure 2.12 show that over the years the conducted research was focused on multi-storey buildings with 3 or 6 storeys.

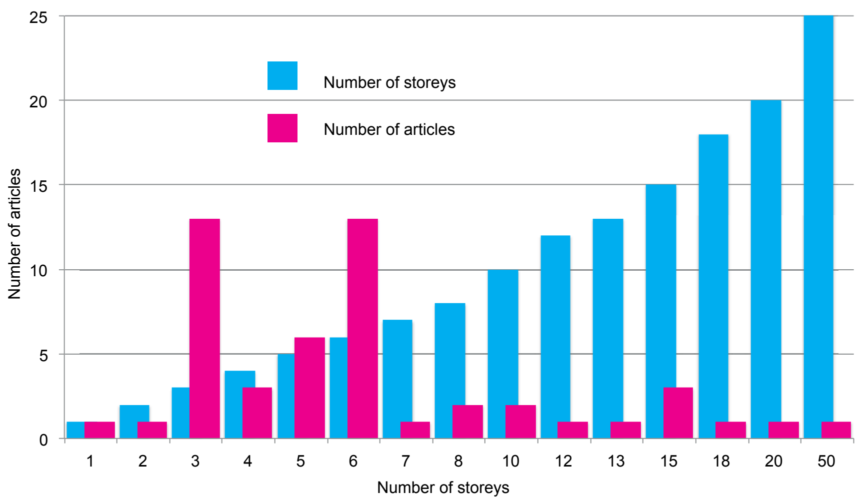


FIGURE 2.12 The bar graphs show the numbers of articles in relation to the number of storeys.

Figure 2.13 shows the reported level reductions in relationship to the planning scope of the conducted research cases. For the group of research in the urban planning scope a smaller range of level reduction was found than in the group of the building planning scope.

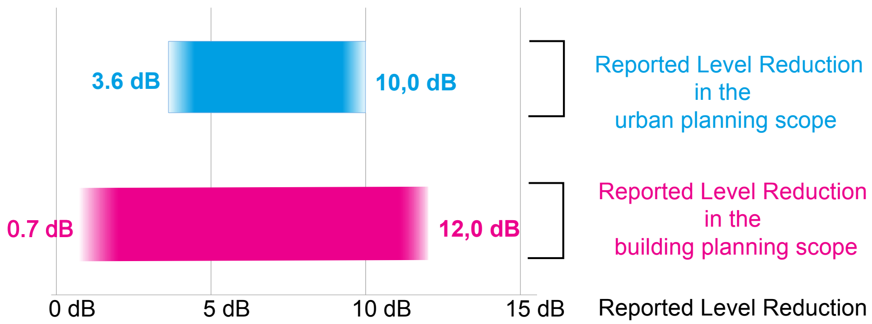


FIGURE 2.13 Reported level reductions in relationship to the planning scope of the conducted research case.

As there is only a slight difference between the reported level reductions in the urban and the building planning scope, both planning scopes bear the same potential regarding an intended acoustic intervention. Thus, it must be feasible to achieve significant level changes with modified façades even in existing urban settings.

The reported level changes of the building planning scope were derived from a broad set of interventions. The minimum level reduction of 0.7 dB was reported for the introduction of a vegetated façade in an urban canyon under realistic conditions (Smyrnova, Kang, Hornikx & Forssen, 2012). The maximum level reduction of 12 dB was reported for the introduction of absorbing material on balcony surfaces of an 18-storey apartment building (May, 1979). Despite the fact that this research conducted by D. May dates from 1979, it is not out-dated. The research represents solutions for the current, ongoing development of apartment high-rises, which are continuously built in metropolitan regions.

According the dimensionality, Figure 2.14 is depicting that the 2D approach is represented more in the urban planning scope while the 3D approach is represented more in the building planning scope. A reason for the shift of the focus can be explained with the use of the scaled model measurement method as a 3D approach. It is impractical to downscale complete urban scenarios and meeting the requirements for the scaled measurement of them.

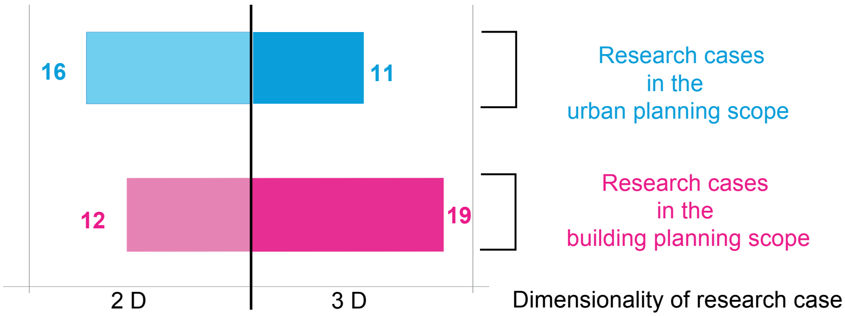


FIGURE 2.14 The dimensionality of the research case in relationship to the planning scope.

The trends of 2D simulation approaches could only be used for proposing an acoustic intervention if they were translated and proofed in a 3D environment.

3 Research objective

The main objective of this research was the development of methods to implement an acoustically driven façade design approach in building design processes. With these methods it should be feasible to quantify the acoustical effects of façades on urban spaces and to determine suitable façade designs for quieter cities.

The aim of this project was not exclusively the development of new surfaces for building envelopes. In order to achieve long-term establishment of an acoustically driven design in the field of architecture, methods were developed with a focus on feasibility and suitability for daily use in a design process. Requirements for a low threshold implementation of new methods regarding the acoustical driven façade design were defined minimizing financial and human resources:

- Typical outcomes of an architectural or engineering design process e.g. scaled models, drawings, and digital 3D models; should be produced with properties suitable for the use in acoustical investigation or measurement methods.
- Open source software should be use first if suitable for acoustical investigations or measurement methods.
- Smartphones should be used instead of or in addition to professional measurement equipment if suitable for acoustical investigations or measurement methods.

High-rise façades were in the focus of this research not only because they constitute the major share of hard reflective vertical urban surfaces. Due to their exposed setting they are important for the impact of nearby inner-city noise sources and distant noise sources. Furthermore, the prestige and the particular attention to high-rise projects provide an opportunity to introduce new aspects to their design.

§ 3.1 Hypotheses and research question

These underlying hypotheses set the basis for this dissertation:

- The development of façades with a defined acoustical impact is feasible within a building design process by introducing extra acoustical investigation methods.
- By using these acoustically effective façades it will be feasible to transform acoustically uncomfortable high-rise comprised urban spaces into more comfortable spaces with improved amenity qualities.
- A successful implementation of extra acoustical investigation methods will only be feasible, if the acoustical investigation methods are at a low level regarding the demand for extra money, material and human resources.

The approach to substantiate the hypotheses was divided in several steps.

- As this research combines the field of acoustics with architecture the status quo of both fields and the relationship between the two fields has to be determined.
- Acoustical investigation methods have to be evaluated regarding their relevance of the results and their feasibility.
- A general façade design strategy for dealing with acoustical issues in challenging urban situation has to be developed by linking these findings and evaluations.

In general, according to the hypothesis the research question is:

How can an acoustically effective façade design approach be developed, which covers the requirements of today's architectural practice and meets the environmental demands for quieter outdoor urban spaces in challenging urban situations?

§ 3.2 Methodology of the research steps

Methodology for the definition of the relationship between architecture and acoustics and their status quo. (Chapter 2: Current status of acoustic urbanism)

How can the status of acoustic urbanism and the relationship between the fields of architecture and acoustics be analysed and evaluated?

In the first step a literature research was conducted with focus on the investigation of urban acoustic spaces in the discipline of the acoustics. In a second step the investigated objects and their results were evaluated regarding their relevance for architectural production in metropolitan regions. This created a broad overview on the existing data on urban acoustics. Furthermore, this delivers an overview of the data, something not yet available regarding the task of an acoustic driven façade design.

Methodology for the evaluating of acoustical investigation methods regarding their results and their feasibility (Chapter 4: On-site measurements/ Chapter 5: Scaled measurements/ Chapter 6: Design studies – design proposals/ Chapter 7: Design studies – laboratory methods)

How can acoustical investigation methods be evaluated regarding their suitability and feasibility in an architectural design process?

The method of conducting case studies and analysing the processes was used to answer this question. The well-known acoustical investigation methods of on-site measuring, scaled model measuring, and surface properties measuring were linked to the typical scaling of products within an architectural design process. In order to reduce the restraints regarding complexity, time and money the attempt was made to simplify the methods. The methods were then evaluated regarding the significance of their results and their precision. The conducted case studies and the evaluation of the acoustical investigation methods provide insight in possible synergy effects between the productions of both disciplines. Furthermore, it showed the effect of simplifications on the results of acoustical investigation methods and their possible influence on an architectural design process.

The results from the literature research and the case studies were merged to answer the question: How can a general acoustic driven façade design strategy be developed? (Chapter 8: Research outcome)

Based on experiences and data of the conducted case studies a strategy for the acoustical investigation methods in combination with architectural investigation methods was proposed. The attempt was made to strengthen the acoustical point of view by reinforcing the synergies between the disciplines of acoustics and architecture.

§ 3.3 Framework of this research

The research was carried out at the Frankfurt University of Applies Sciences in the period from 1. August 2013 to 30 March 2016. The first project partner Fraport AG funded the research project over the whole period. The second partner involved in this research as a strategic partner was the Office for Environmental Affairs of the City of Frankfurt contributing data and knowledge to this research. At both cooperation partners, contact persons were physicists or environmental engineers involved in noise abatement programs. With their experience and knowledge, they supported the project with fruitful discussions.

The major part of the research case studies was conducted in the area of Frankfurt / Main because of its unique situation of a high-rise cluster in the city centre surrounded by green areas or historical buildings. Also, the spatial arrangement and traffic volume of the existing noise sources in the area of Frankfurt / Main is unique: Frankfurt airport (160,000 passengers a day in 2016), the „Frankfurter Kreuz" (310,000 cars per day) and Frankfurt Main station (450.000 passengers per day) located within 8 km. The urban setting of multiple noise sources and high-rises characterises European metropolitan regions. As Frankfurt / Rhine Main represents one of the European metropolitan regions, the tools developed in this research are transferable to other metropolitan regions in Europe.

A part of the laboratory studies was conducted at TU Delft, Institute for Imaging Physics. The other part of the laboratory studies was conducted at the German Federal Highway Research Institute. At both institutes, the topic was further discussed and developed during extensive discussions with experts in the field of acoustics.

§ 3.4 Limitations of this research

This research's focus is on high-rise façades. Because of their exposed setting they are important for the impact of not only nearby inner-city noise sources, but also of distant noise sources into the urban space. High-rises in this research context are buildings towering above the surrounding city structure with a height of more than 22 m above ground level.

The research is not able to cover all types of noise sources in all types of urban settings. Exemplarily case studies were conducted with the focus on the reflection effect of high-rise façades in relation to car traffic noise or aircraft noise.

The research was focused on the detection, determination and transforming of the acoustical effect of reflected noise. The acoustical effect of diffraction was neglected in this research to sharpen the approach for new acoustically effective façade surface designs. The controlling of the diffraction effect with a specific façade design should be part of future research projects in the field of urban acoustics.

The design studies in this research were only geometry-based designs for several reasons:

- If a geometric design works properly, the introduction of absorbing surface properties will improve the possible level reductions. Level reduction effects caused by destructive interferences were not considered as important in this context as they are located in very small spots regarding the matching of time and phase there.
- Many restraints exist in the architectural context for the introduction of open porous materials to façade designs: dirt, appearance, fire resistance and durability. Excluding the introduction of open porous absorbing materials will deliver a set of geometry based designs. The introduction and development of open porous materials on the outside of buildings should be part of future researches.
  This research will not propose solutions for all kind of façades.

Acoustic simulations with noise mapping software, OPEN PSTD or indoor acoustic simulation software were excluded from this research for several reasons:

- Ahead of an intended noise map calculation, many presumptions have to be made in order to define the acoustic setup in the simulation environment. The work of Jäschke shows that even in the highly regulated EU noise mapping process based on the European Noise Directive (END) the operating engineers have to decide on the setting of 50 parameters (Jäschke, 2015; EU, 2002).
- In the noise mapping software, it is not possible to introduce specific façade designs. The parameters of an intended façade design have to be defined by a comparison with known acoustical elements e.g. noise cancelling walls. This turns the basic idea of testing acoustic performance during a design process upside down as the designing engineers must know in advance how the intended façade design will perform acoustically before they can simulate the performance of the acoustic design.
- OPEN PSTD simulations were not included in this research as the results are currently only 2D or 2.5D. Furthermore, this highly specialised simulation tool is under development in many research projects and not yet available in the market as a user ready simulation software.

– With indoor acoustic simulation software, it is possible to introduce different façade geometries with specific absorption qualities but regarding the intended outdoor simulation environment many assumptions have to be made to match an existing outdoor environment. E.g. outdoor noise sources as cars, aircrafts and trains can only be represented in the simulation environment by manipulated indoor noise sources like loudspeakers. Nevertheless, this is the most promising type of software as the introduction of façade geometries and surface properties is analogue to common architectural drawing software. With regards to its relation to other simulation software tools and the complexity of them the introduction of indoor acoustic simulation tools to an urban acoustic design has to be part of a new research.

§ 3.5 Glossary

Acoustical events in this context are sound events, which can be determined by the human ear regarding their duration, location and intensity.

Acoustically effective façades minimize the impact of environmental noise sources on people in their vicinity through defined absorption properties or controlled reflection capabilities of sound energy.

Acoustical mechanism: The acoustical mechanism of an urban acoustic space or an acoustic environment is defined by the interaction of noise sources and façades. An acoustical mechanism is based on a combination of the acoustic principles of sound transmission on the direct path or on the indirect path.

Acoustically uncomfortable spaces in this research are the opposite of **comfortable spaces**, urban spaces with average noise levels of more than 50 dB(A) and low quality of stay ratings.

Acoustically trained person: A person, who is able to detect and localise specific sound phenomena in an urban space meets the demands of an acoustically trained person in the context of this research. From the experience of several sound observation walks conducted during the studies it can be concluded that it will take half a day to train an untrained person in the detection and localisation of mislocalisation effects or noise hot spots. The task for such a person is to listen, locate and document an acoustical event.

Aircraft event: The full time-span of an aircraft which could be noticed from the first sounds of its approaching to the last sounds of its leaving. The aircraft event is an acoustic event.

High-rises in this research context are buildings towering the surrounding city structure with an overall height of more than 22 m.

Mislocalisation: The following example illustrates the effect of mislocalisation: An aircraft is visually noticed arriving from the east, but the audible perception reports an arriving aircraft from the west. In this case the audible and visible perception is not congruent.

Noise source:

1 Sound sources that emit noise in a predefined range for the use in scaled measurements. e.g. loudspeaker or pneumatic noise source.

2 sounds generated by human activity, which transform comfortable urban space into uncomfortable urban space. In the context of this research only the traffic noise sources e.g. cars, trucks, aircrafts, trains were considered

On-site measurements: On-site measurements in this context are acoustical measurements that take place on a projected site in order to collect acoustic data as an input parameter for the façade design process.

Place of interest: A space in the planning scope where the intended usage requires a defined level of environmental noise. An example for a quiet place in this context is the terrace in front of a restaurant, where a high quality of stay is obligatory for successful gastronomic business.

Receiver point: Receiver points in this context are positions in urban space were people walk or stay and a measurement microphone can be positioned.

Receivers are people or microphones reporting the acoustic space.

Researchers' ears: Researchers' ears in this context are the ears of engineers and architects investigating the first basic impression of the acoustical characteristics of an urban space by walking around there.

Silent place: Based on the definition in the European Environmental Agency document „good practice on quiet areas" a silent place in an urban context is a place with an average noise level below 40 dB(A) over a year (EEA, 2014).

Steps in a façade design process: The here-described steps in a façade design process were used as defined in the work of Klein, [91]. Despite the fact that the definition was supposed to be for curtain walls the design process in the early phases of a project is similar for other materials or construction technologies. In this research only the steps of predesign/development, architectural design and executing design were taken into consideration.

Soundscape: In the definition of ISO 12913-1:2014(E) the soundscape is described as an „acoustic environment as perceived or experienced and/or understood by a person or people, in context"(Technical comittee ISO/TC43/ SC Noise[ISO TC43], 2014).

Sound source: In the definition of ISO 12913-1:2014(E) the sound source is described as: „sounds generated by nature or human activity"(ISO TC43, 2014).

Sound events not in the line of sight: if an obstacle blocks the direct view from a noise source to a receiver in an urban space the noise will transmit on indirect sound paths. Obstacles in this context are buildings, walls or other urban objects. The transmitting of sound energy on indirect sound paths is based on the acoustic principles of reflection or the diffraction of sound energy.

Trained ears: A person with trained ears in this context is a person with average hearing abilities but with awareness for noise events and spatial acoustic effects e.g. the mislocalisation of an aircraft. Furthermore, the ability to identify a reoccurring noise event on a digital recording is mandatory. A trained ear in this context does not represent an absolute hearing ability as for classical instruments. An absolute hearing ability regarding the frequency properties of a sound event is not required nor necessary in the context of environmental noise.

Urban acoustic space: Urban acoustic spaces are defined in this research as spatial arrangements of mobile traffic noise sources and immobile reflective surfaces of buildings creating different acoustic environments. In the ISO 12913-1:2014(E) the acoustic environment is defined as „sound at the receiver from all sound sources as modified by the environment"(ISO TC43, 2014).

4 On site measurements

§ 4.1 Summary

In the course of this research an on-site measurement method for analysing urban spaces regarding their acoustic status quo was developed. Three case studies in Frankfurt/Main are presented, testing the applicability of this method to analyse existing complex urban spaces in the vicinity of projected building sites. In preparation of the acoustical measurement the methods of geometrical analysis or on-site inspection by ear were introduced to the field studies. The on-site measurements were conducted with the limitation of one type of noise source for an urban space. With the analysed measurement data, it was possible to identify and quantify influencing factors of each urban acoustic space presented in this research. The final discussion of the collected data summarizes that with the developed measurement setup a detailed view on urban acoustic spaces and their determining parameters can be obtained.

§ 4.2 Introduction

Urban spaces in European metropolitan regions such as Frankfurt / Main are comprised of hard reflective façades and numerous noise sources on the streets and in the air. The impact of noise sources on these urban environments is different to the spreading of sound in an open field. Among others, Lyon described in 1971 that the measured sound pressure level of airborne noise sources above a city canyon is 6 dB higher at street level than in an open field (Lyon et al., 1971). The reflection of noise energy at hard reflective surfaces is causing higher sound level readings whenever the direct noise and the reflected noise could be perceived simultaneously. The drawing in Figure 4.1 depicts the acoustical mechanism behind an urban setting and its elements.

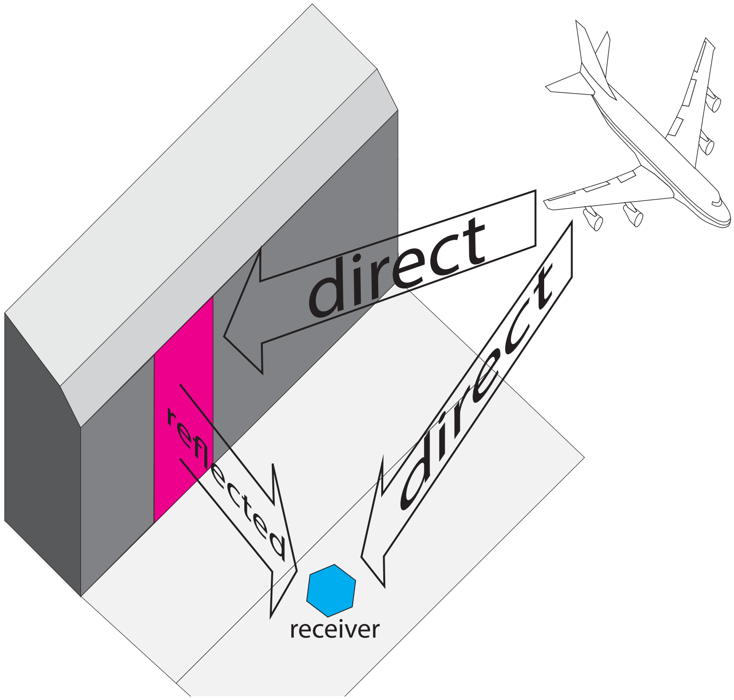


FIGURE 4.1 The effect of a façade on the perceivable and measurable noise in an urban space.

This basic setting only partially represents the architectural context of a complex urban space in European metropolitan regions. The variation of façades due to their position, dimension and reflection properties combined with multiple noise sources in the air or at street level leads to a heterogeneous noise spreading. An example for such an urban space is shown in Figure 4.2.

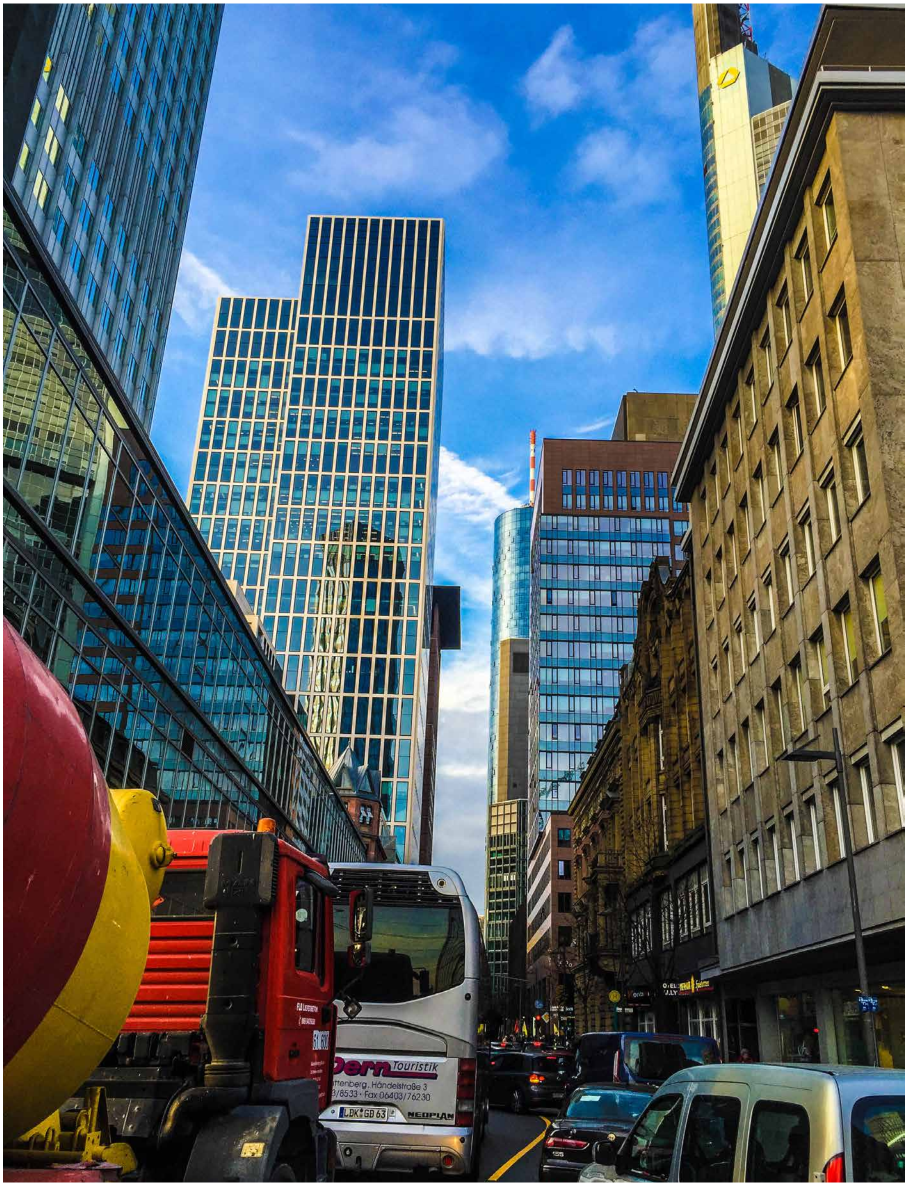


FIGURE 4.2 Car traffic in the high-rise canyon of the Neue Mainzer Strasse in Frankfurt / Main, 2015. Moving noise sources between hard reflective surfaces lead to an extremely noisy urban canyon.

In the on-going research presented in Chapter 2, there is no acoustical measurement method present yet, which can provide data on the acoustical status of such a space regarding the effect of façades on the noise impact. Thus, there is also no data available for the development of an acoustically effective façade design in complex urban spaces. Introducing to architecture the concept of modifying urban soundscapes with a specific façade design basic questions regarding available data and suitable methods have to be considered.

§ 4.2.1 Which data is available on the acoustic properties of urban spaces? Are they suitable to be used for façade design?

One of the factors determining an urban acoustic space is the noise source. In the area of investigation, Frankfurt / Main, two databases for traffic noise levels are available: 1) measured noise levels and 2) noise maps.

Measured levels are generated for aircraft noise only and are available on websites, e.g. „http://inaa.umwelthaus.org“ from „Gemeinnützige Umwelthaus Gmbh“ and „http://www.dfld.de“ provided from „Deutscher Fluglärmdienst e.V“. These websites provide data from a net of noise monitoring stations in the Rhine-Main area.

All contributing stations are located close to the flight paths of Frankfurt Airport in order to mainly monitor the noise levels of aircrafts flying by. The arrangement of monitoring stations being close to a flight path is optimised for accurate monitoring of aircraft noise levels and possible irregularities in the aircraft engine management. Figure 4.3 shows an example for the spatial setup of monitoring stations in relation to the newly built European Central Bank. In this example, the distance of the direct measurement between the noise source and the receiver d1 is 430 m. The distance between the noise source and the point of reflection at the European Central Bank Tower is five times d1, 2160 m. Every doubling of the distance from the noise source (aircraft) to the receiver (noise level meter in the monitoring station) reduces the measurable sound level by -3 to -6 dB. Considering that sound waves move to the point of reflection and back to the receiver, the total travelling distance is nine times d1, 3870 m. In this case, when considering the case of -6 dB for the level reduction, the measurable level of a potential façade reflection is reduced by 54 dB. The noise level value of the direct measured aircraft noise is always higher, because the distance from the aircraft to the monitoring station is only d1 = 430 m. These higher noise levels are masking the façade effects in the measurement data. As shown for this example, the identification of reflection effects on façades located in a higher distance to the monitoring station is not possible.

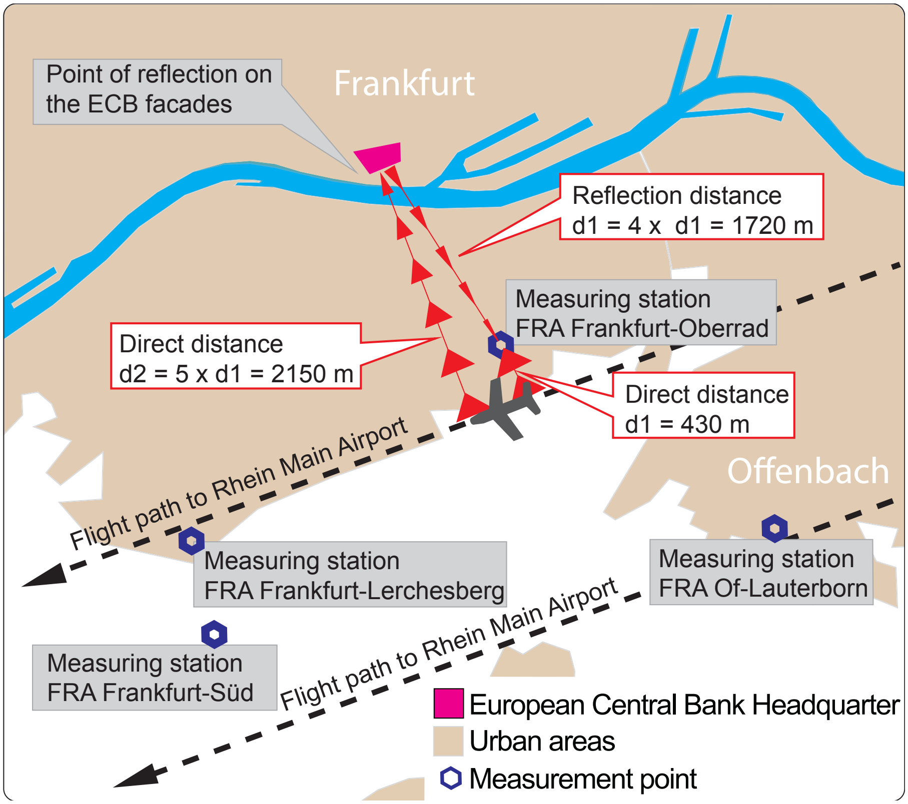


FIGURE 4.3 Spatial arrangement of the measurement stations in Frankfurt / Main operated by „Gemeinnützige Umwelthaus Gmbh". Drawing based on the webpage http://inaa.umwelthaus.org (UNH, 2013).

The second database for traffic noise levels is noise mapping. Noise maps are graphical representations of numerical level simulations based on the European Noise Directive (END) published in 2002 (EU, 2002)]. Noise maps are always the graphical outcome of a computer based simulation. They are not based on measured noise level values. Noise maps have been calculated for Europe in 2007 and 2012 for road traffic noise, railway noise, aircraft noise and industrial noise. One noise map represents only values for one type of noise source. Figure 4.4 shows a screen shot of the Frankfurt city noise map regarding car traffic noise in the area around Neue Mainzer Straße, which is depicted in Figure 4.2.

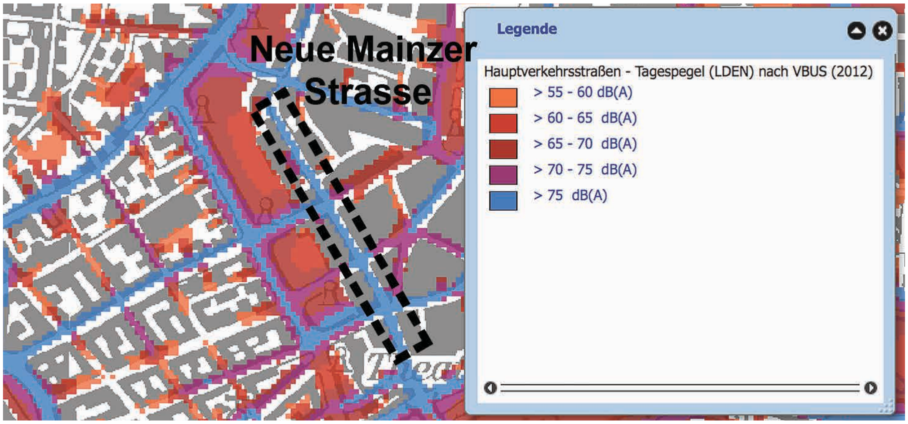


FIGURE 4.4 Noise map screen screen shot showing the area around the Neue Mainzer Strasse in Frankfurt/ Main. Retrieved from HLUG.de (Hessian State Office for Conservation, environment and geology [HLUG], 2013)

The graphical outcome of the noise mapping procedure represents calculated noise levels in a 10 m by 10 m grid in 4 m height above street level in steps of 5 dB. The example in Figure 4.4 depicts that the 10 m by 10 m grid represented by hatches ignores the underlying structure of the city. By setting the scale resolution to 5 dB, a reliable detection of reflection effects in the range below 5 dB becomes unfeasible. The influence of a noise source on a reflecting façade is controlled in the map algorithm by parameters, which are defined in European Noise Directive (EU, 2002). The directive does not regulate parameter setting. The parameter setting is done by the commissioned executing engineer following guidelines of the local authorities or his experience. This leads to noise maps with different parameter settings for each calculation area. The parameter values are generally not documented on the maps; therefore, it is impossible to evaluate urban situations in a map considering the topic of façade reflections. A further limitation of the values extracted from END regulated noise maps is caused by the introduction of threshold values for the calculation process. In the maps from 2012 levels below 55 dB(A) and levels on roads with less than 8000 cars per day are neither calculated nor represented. This results in numerous blind spots because only main roads are represented and the lack of data on the levels in urban acoustic settings below 55 dB(A). In Figure 4.41 white spots in the area close to Neue Mainzer Straße in Frankfurt/Main can be detected. This does not represent the acoustical status quo. The local governments are in charge when deciding on the scope of the noise mapping processes. Taking into account the weak points of insufficient resolution, limiting threshold and no documentation of variable parameters in the noise maps, it is neither possible to come to reliable statements on urban acoustic arrangements nor is it possible to compare the noise maps of different cities in Europe. In fact, only a close investigation of a selected urban acoustic space could deliver a detailed view on the behaviour of urban acoustics.

Summarizing, the available data for measured noise levels and noise mapping are of limited use for this research, thus it was necessary to develop a suitable method for obtaining the required data.

This leads to the next question.

§ 4.2.2 How to develop an on-site measurement method that meets the acoustical and practical requirements of an acoustical effective façade design?

From the literature research in Chapter 2.2 and 2.3 summarising the research on urban acoustics, it can be seen that extensive work is published on the topic of façades and their influence on the measurable noise levels in the streets. In these research works the results of field measurements were used to calibrate and validate computer simulations or scaled model measurements aiming for a precise prediction of urban noise spreading. From the acoustical point of view long elevated building blocks were taken into account in order to prevent blurring of the results by excluding unwanted border effects. This does not describe the common practice of a projected façade design for one building. When there is only one façade of a building block in the planning scope, information is required regarding the acoustical effect of this single façade. Specific acoustical data is required for the individual planning scope of each project. The intended on-site measurement should deliver data regarding the dominant noise source, the direction of the dominant noise source in relation to the projected façade and the proposed quiet space in relation to the building façade. An example for a quiet place in this context is the terrace in front of a restaurant, where a high quality of stay is obligatory for successful gastronomic business. Refer to Figure 4.5.

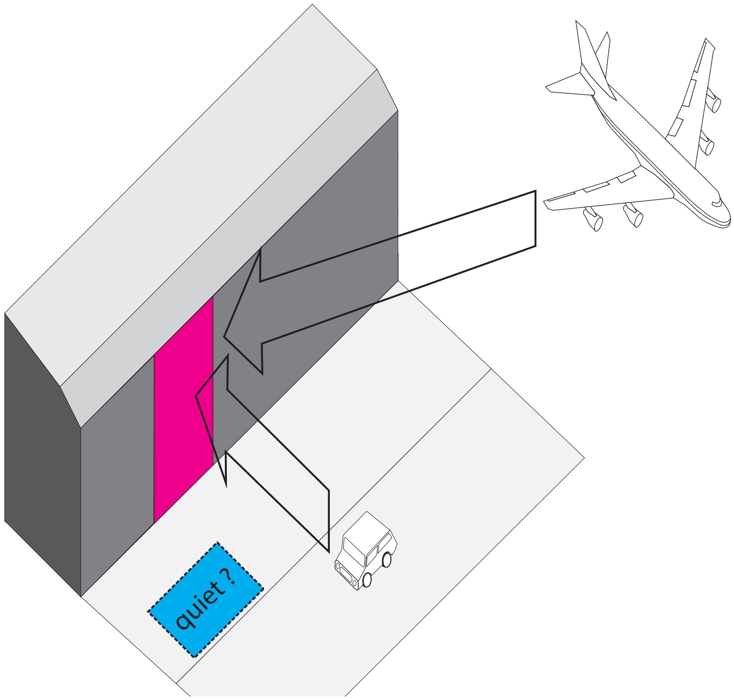


FIGURE 4.5 The position of a projected quiet space in spatial relation to the projected façade and the noise source

In order to develop an on-site measurement setup, which is capable of delivering the required data for a façade-building project, the following basic requirements were defined.

- The on-site measurements should be conducted with more than one microphone position in order to enable acoustical comparison of different spaces.
- One microphone (receiver) should be at a position where only the emitted direct noise can be captured without any reflections from façades.
- One more microphone (receiver) position should be at a position where the reflection of the direct noise at the façade is clearly audible or at a projected quiet space.
- Only one dominant noise source at the building site should be taken into account per measurement.
- Other noise sources should be excluded from the measurement by measuring at specific time points during a day.

In order to evaluate the suitability of on-site measurements following the above-mentioned requirements several locations in the area of Frankfurt am Main were acoustically measured. The locations of the case studies were selected based on the intention of the measurement method and on recommendations of the office of environmental affairs of the city of Frankfurt.

The location of the Henninger Turm in Frankfurt am Main was selected for the first case study because of the unique opportunity to document the vanishing of a high-rise and its effect on the urban acoustic space. Additionally, it was expected that this case study would reveal the acoustic potential of a high-rise façade. Furthermore, in 2013 the urban plot around the Henninger Turm represented a typical landmark architecture case: the arrangement of a solitary high-rise in a 6-storey building surrounding. In today's architecture production the Tribea tower in New York gives an example for this urban arrangement caused by the creation of added value from limited available city ground (Alexico Group, 2016).

The location at the Goethe Platz was selected for conducting a case study because people reported to the government of Frankfurt a low quality of stay. Despite the fact of several refurbishments the public space at the Goethe Platz remained as a transit zone and not, as intended, a place to stay. The government was searching for data causing the low amenity qualities there. At the Goethe Platz it was intended to reference road traffic noise as an input to a measurement. The outline of the case study was to proof the feasibility of documenting a public urban space with the here-proposed on-site measurement.

The building site at the Lyoner Strasse 54 in Frankfurt am Main was selected for conducting a case study as this represents one of the redensification strategies in metropolitan areas: The conversion of former office buildings surrounded by multiple noise sources into residential areas. The aim of this study was to reveal the acoustical mechanism in the vicinity of a building close to flight paths. This urban plot is typical for parts of metropolitan areas as any European metropolitan area produces a high amount of air traffic.

The first on-site measurement was the long-term Henninger study with an extensive use of material and time. With this experience the investigation methods for the following studies at Goetheplatz and Lyoner Straße were modified. Long-term measurements were changed to short-term measurements in order to meet the time requirements of an on-site inspection, which is a common and accepted tool for building projects. In the on-site measurement at Gotheplatz the attempt was made to substitute the high priced calibrated noise level meters by digital hand-held recorders in conjunction with a calibrated noise source. Table 1 gives an overview regarding time and initial costs of the measurement equipment.

STUDY	Time on-site	Time for data evaluation	Number of measurment points	Number of calibrated noise level meters	Number of digital hand-held recorders	Costs for Hardware and Software
Henninger Turm	108 h	96 h	2	2	0	24.000 €
Goethe-platz	15 h	40 h	35	0	2	1000 €
Lyoner Straße 54	2 h	10 h	6	1	0	13.000 €

TABLE 4.1 Overview of the on-site measurements regarding time and costs

The designs of three on-site measurement setups meeting the specific requirements of each unique project site as well as the predefined requirements are presented in the following case studies.

§ 4.3 On-site measurement "Henninger Turm", Frankfurt

§ 4.3.1 The situation on site

Between January 2013 and December 2013, the Henninger Turm in the district of Frankfurt Sachsenhausen was dismantled. The storage silo for brewery barley of the Henninger Brewery was constructed out of concrete between 1959 and 1961 with the first ever-used sliding formwork in Europe. The architectural design, the building process and the requirements for the storage of grain resulted in a squared concrete plinth measuring 25 m wide and 87 m high and a huge cylinder on top. The brewery barley was stored in the plinth while the representative needs of the brewery were situated in the cylinder. A restaurant and an observation deck were placed there.
The tower being 119.5 m tall was located in a mixed used area with characteristic five storey dwellings and former industrially used properties. Figure 4.6 shows the Henninger Turm four months after the dismantling process had started. Since there were hardly any acoustic relevant disturbances observed on the surface and considering the reflective properties of the building, these façades could serve as nearly perfect acoustic model for hard reflective façades.

FIGURE 4.6 The Henninger Turm in Frankfurt Sachsenhausen four months after start of the dismantling process

The reconstruction of the high-rise is scheduled from 2014 until 2017. The high-rise will be reconstructed in the same shape as the former building, but the new Henninger Turm will be mainly for residential use.

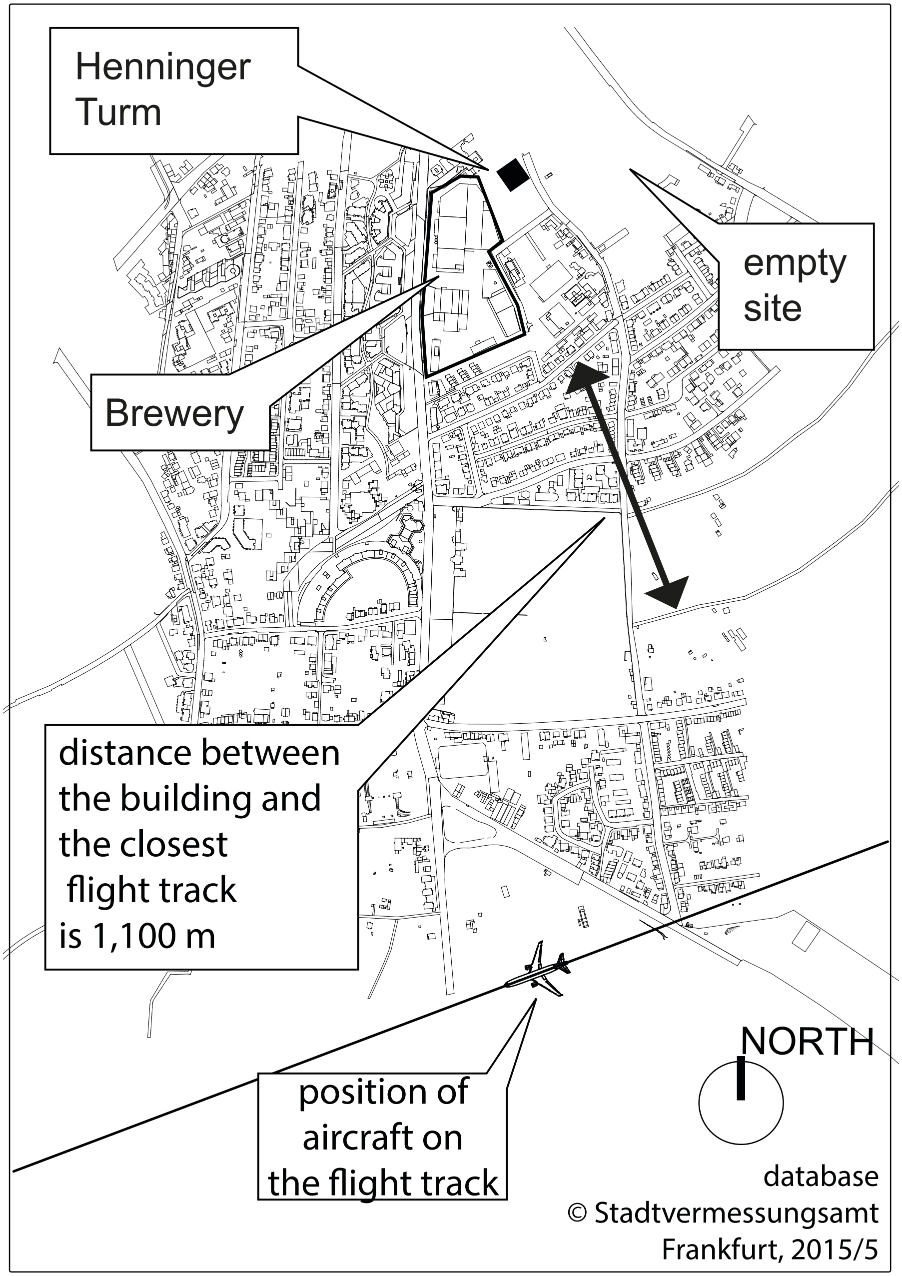


FIGURE 4.7 Map of the urban space and its noise sources around Henninger Turm. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

The overall situation in this mixed-use district in Frankfurt Sachsenhausen is characterised by four noise sources. Figure 4.7 shows one main flight path of the Rhein Main Airport running in 1100 m distance perpendicular to the south façade of the tower. Parallel to the flight path in 1100 m distance to Henninger Turm, a second one runs at 2600 m distance. Aircraft emitted noise can be observed between 5 am and 11 pm. The cooling machines of the nearby Binding brewery running 24 hours 7 days a week produce the constant noise floor noticeable around the building site. Throughout the day, an intensive traffic with a high percentage of trucks and busses added road traffic noise to the overall acoustic impression. During the one-year dismantling period the residents were impaired by an uncomfortable noise emitted from a drill-bit breaking down the concrete construction of the silo piece per piece every week from Monday to Saturday between 6 am and 8 pm. This combination of urban noise emissions generated a highly uncomfortable acoustic space.

§ 4.3.2 Spatial investigation of the acoustic situation

In the first phase the acoustic status quo of the quarter „Sachsenhäuser Berg" was analysed during surveys on foot (walks) by the author. The first walks in the area around the tower were done loosely in order to capture the overall scheme of this acoustic space. This was done without the use of technical audio equipment. During these walks the focus points of noise events were noticed. In order to achieve a rather reliable quality of repeating the audible walks, listening points and listening parameters were defined based on the these first sketchy walks. Due to easy access the listening points were defined on public ground in the streets around the building site of the Henninger Turm. The plan of the listening points is shown in Figure 4.8. The listening positions were located along the south façade in the Aschaffenburger Strasse (AB) and along the Hainer Weg (HW) parallel to the east façade. The distance between the observation points along the streets is 35 m. Two of the points are located perpendicular to the east and the south façade because the observation walks revealed that at these points the most impressive effects of mislocalisation can be perceived. The mislocalisation effects were noticed as a result of strong reflections of noise events on the surrounding façades. The following example illustrates the effect: An aircraft is visually noticed arriving from the east, but the audible perception reports an arriving aircraft from the west. In this case the audible and visible perception is not congruent.

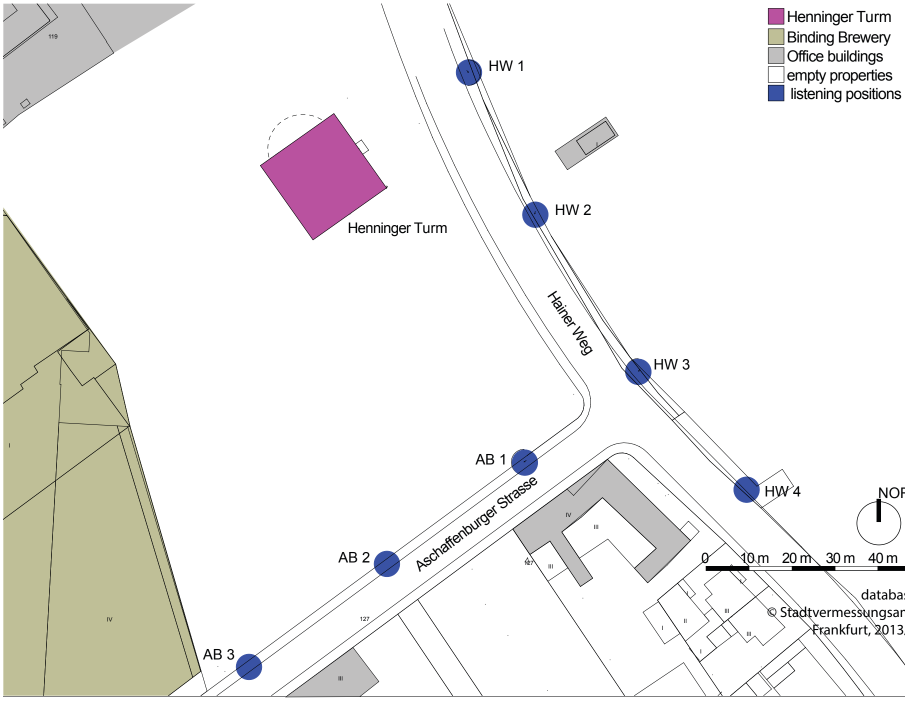


FIGURE 4.8 Plan of the listening positions around the Henninger Turm in March 2013. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

.

The following listening parameters were defined for further observations considering the results of the second round of walks.

- Sound level of road traffic noise
- Building site noise level coming from the dismantling machines
- Industrial noise level emitted from the cooling machines of the nearby brewery
- Airborne noise level
- Range of mislocalisation effects from a congruent notion to a non-congruent notion of noise events.

For the acoustic evaluation of the site, the predefined listening positions were visited twice a day for five minutes over a period of 7 days in March 2013. The noticed sound impressions of an accurate localisation and the contribution of every audible noise source to the perceived noise floor were documented by filling out a questionnaire. The questionnaire required four answers on the level of different noise sources and one answer regarding the coherence of aural and visual perception. The answers were given in values from one to five on a five-step scale. The scale was defined from hardly noticeable (1) to a very loud audio impression emitted from a noise source (5). The subjective localisation effects experienced by the researchers' ear were also documented. The range is spread from perceiving one event in one direction up to one event returning from many directions. The basic questionnaire is shown in Figure 4.9.

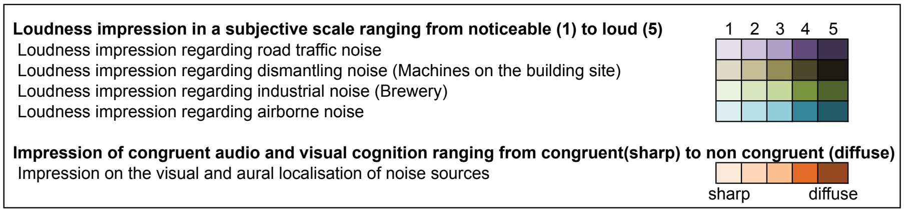


FIGURE 4.9 Questionnaire for the five-minute investigation of each listening point defined in Figure 4.8.

An excerpt of the results is shown in Figure 4.10. The documentation of different days at different times of the day demonstrates a rather heterogeneous situation. On weekdays an intense mix of all noise sources changes to an airborne noise dominated scenario on Sundays. Also, it becomes obvious that nearly all noise sources are time dependent except the brewery, which runs 24 hours 7 days a week producing a constant noise floor. Additionally, the mislocalisation effect showed a strong dependence to the documented aircraft noise and not on the overall noise level. Comparing the results of all listening points leads to the conclusion that the addition of road traffic noise or dismantling noise does not have any important effect on the notion of mislocalisation. From the aural observations it was concluded that the best time frame for measurements is between 5 am and 6 am on Saturday mornings and between 5 am and 7 am on Sunday mornings. During this time the aircraft noise dominates the overall sound impression of the area around the tower with a slight overlay from other noise sources. In relation to the aircraft noise the delocalisation effect is appearing strongly at several points. With regards to the mislocalisation effect, the lowest values are at listening point HW3 and, in contrast, the highest at AB1. With the missing of interfering noise events on Saturdays between 5 am and 6 am and between 5 am and 7 am on Sunday mornings these two points were considered to deliver significant measurement data on the effect of the façade and the potential changes during the dismantling process.

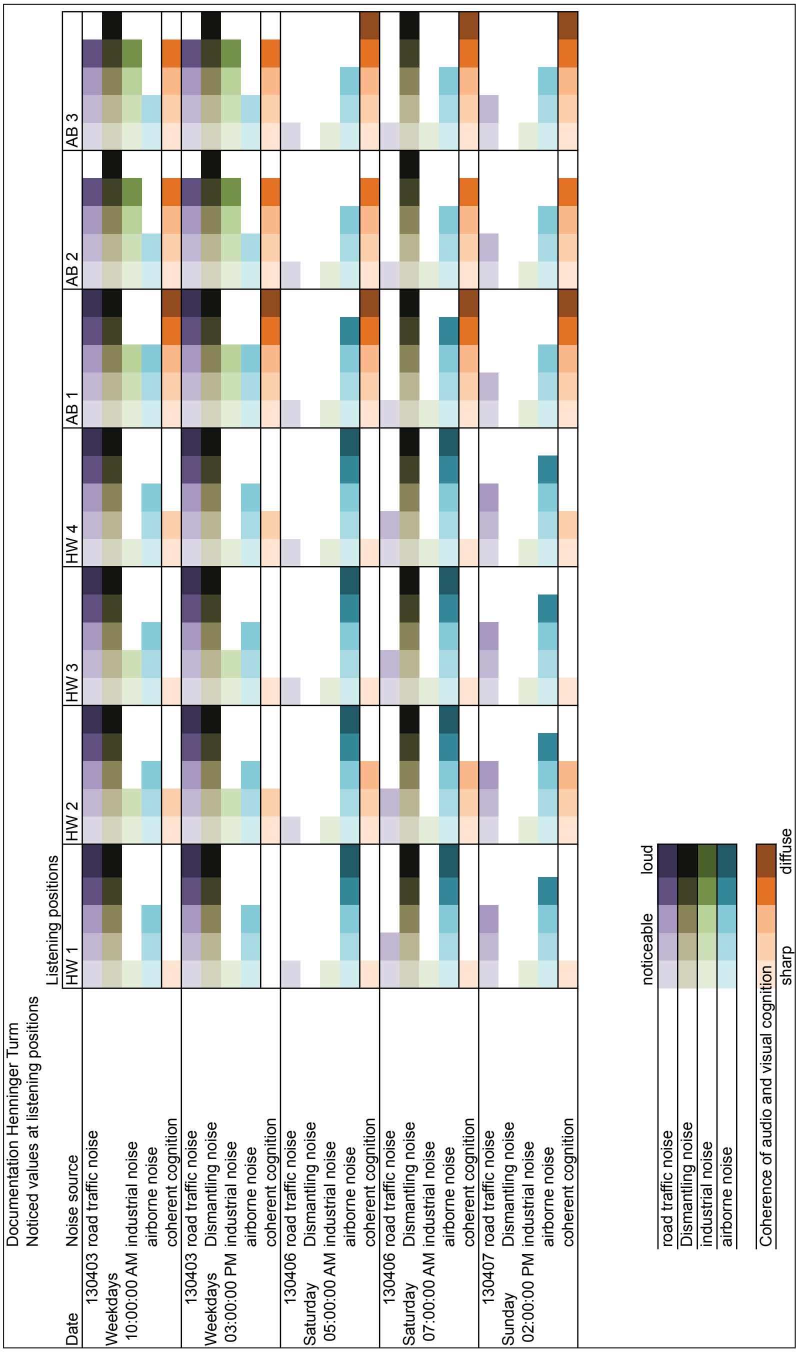


FIGURE 4.10 Documentation of the results from the aural investigation close to the Henninger Turm.

These results of the aural investigation led to a sketch of the measurement procedure:

- Measurements are promising on Saturdays between 5 am and 6 am and between 5 am and 7 am on Sundays because one sound source (aircrafts) dominates the noise mix. With only one sound source in the measurement it is believed that effects of the façade on the acoustics can be detected there. Furthermore, the aircraft noise can be referenced with the help of a web-based flight-tracker. These websites provide data of all flights arriving or taking off at Rhein Main Airport. In order to compare different measurements throughout the dismantling process of the building, the same type of aircraft travelling on different days can be identified. This introduced a referenced sound source to the measurement setup.
- In order to detect the reflection effect of the façades all measurements should be done with at least one listening point with a strong delocalisation effect.
- To be able to compare the measured data with noise map data all measurement points must be positioned at the same height above ground as the calcualation grid points of the noise mapping software, which are calculated in 4 m height above ground.

For this research it was decided to conduct measurements during the dismantling process only. Measurements during the new construction process were not planned because of an additional, new dwelling close to the site. This would change the acoustical parameters in such a way that the results would not be comparable due to information on the reflection effect of the tower façade.

§ 4.3.3 Graphical considerations

Beside the observation walks a graphical approach was conducted to obtain a promising measurement setup. The underlying idea was to measure two points simultaneously in order to compare the recorded data for the same points in time. A geometrical setup was designed considering the aircraft as a moving sound source in relation to the expected reflection on the south façade of the tower. The movement of the noise source was divided into discrete points aligned on the moving path parallel to the façade. One measurement point should be precise perpendicular to the south façade. The second measurement point should be located on the bisecting line of the corner angle close to the perpendicular measurement point. Refer to Figure 4.11.

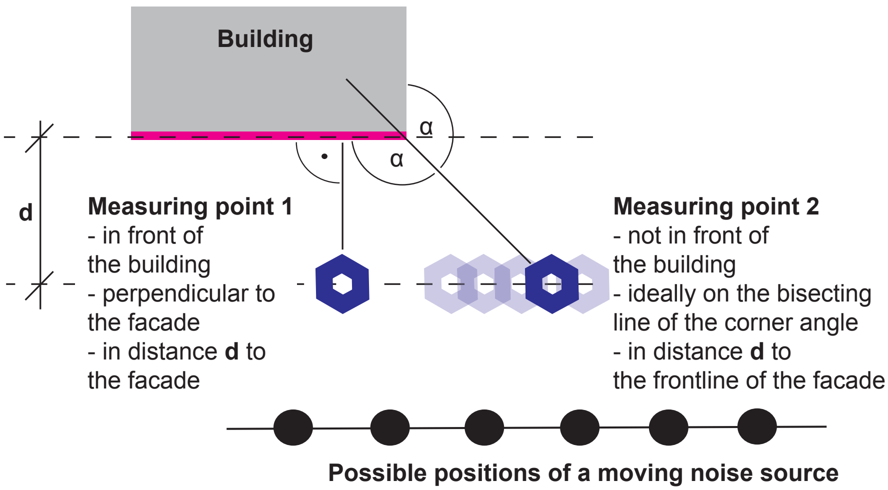


FIGURE 4.11 Basic scheme of the measurement setup

The path of rays' drawings in Figure 4.12 and Figure 4.13 show the ideal geometrical layout of the proposed measurement setup in a simplified way for two positions of the noise source. In order to keep the complexity for the measurement design on a low level, scattering or edge diffraction effects were not taken into account for the development of the measurement setup.

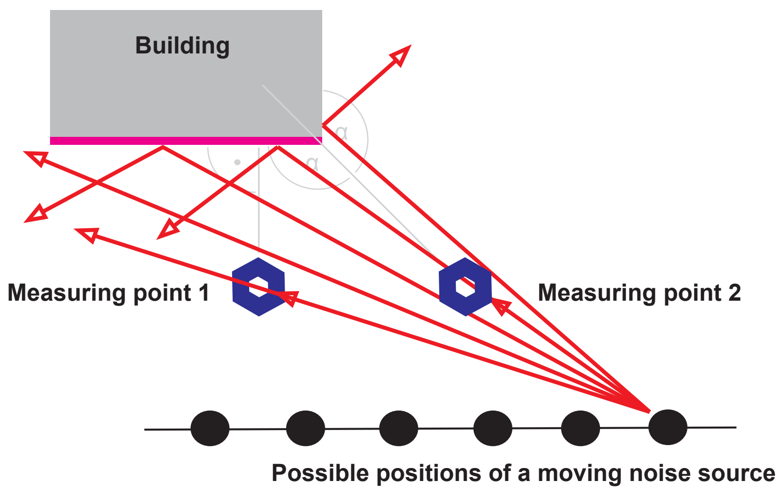


FIGURE 4.12 Manual/graphical ray tracing for the noise source being distant to the building

Figure 4.12 shows the noise source located distant to the building façade. This causes direct measurable signals in measuring point 1 (MP1) and Measuring point 2 (MP2). No reflection from the tower's façades will reach both measuring positions. In Figure 4.13 the noise source is located closer to the building. In this case the direct signal will be measurable at MP1 and MP2. Additionally to the direct measured level, the reflection of sound energy from the tower's south façade will increase the measurable noise level at MP1.

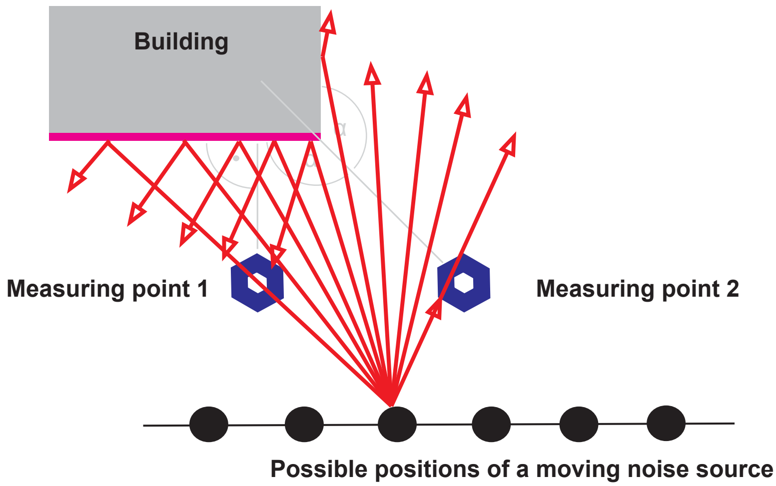


FIGURE 4.13 Manual/graphical ray tracing for the noise being close to the building

For mirror sources it is valid that the input angle of the noise energy is equal to the output angle of the reflected noise energy. If we measure a reflection event in the measuring point perpendicular to the façade it is believed that we do not measure a reflection event at the measurement point located on the bisection line of the corner angle at the same time. Comparing the measured values at both measurement points for two positions of the noise source the effect of the façade reflection should be visible in the data. Based on this hypothesis the requirements for the measurement setup were defined.

§ 4.3.4 Measurement specifications Henninger Turm

The measurements and the equipment should fulfil the following requirements:

- Calibrated noise level meter with a calibrated microphone meeting class1 requirements
- Measurements should be done when the main flight path is active
- Use predefined measurement positions
- All measurements should be performed with at least two measurement positions
- During the measurement all observations on weather, road traffic or other disturbances should be documented.
- Measurements should not be taken during storm, snow, heavy wind or heavy rain
- Measurements should be done between 5 am and 6 am on Saturdays and between 5 am and 7 am on Sundays

§ 4.3.5 The measurements in situ at Henninger Turm

The measurements around the Henninger Turm were conducted from end of March 2013 to end of December 2013 on Saturdays between 5 am and 6 am or on Sundays between 5 am and 7 am when there was no snow, rain or heavy wind. The climate influence could be neglected as in this setup the data of each measurement day was compared only to data of the same measurement day. In this period from March to December 2013 the dismantling machines were removing the 80 m high plinth piece per piece. For the measurement two calibrated noise level meters with the possibility of an external storage and a parallel digital audio recording were used. On site the noise level meters were placed on tripod stands. The head of the tripods can be pulled out to a maximum height of 4 m. The noise level meters were fixed to the tripod head. Moving the tripod stand with the fixed noise level meter to the marked measurement position on the pavement and extending them there to the maximum height extension complies with the given requirements for a precise positioning. During the measurements all observations in the surrounding area, which could result in a possible disturbance of the measured signal were documented. One measurement point perpendicular to the south façade was set up at „AB1“. In the following this measurement position is named „MP1“. The angled measurement point was set to listening point position „HW3“. Refer to Figure 4.14. This measurement point in listening position HW3 is named MP2 in the following. The angling of the direction from MP2 towards the normal of the south façade is 19° degree. Most of all measurements were taken at MP1 and MP2. In direction of the east façade the delocalisation effects on aircraft noise events were not as representative as in the direction of the south façade, therefore only a few measurements were done at positions *MP HW1* and *MP HW2*. During all measurements the gathered data was automatically stored on memory cards in the noise level meter. For analysing and visualising the gathered data the data was then processed on a computer with the noise review software developed by the manufacturer. This noise review software complies with the international standards of noise measurement calculations.

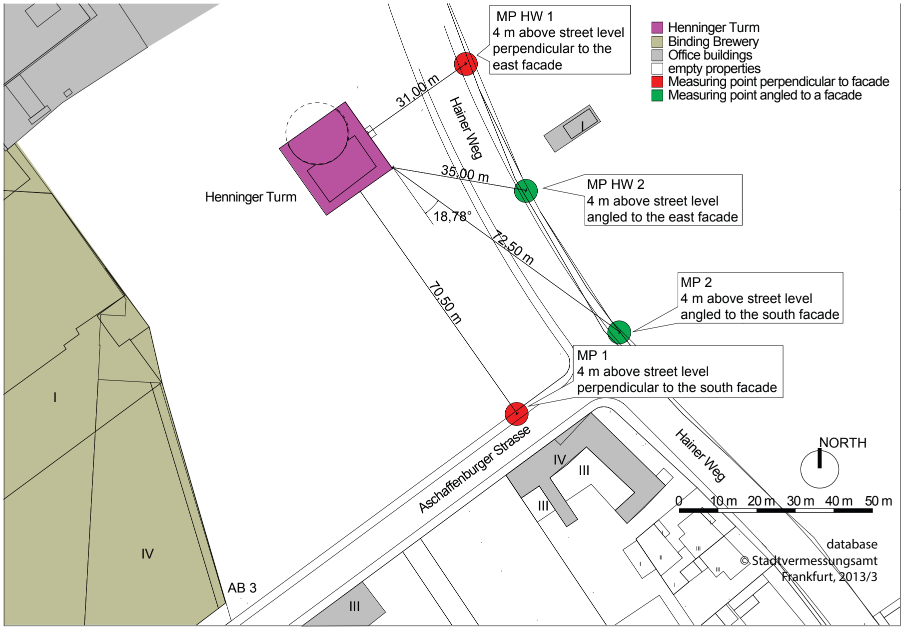


FIGURE 4.14 Plan of the measurement points around the site of the case study. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

The gathered data was sorted into single flight events. One valid flight event is defined in this research as one identified plane measured by the instruments without any disturbance of the measured signal caused by other noise events appearing on site or by emitted noise from aircrafts ahead or behind on the flight path. The decision due to the validity of every documented single flight event were based on the notes during the measurement and on listening to the recorded digital audio files with headphones afterwards. The notes done during the measurement on site deliver helpful information for identifying the aircraft and its position on one of the two flight paths. Web based flight trackers provide more detailed information on flight routes and individual aircraft data. For this research the accurate data on aircrafts was acquired from two web based flight tracker websites. One source available for the flight paths around the Rhein Main Airport is the website from the UNH [93] The second source being in use for picking out data is the website flightradar24.com [97]. Combining the two information sources the flight route and the model of the measured aircraft could be identified for nearly all monitored flight events.

For the evaluation of data during one aircraft noise event time points were defined by identifying the highest audible notion of the direct signal or by detecting high noise levels caused by reflections. The thorough listening to the captured digital audio files carried out three significant points on the time line.

- The time point „t1" called „Event Street" is defined for an approaching aircraft causing the highest-level reading at measurement position MP2.
- Time point „t2" named „event Tower" is set to the audible detection of the reflected sound energy from the tower resulting in a high level reading at measurement position MP1.
- A third point on the time scale „t3" was defined for the clear audible notion of a reflection event when the rear of the aircraft could be seen on its way to Frankfurt Airport.

The time intervals between the time points t1, t2 and t3 can be extracted from the measurement data. As there were no mislocalisation effects audible at MP 2, the level readings at time point t2 should be nearly independent of the status of the tower during the dismantling process. Thus, time point t1 will be the reference time point for the measurement evaluation of data sets captured before and after demolition of the tower. The time intervals between t1, t2 and t3 define the investigation points in relation to the point t1. Refer to Figure 4.15.

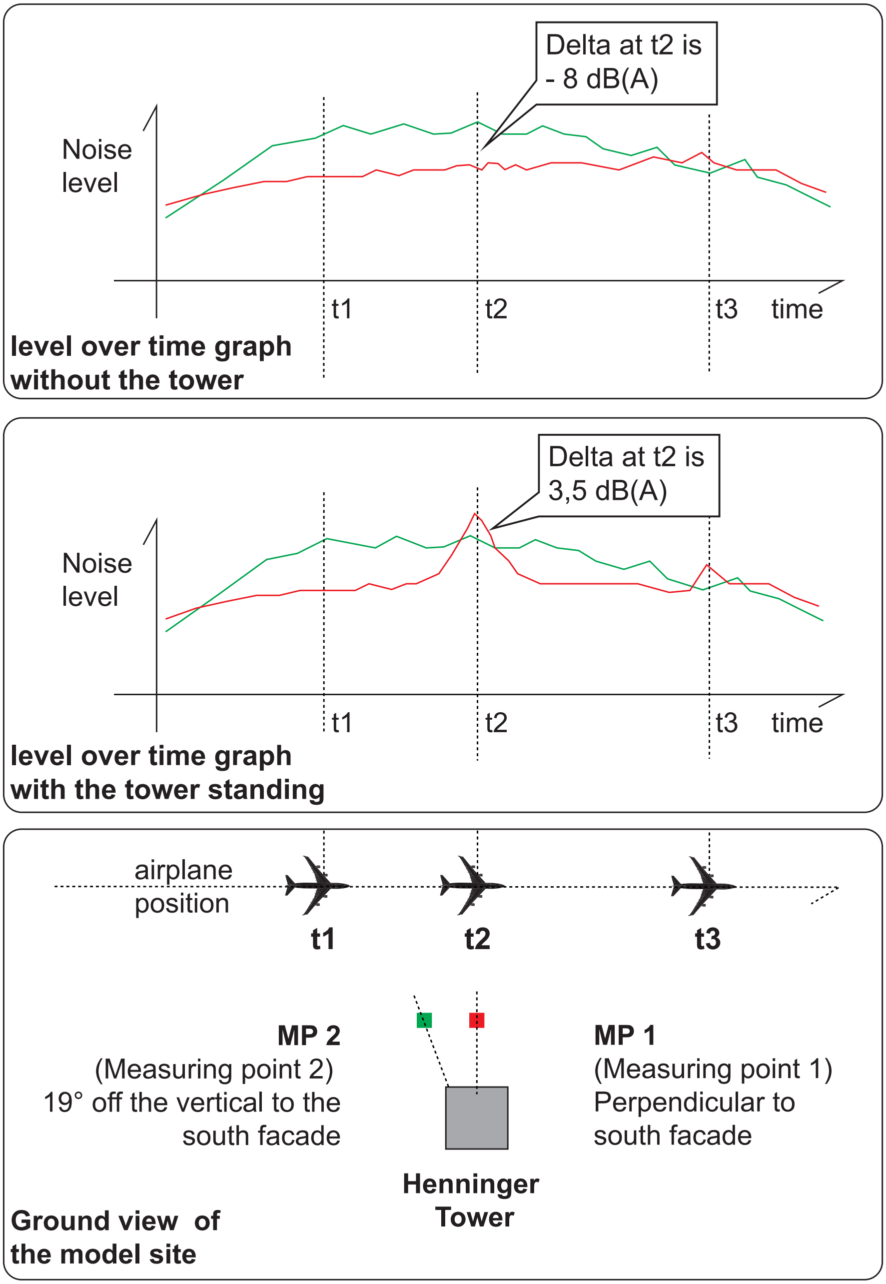


FIGURE 4.15 Correlation graphic of the results from the measurements in relation to the position of the aircraft.

§ 4.3.6 Results:

Level-over-time graphs in Figure 4.15 represent the captured noise level in relation to the aircraft on its way on the flight path to Frankfurt Airport. Measuring unit one (MP1) receives the reflection of the aircraft noise on the tower façade while measuring unit two (MP2) receives the aircraft noise on a direct path. Values from MP1 are represented in the results with red lines. MP2 values are shown in green lines. The two level-over-time line graphs show the noise level-over-time for one single measured aircraft noise event with tower (graph in the middle of Figure 4.15) or without tower (graph on top of Figure 4.15). The reflection effect of the existing tower is obvious at the interval t2, where the difference is 3.5 dB between both values. The effect is detectable with very small variations for a measured aircraft at 2600 m and at 1100 m distance to the tower. The measurement after the demolition of the „Henninger Turm" showed unexpected results. With the finished dismantling of the tower there is no reflection event at point t2 in the measurement data from measurement position MP1 detectable. Thus, the dismantling of the tower leads to a level change of 8db at Measuring point MP1 at the time point t2. At the time point t3 a level change of +3 dB can be detected. Without the tower the noise level at t3 for the „Event late reflection" increases up to 3 dB at measurement point MP1.

§ 4.3.7 Discussion

The results of the field measurements at Henninger Turm demonstrate the acoustical impact of a high-rise façade on the surrounding urban space. A level change of 8 dB is clearly perceptible, even for untrained persons. Furthermore, the results point out that in complex acoustical urban settings the change of one object is followed by other than only the expected changes. With the vanishing of the tower the „late reflection event" appears at a 3 dB increased level, because before dismantlement the tower acted as an acoustical shadowing for this noise event. The results emphasise that complex urban acoustic spaces have to be thoroughly investigated in order to predict effects of changes in the existing urban layout.

§ 4.4 Measurements at Goetheplatz, Frankfurt/Main

§ 4.4.1 The situation on site

The Goetheplatz in Frankfurt/Main is an inner city public place with low amenity qualities. The west side of this public place with the two-lane road is shown in Figure 4.16. Because of the crowded two-lane street running on the east side, the place is covered by noise levels in the range from 60 dB(A) to 65 dB(A).

FIGURE 4.16 Goetheplatz, Frankfurt/Main, view to the west side with the two-lane street running parallel to the façades.

The soundscape, which can be perceived on the „Goetheplatz" is dominated by road traffic noise. An aural investigation of the situation on site pointed out that by using the time slots of the traffic lights on the two-lane street as a reference time point, the road traffic noise can be defined as an input source to the measurements. With audio recordings the quality of the emitted traffic noise was evaluated searching for time slots with constant levels or constant frequency distributed levels. This leads to the requirement regarding the timing of the measurement. After 30 seconds when the traffic lights turned green the noise mix emitted by different cars or trucks is nearly constant for one minute regarding noise level but not frequency distribution. The interval for the measurements was defined as a one-minute period starting 30 seconds after the traffic lights switched to green. Due to the impossibility of recording 35 measuring points simultaneously and the unstable frequency distribution of the emitted road traffic noise only single value noise levels for the defined frequency range of 90 Hz to 6000 Hz can be extracted out of the data. Further inspections of the site revealed that on weekdays between 10 am and 11:30 am the traffic flow is at a medium level. At other times of the day too much vehicles cause traffic jams or especially in the evening hours extreme loud motorbikes or tuned cars were disturbing the constant traffic noise. The interruption of traffic flow in the night hours also leads to an interrupted input noise level for the measurement. To obtain meaningful data on the reflection effect of façades 22 measurement points were defined along the road in 5 m spacing between each of them and at a distance of 2 m to the kerbstone. A reduction of the grid spacing to 1 m in front of the projected façade would lead to more detailed data. But due to limitations in time and costs the 5 m setup was conducted. On the public place along the east façades at 20 m distance to the road 13 measurement points were set with equal spacing of 5 m between the positions. According to the experiences from the Henninger Turm on-site measurement the row of points was arranged in relation to the façades that measuring position are taking place at corners and in the middle of street crossings. Figure 4.17 shows the final layout of measuring positions at Goetheplatz.

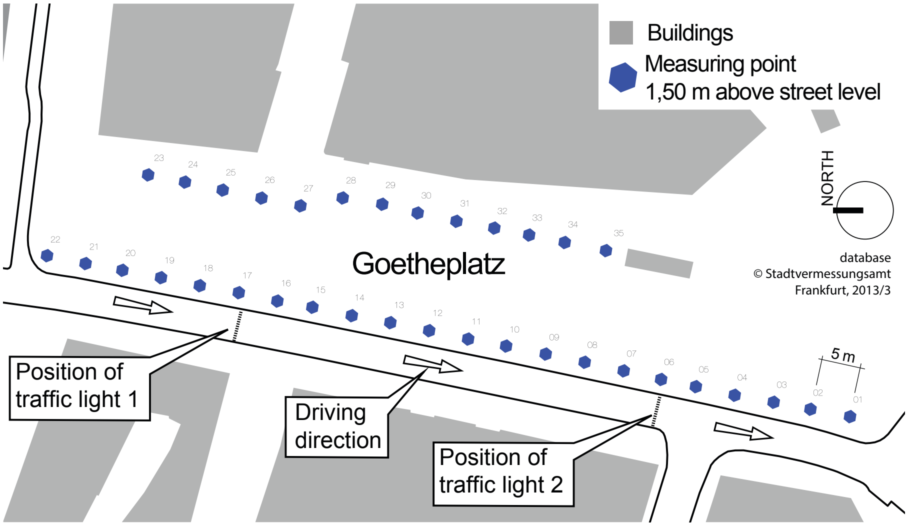


FIGURE 4.17 Measurement setup at Goetheplatz, Frankfurt/Main. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

Concluding investigations and considerations, the requirements for the measurement procedure and the equipment were defined.

§ 4.4.2 Measurement equipment and setup specifications

The measurement setup should fulfil the following requirements:

- Handheld digital recorders.
- External microphone to the digital audio recorder must meet the international standards of class 2
- Recording unit must record a reference audio file of a test signal from a calibrated sound source.
- Automatic input gain option must be switched off.
- The measurement positions must be set up in 1,6 m above street level.
- For one sequence in all 35 positions a one-minute measurement should be performed.
- A single measurement for one measurement point should start 30 seconds after the traffic lights 1 for crossing Goethestraße/Steinweg have switched to green.
- During the measurements all observations on weather, road traffic or other disturbances should be documented.

- Measurements should not be taken during storm, snow, heavy wind and heavy rain
- Measurements should be done between 10 am and 11:30 am on weekdays

§ 4.4.3 The measurement in situ at Goethe Platz

The measurements were performed twice on weekdays between 10:00 am and 11:30 am at all defined positions step by step. Before the on-site recording started a reference recording of a calibrated noise source was made with all handheld recorders engaged in the measurement. For every position two digital audio files were saved. Disturbances (e.g. loud cars or motorbikes) were documented. The recorded digital audio files with duration of one minute were aurally inspected afterwards in order to detect disturbances in the signal. Only audio files without any disturbance were further processed. For the frequency range from 90 Hz to 6000 Hz the levels of each octave frequency band were calculated using an open source frequency analysis software tool. (Audacity, 2014) The noise levels for each band in dB were recalculated for the sound pressure. The sound pressure value of all frequency bands was averaged and calculated back to the dB value. This method of recording and analysing is not capable of delivering absolute levels. For referencing the values of the individual recordings the reference recording of a calibrated noise source was analysed in the same way. When performing this measurement procedure with a handheld digital audio recorder it is feasible to compare the final values and evaluate the noise level changes between them. In order to achieve an insight on the correlation between the façade and the measured noise level, the measured values were linked to the plot of the Goetheplatz and to a picture of the façades.

§ 4.4.4 Results

The bar graphs represent noise level values for all points in a line. The 22 noise level values of the measurement next to the road illustrate the effect of the buildings on the noise level. By linking the evaluated noise level values with the position of the measurement point and the façade being located perpendicular to a measuring position the interdependences became visible. From the correlation graphic in Figure 4.18 it can be seen that on the corners of a block to the street, the level decreases in relation to neighboured level values. Refer to line A, C and D in Figure 4.18. The highest levels can be detected in the middle of the centred block. Refer to line E, G and H in Figure 4.18. In the measurement data there are level changes of 10 dB. Considering the measurement results around the Henninger Turm such a level change at a 5 m distance is possible. The noise level values of the east side of the Goetheplatz show similar characteristics as described for the west side façades. These results of the east side in combination with the west side are shown in Figure 4.19.

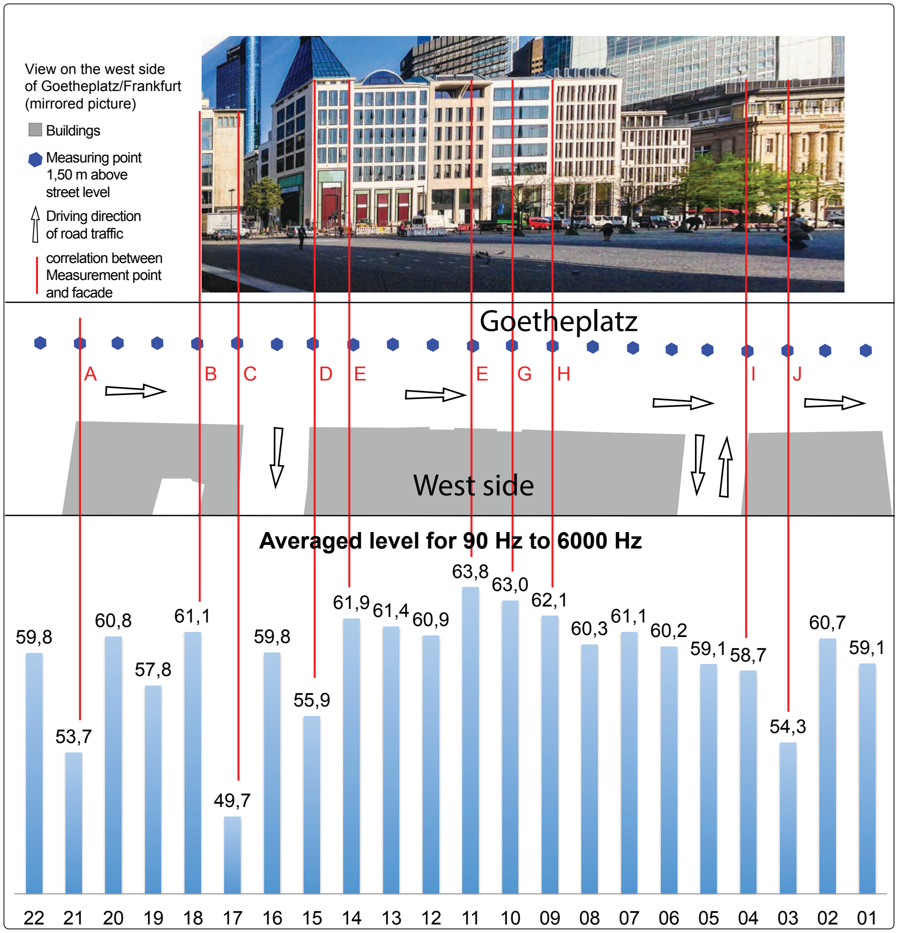


FIGURE 4.18 Correlation graphic for analysing the interdependences between the road traffic and the close façades of the west side of Goetheplatz. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

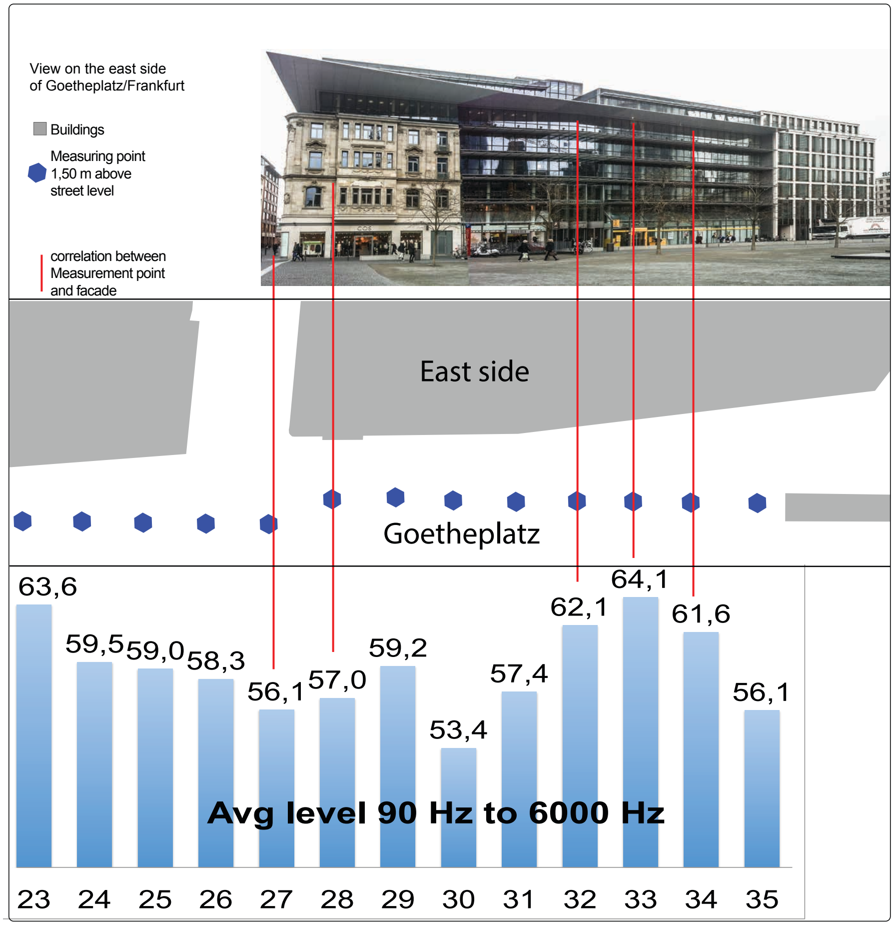


FIGURE 4.19 Correlation graphic for the east side of Goetheplatz. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

§ 4.4.5 Discussion

The results show a diffuse picture of an acoustic urban space.

The measured data shows the effect of buildings on an urban acoustic space. Nevertheless, a clear allocation of the observed effects to a particular façade is impossible. But in general, the reported noise levels do not represent a different expression then those experienced by researchers' ears.

With this method of time-wise analysing unsynchronised digital audio recordings, a detection of the direction of a noise signal is not feasible. This method delivers data with a resolution of 5 m on one axis that can be used for the detection of noisy areas.

From the results it can be concluded that the low-cost way of using digital recorders and the post processing of the data with open source software instead of calibrated multichannel noise level meters seems to be a feasible way of analysing urban spaces.

§ 4.5 Measurements at Lyoner Straße 54, Frankfurt/Main

§ 4.5.1 The situation on site

In this case study, the urban acoustic space around an eight-storey office building was investigated with a focus on aircraft noise. The building is located on the south part of the Lyoner Strasse in Frankfurt/Main, see Figure 4.20.

FIGURE 4.20 Lyoner Straße 54, Frankfurt, the abandoned office building on Lyoner Strasse 54, picture by the author.

At this site, the typical case of a building located nearby a flight path to Frankfurt Airport was investigated. The 100 m long and 15 m wide building is orientated nearly perpendicular to the arrival flight path of Frankfurt Airport. The spatial setting of is shown in Figure 4.21.

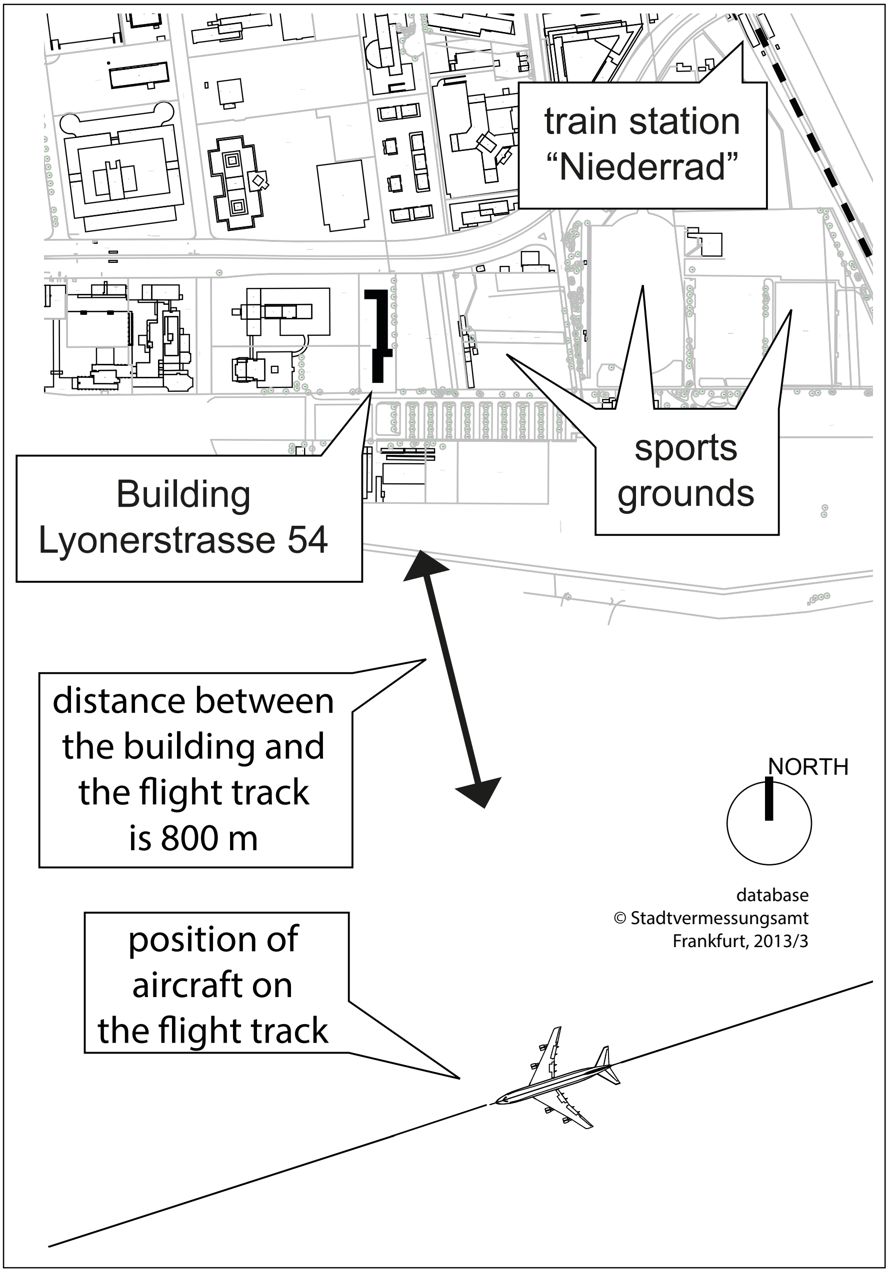


FIGURE 4.21 Drawing of the urban space and its noise sources around Lyoner Straße 54. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

Observation walks on site were performed as the first stage of the acoustical investigation. The walks pointed out that the soundscape perceived around the former office building is unique for every orientation of the building.

- At the north façade the four-lane Lyoner Straße with a tramline running down the centre of the street dominates the noise impression.
- Moving from north to south along the east façade the audible noise changes from cars and trams driving by to aircrafts inbound for Frankfurt Airport. In the intervals between the aircraft events the road traffic noise produces a constant noise floor.
- In front of the south façade aircraft noise seems to be the dominant noise source at this place but with a different time dependent audible impression than in front of the east façade. In the intervals between the aircraft events the road traffic noise is producing a constant noise floor but with lower levels due to the level reduction by the distance of 120 m to the street in the north.
- In front of the west façade the aircraft noise is the dominant noise source as road traffic noise is shadowed by a two-storey annex building located parallel to Lyoner Straße. The time-related noticeable change of audible perception was caused by the acoustic shadowing of the building itself in relation to the position of the aircraft on its way to Frankfurt Airport. On the east side an approaching aircraft can be noticed earlier than on the west side being in the acoustic shadow of the building. The acoustic shadowing also occurs with departing aircrafts. On the west side the aircraft is noticeable for a long time. At the same time point the noise emitted by the same aircraft is rather perceivable on the east of the building. The aural investigation of the situation on site was documented in a chart with focus on the different perception of the aircraft events. Refer to Figure 4.22. The description of the aural investigation procedure can be found in chapter 4.3.2.

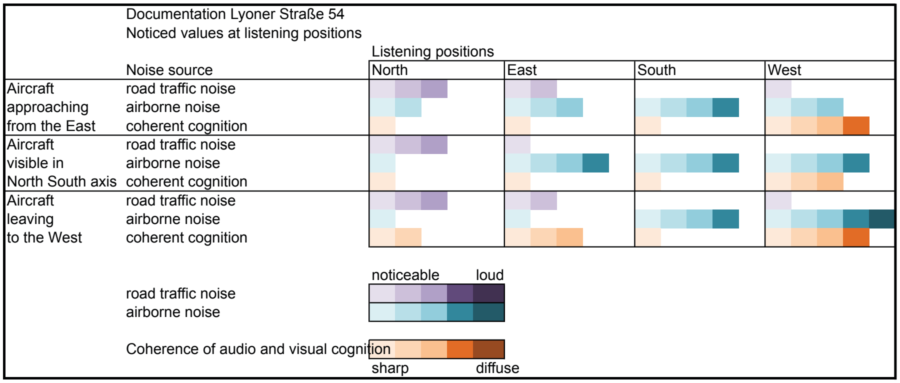


FIGURE 4.22 Documentation of the observation walks around the building Lyoner Straße 54

The aural investigation pointed out that for measurements in front of the north façade the traffic noise source could produce unclear level recordings regarding aircraft noise events. In order to capture the façade effect of the building in relation to the aircraft position on the flight path six measurement positions were defined around the building; four located on each corner and one each in front of the east and west façade. Refer to Figure 4.23.

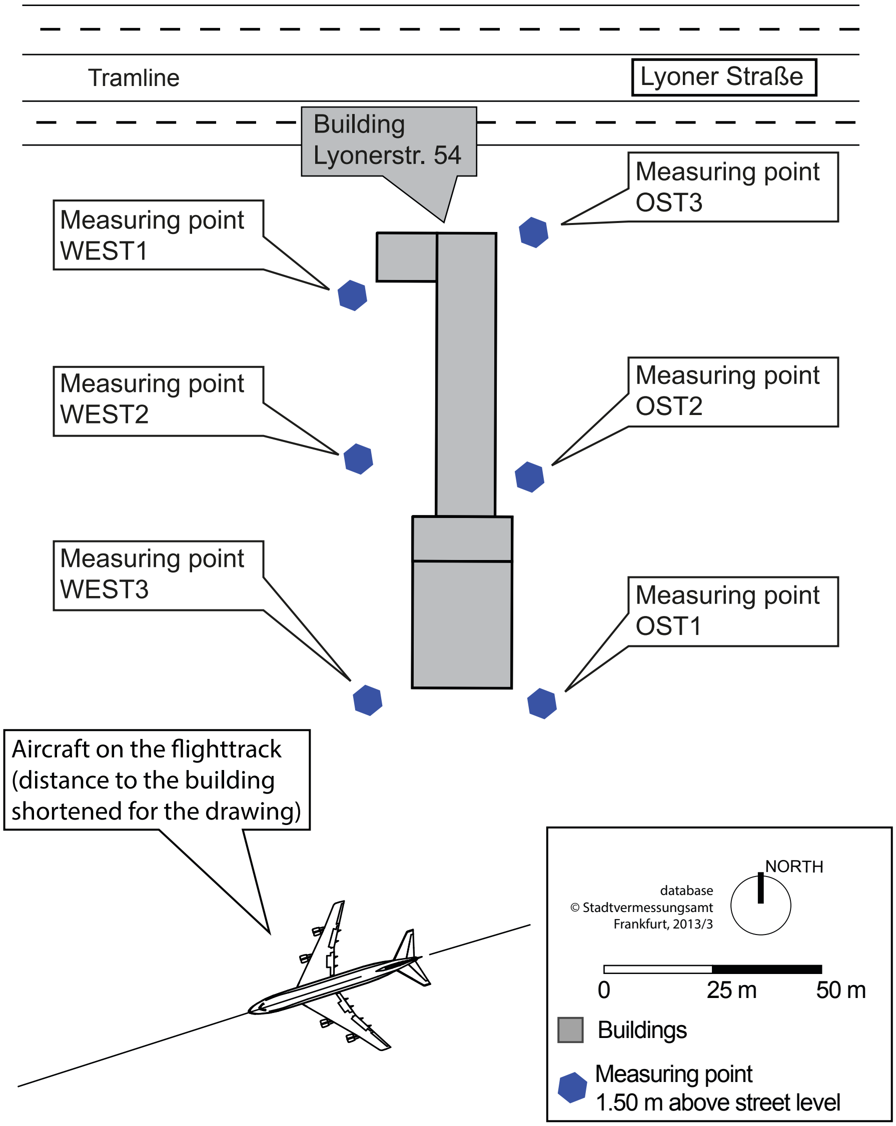


FIGURE 4.23 Layout of the measuring points at Lyoner Straße in Frankfurt/Main. Drawing based on data © Stadtvermessungsamt Frankfurt, 2015/5.

§ 4.5.2 The measurements and the equipment should fulfil the following requirements:

- Calibrated noise level meter with a calibrated microphone meeting class1 requirements with the feature of setting markers during the running measurement.
- Measurements should be done when the main flight path is active
- Use predefined measurement positions.
- All measurements should be performed for at least two flight events per measurement point.
- The time point during every aircraft event should be marked when the aircraft is in one line with the North-South elevation of the building.
- During the measurement all observations on weather, road traffic or other disturbances should be documented.
- Measurements should not be taken during storm, snow, heavy wind or heavy rain

§ 4.5.3 The measurement in situ at Lyoner Straße 54

The measurements at the Lyoner Strasse 57 took place in August 2015. The four runways of Frankfurt Airport are active in several scenarios depending on the wind direction. In the scenarios the direction for take-off is changed from west to east. In order to capture the aircrafts under similar conditions regarding their distance and height above ground the measurements were performed when the main path to Frankfurt Airport was active in the west direction. For the Lyoner Strasse 57 the direction west results in a perception of approaching airplanes on their way to Frankfurt Airport. At all six measurement positions two to four aircraft events were recorded with a noise level meter meeting class1 requirements. For every position a digital audio file and a measurement data file were saved. Every time an aircraft was in line of sight and in direction of the north-south elevation, a marker was set on the recording manually. Disturbing noise events like a driving by tram or construction noise were documented and marked. Listening with headphones all audio-recordings were inspected with the focus on heavy disturbances or noise overlays. The markers and the first slightly noticeable sound of the approaching aircraft on the recording defined time intervals for the level evaluation of each single aircraft event.

§ 4.5.4 Results

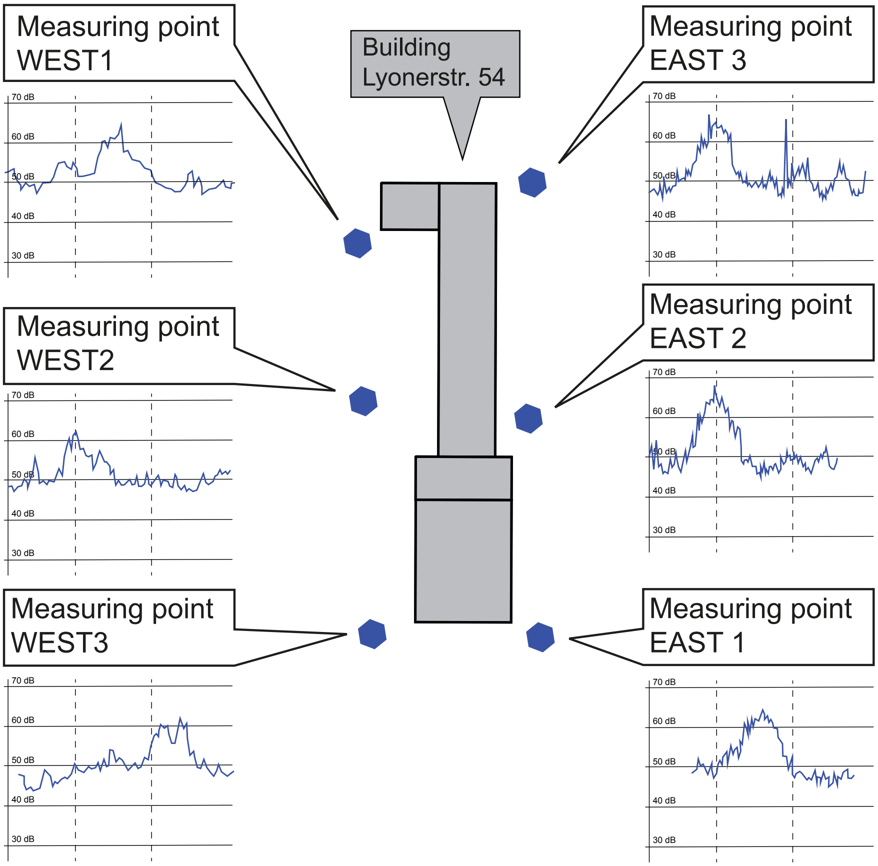


FIGURE 4.24 The level-over-time graphs for an aircraft event recorded in each measurement point.

Results from the analysis of the level-over-time graphs in Figure 4.24.

- A unique level-over-time graph is characteristic for each side of the building. Thus, the level-over-time graphs are confirming the acoustic experience of the observation walks.
- The graphs depict that during one recorded aircraft event the levels at the east side are about 5-8 dB higher than on the west side.
- The duration of higher-level readings is shorter on the east side than on the west side.
- With the highest-level readings in the measuring points WEST 2 and OST 2 the graphs are giving evidence for the façade effect at these measurement points.

§ 4.5.5 Discussion

The conducted on-site measurement results around the building Lyoner Straße 54 give evidence of the façade effect. The level readings at the façade related measurement points WEST 2 and OST 2 are 5 to 8 dB above the level readings of the corner related points WEST 3 and OST 1. The higher level readings were caused by reflection of sound energy on the façades. Furthermore, it can be observed that the levels on the approaching side of the building are higher but with a shorter duration. On the aircraft leaving side the duration is longer, and the levels are lower. As there are only two or three aircraft events recorded per measurement position one weak point remains. The quality of the recorded aircraft events has to be evaluated due to its significance for the urban space there. At this time of the research this evaluation is done manually by inspecting the recorded data during the measurement and afterwards by listing with headphones. Therefore, trained ears and experience is needed. A trained ear in this context does not represent an absolute hearing ability. It stands for the ability to identify a reoccurring noise event on a digital recording. With this compact setup of six measurement positions the decoding of the acoustical mechanism of a building in the vicinity of a flight path is feasible. It is believed that with more microphone positions at projected outdoor places like a public terrace in front of the building this setup will deliver a solid data base for an acoustical driven façade design implementing further investigation methods like scale model measurements.

§ 4.5.6 Are the here proposed on-site measurements methods able to deliver specific data, which are needed in additional to the insufficient data from existing sources like noise mapping/noise maps or the data of noise monitoring stations?

The conducted three different on-site measurements prove their practical feasibility as the results are providing detailed insight on the effect of façades on the surrounding urban space. In all three cases there is the façade effect present in the measurement data. In the conducted on-site measurements, the microphone positions were optimized due the capturing of the façade effect. Shifting the microphone positions to projected quiet places will deliver data on the façade effect regarding these projected places in relation to the impact of the noise source. With this data it will be possible to quantify the façade effect and formulate requirements for an acoustically effective façade design there. Beyond this the case study at Goetheplatz has pointed out that it is feasible using low cost digital handheld recorders calibrated with a recording of a referenced noise source instead of expensive calibrated class 1 noise level meters if an elaborated post processing of the gathered data is possible. The case studies at Gotheplatz and Lyoner Straße have further shown that a clear statement on the frequency distribution without limitations is only feasible if all measurement points were recorded simultaneously.

§ 4.6 Short discussion on practical applicability

Engineering or architectural offices mainly focus on one building or one façade being under refurbishment or construction at a time. If for this façade an acoustically effective design is intended the engineers must have two levels of information on the acoustical mechanism creating the surrounding urban space. The global level shall provide insight on the acoustic mechanism of the observed urban space. Noise maps or other forms of computer simulations can provide the global level of acoustical information. Narrowing down and stepping into specific acoustical design, more detailed information on the acoustic performance of the projected façade is required. This research focuses on a single surface, being part of a complex urban space. Similar to an obligatory subsoil exploration when dimensioning a buildings' foundation structure, an investigation method providing a full understanding of the acoustical mechanism of an urban acoustical space is mandatory. Acoustical on-site measurements meet the requirements of a field investigation as an analogy to the subsoil exploration in the early phases of every building project. A subsoil exploration proves information provided by engineering soil maps and narrows down the information in order to deliver more detailed information on the existing soil characteristic at all points of interest for the building project. Combining hands-on experience from working in architectural offices and the here presented work of developing and conducting on-site measurements, a basic setup of on-site measurements can be defined. Refer to Figure 4.25.

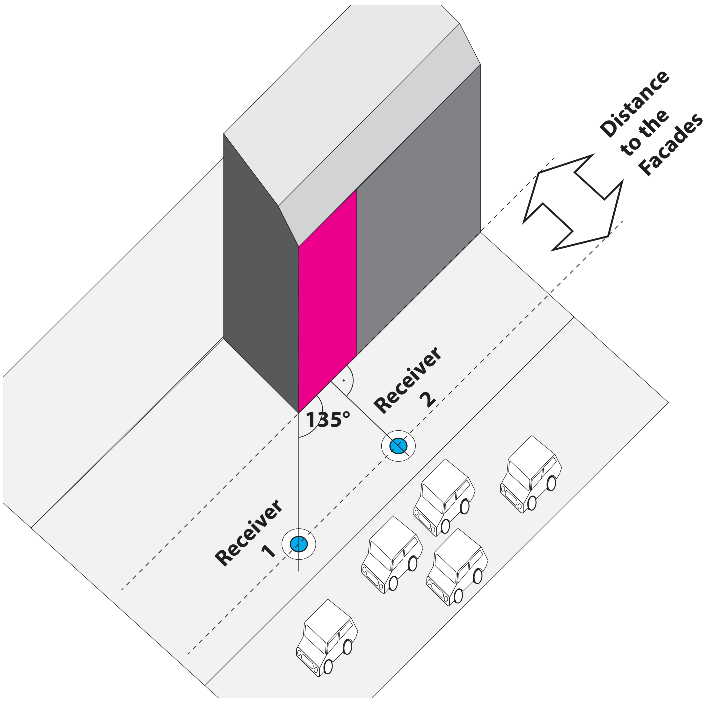


FIGURE 4.25 Basic setup of an on-site measurement for the façade located at a corner.

Figure 4.25 pictures the successful measurements around the Henninger Turm and at Lyoner Straße 54. Figure 4.26 shows a simplified version of the on-site measurement at Goetheplatz. Additional measurement points can extend the setup if the façade under construction is not located at a corner. Important in this context is the distance between the measurement points as it impacts the resolution of the gathered data regarding the localisation of the specific level readings.

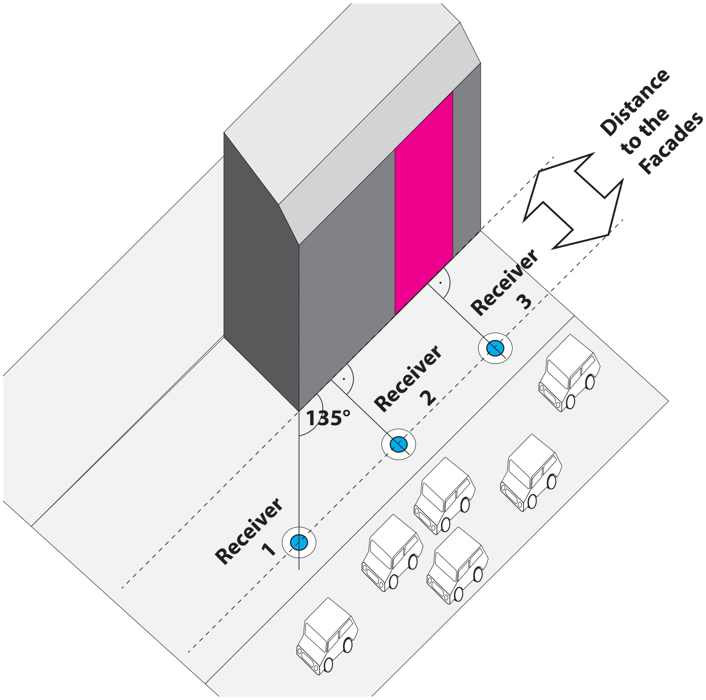


FIGURE 4.26 Basic setup of an on-site measurement with the façade being not located at a corner.

Considering all linear dimensions of the conducted measurements illustrates that this basic setup works for a wide range of distances between the single elements of it. Refer to Table 4.2.

CASE STUDY	Distance between source and façade	Distance between angled measuring point and façade	Distance between perpendicular measuring point and façade	Spacing between measurement points
Henninger Turm	2600 m or 800 m	72 m	70 m	30 m
Goetheplatz	12 m	17 m	15 m	5 m
Lyoner Straße 54	400 m to 800 m	6 m	5 m	50 m

TABLE 4.2 The distance dimensions in the conducted on-site measurements.

The absolute essential basis for a successful on-site measurement setup development and conduction is the preliminary investigation of the projected site by a trained person. A trained person in this context is a person with average hearing abilities but with awareness for noise events and spatial acoustic effects e.g. the mislocalisation of an aircraft.

The 1 to 1 implementation of this field measurement procedure can only be applied for refurbishment or substitute-building projects where the urban plot already exists. For the investigation of undeveloped sites measurements should be conducted to identify existing noise sources taking the projected building into consideration. The measurement positions should be defined in such a way that afore mentioned requirements regarding the façade effect are met. Refer to Figure 4.25 and Figure 4.26. This gives the opportunity to use the data as a basic setup for scaled measurements as described in the following chapter.

5 Scale measurements – laboratory methods

§ 5.1 Introduction

This section describes the method of scaled measuring and the application in geometry design studies.

The scale measurement method used in these geometry studies was based on the method of dimensional analysis by Lord Rayleigh (Rayleigh, 1915). With this method it became possible to scale down measuring setups applying the same dimension factor for scaling the setup and the signal to be measured. The first scale model investigations in engineering were done in the middle of the 18th century for the analysis of rivers and bridges. Later on, the method of scale modelling became common in the development of aeroplanes, cars, ships, bridges, and concert halls. Scale measurements are widely used in industry and research because they facilitate testing the impact of changed shapes or changes in size of downscaled elements, thus saving time and resources. For example, in a 1:1 scaling it is virtually impossible to change the entire construction of a bridge over a valley in order to select the construction that would deliver a better performance due to airflow in this valley.

When setting up acoustical measurements of an existing urban situation, the building layout has to be scaled applying the same factor as for the wavelengths of the audio signal emitted from the source. If the building layout is scaled down by a factor of 10 the frequency has to be scaled up by a factor of 10 to achieve a wavelength scale down of 1:10. Limiting factors to scaling in acoustical measurements are laboratory space and threshold frequencies of the equipment. The method of scale model engineering used for the acoustical investigations was developed using recommendations and formulas of D.J. Schuring (Schuring, 1977). Besides the work of Schuring, the recommendations derived from the scale model studies included in Chapter 2, Current status of acoustic urbanism, were taken into account. All scaled measurements done for this research were focused on pure geometry because one important limitation of the scaled model measurement method is the complexity of downscaling material absorption properties. Regarding the feasibility in an architectural design process the decision was made to use only simplified scaled model setups excluding absorbing properties, thus saving working time. As Nijs has shown in 1977 it is possible to calibrate an urban situation to a real situation with a minimum deviation by introducing materials with absorbing properties representing the material properties in reality. In the presented example intensive research over weeks was necessary to find a matching material for representing grass in the model. Models without these absorbing qualities show a deviation of 3 dB to reality (Nijs, 1977).

The first scaled model study refers to the urban setting at the Henninger Turm, Frankfurt am Main. Considering the interdependences of limiting factors, a laboratory setup for a façade design study on the Henninger Turm has been developed. During two measurement campaigns at TU Delft, several façade geometries were applied to a scale model of the tower and measured in equivalent measurement positions, which have been defined for the on-site measurement before. The scaled measurement data was first evaluated and then interpreted with a focus on the frequency distributed sound level differences between several façade geometries.

The second study was developed for the urban situation at Lyoner Straße 54, Frankfurt am Main. Data of the compact on-site measurement method described in chapter 4.5 was compared to data of the scaled measurement setup regarding similarity. In addition, the acoustical potential of an acoustically effective façade design close to flight paths was investigated.

As the case studies should represent daily practice in engineering or architecture, the approach to an acoustic façade intervention was different for both case studies. In the case study “Lyoner Strasse 54”, design consideration dominated the decisions leading to a façade design. The possible acoustical qualities were considered in a second step. In contrast, the façade modifications of the “Henninger Turm” study were developed to identify the acoustical effect of adding horizontal or vertical structures to the south façade and for the detection of the best modification.

§ 5.2 Scaled model study “Henninger Turm”

§ 5.2.1 Measurement setup at Delft University of Technology

The measurements of the “Henninger Turm” scale model study were conducted at the Delft University of Technology, Faculty of Applied Sciences, Department of Imaging Physics.

The equipment installed in the laboratory provides a 3D computer controlled rail system for the positioning of the measurement microphone covering a measurable space of 2.5 m to 3.0 m, 2 m high. Refer to Figure 5.1.

FIGURE 5.1 The 3D microphone positioning rail system at the laboratory at TU Delft, picture by Jelmer Niesten, 2015.

Meeting the international class 1 standards for audio measurements, the input stage of the equipment consists of a 1/4 Inch microphone and a matching preamplifier. The sound card of the measurement computer is capable of converting the analogue microphone signal to a digital signal with an upper frequency limit of 100 kHz. The output chain consists of a high frequency speaker and a high frequency amplifier linked to the sound card output. A program code controls the processing of measurements in relation to the programmable position of the microphone rail and the automatically saving of data to the hard disk drive. Refer to Figure 5.2.

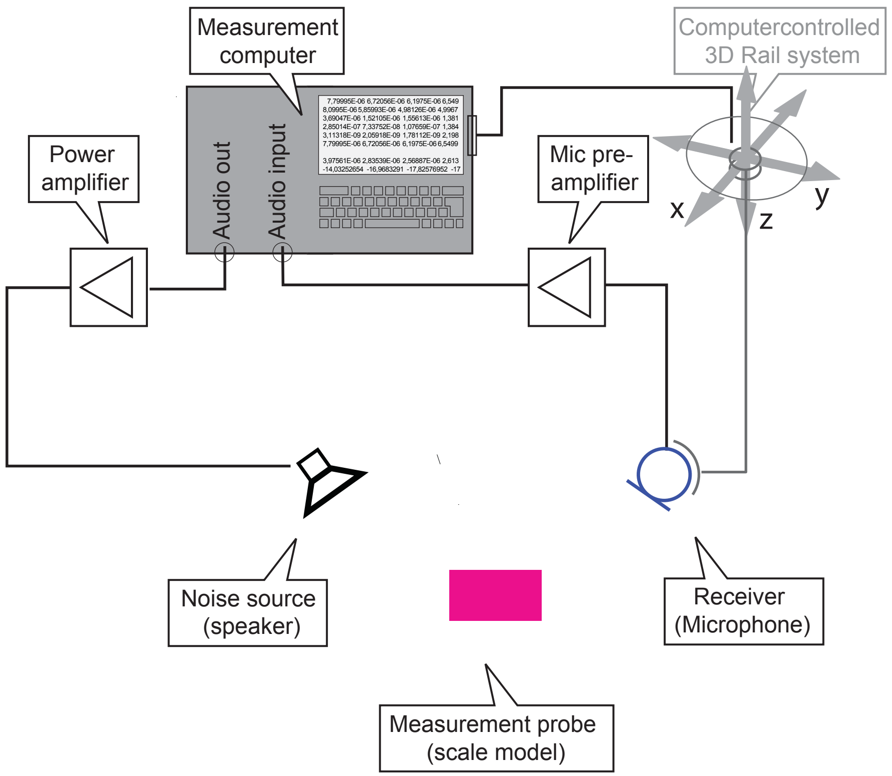


FIGURE 5.2 Measurement setup at Laboratory TU Delft

The validation of this basic setup was carried out by Lau Nijs in 1977 by comparison of environmental data and scale measurement data of an urban setup (Nijs, 1977).

The results of field measurements around the Henninger Turm were taken as a basis for the principle layout. Refer to Chapter 4.3. In preparation of the measurements, the existing building arrangement around the Henninger Turm was translated into a 3D geometry. Using the generated virtual 3D model, a scaling factor could be easily applied and the dimension of all parts and distances could be extracted. The measurement positions MP 1 and MP 2 are located at the same positions as they had been in the field measurements. Refer to Figure 5.3.

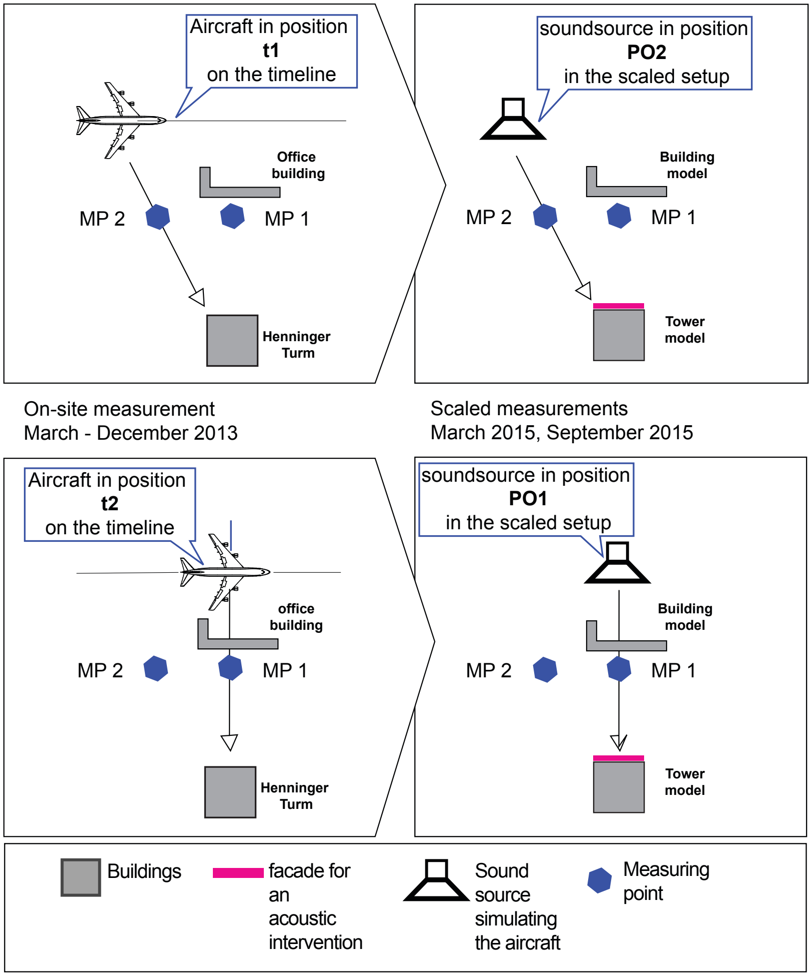


FIGURE 5.3 Translation of the on-site measurement to the scale measurement

The aircraft, which is a moving noise source in reality, was substituted by two fixed positions on the flight path, named PO1 and PO2. PO1 is set perpendicular to the south face of the tower. Measurements for PO1 were defined as "on-axis". Position PO2 is located in direction of the southeast corner. Measurements for PO2 were defined as "off-axis" measurements. The positions of the noise source are comparable to the real existing ones with respect to the resulting angle towards the ground plane and towards the south façade of the tower. Due to the limitations of the laboratory, the distance between the noise source and the tower had to be shortened from 16 m to 1.8 m. Figure 5.4 shows the principle setup.

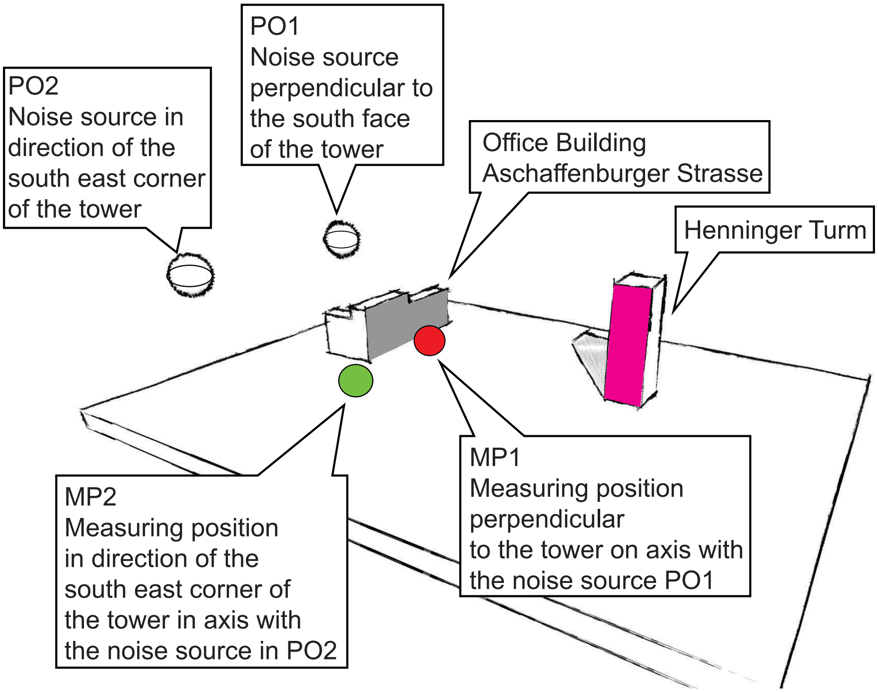


FIGURE 5.4 Situation around the Henninger Turm in the scale model measurement setup in 2015

For scaling, the suitable frequency range of the equipment was determined with regards to the threshold frequencies of every unit in the measurement chain. The low frequency threshold for the measurement chain is defined by the highest value for the low frequency threshold. The high frequency limit of the measurement chain is defined by the lowest value for the high frequency limit. The frequency range determined for the measurement chain in the laboratory was 600 HZ to 70,000 Hz. In order to exclude external factors, for example room size or air dissipation, a validation measurement for the source and the room was conducted. The measurement validated a frequency range from 800 Hz to 40,000 Hz. With this result the scaling of the measurement frequency range of the equipment was calculated by dividing the frequency with the scale factor. For the scale factor of 50 a frequency range from 16 Hz to 800 Hz was calculated. The determination of the frequency range is shown in Figure 5.5 for the 1:50 scaling.

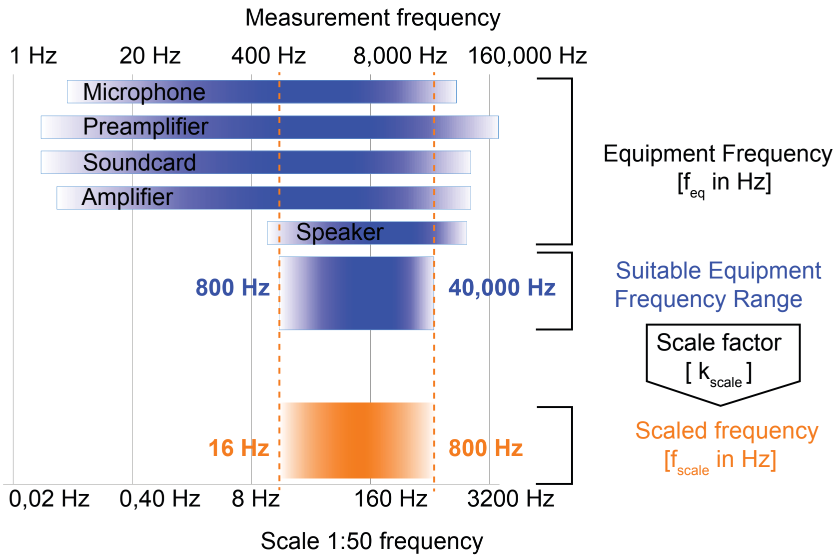


FIGURE 5.5 Determination of the scaled frequency range for a 1:50 scale

To evaluate the validity of a measurement sequence, the measurement of a flat reference surface is always operated in the first and the last step of an enclosed measurement sequence. The detachable façade modifications were measured one after another between the first and last reference measurement. Comparing the values of the first reference measurement with the last one determines the reliability of a measurement sequence. The results of this comparison provide insight into the effect of air dissipation on the measurement. The precision of a measurement sequence was defined by the maximum level deviation between both reference measurements.

The measured data of façade modifications were correlated with the reference measurement by subtracting the modified surface measurement values from the measured reference values. This procedure delivers results for frequency distributed level changes of the modified surfaces correlated to the reference surface.

For the measurement, planed wooden blocks represented the downscaled urban setup. The detachable façade models consisted of wooden or polystyrene profile rods mounted on a sheet of plywood. The dimensions of the profile rods were defined for a representation of known architecture elements such as lamellas, cornice stripes or balconies. The various dimensions of profile rods in scale and reality are shown in Figure 5.6.

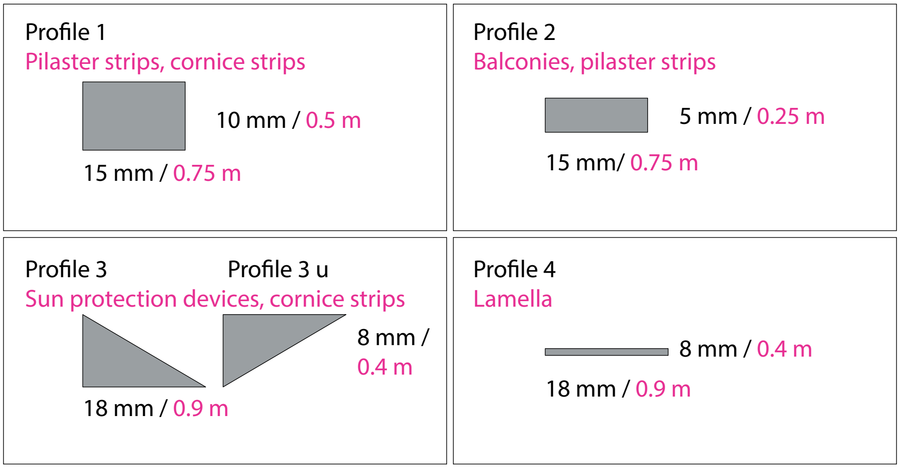


FIGURE 5.6 Section of profile rods used for building the detachable façade models.

The different types of profiles were mounted on a sheet of plywood in order to produce variations regarding orientation and spacing of profiles. Horizontal façade geometries with a different spacing between the profiles are shown in Figure 5.7. Two variations for façade geometries with a different spacing between horizontal lamellas are shown in Figure 5.8. A façade model during measurement is shown in Figure 5.9.

FIGURE 5.7 Horizontal façade geometries comprised of wooden „profile 1“ with three variations for the spacing.

FIGURE 5.8 Horizontal façade geometries comprised of polystyrene „profile 4“ with two variations for the spacing.

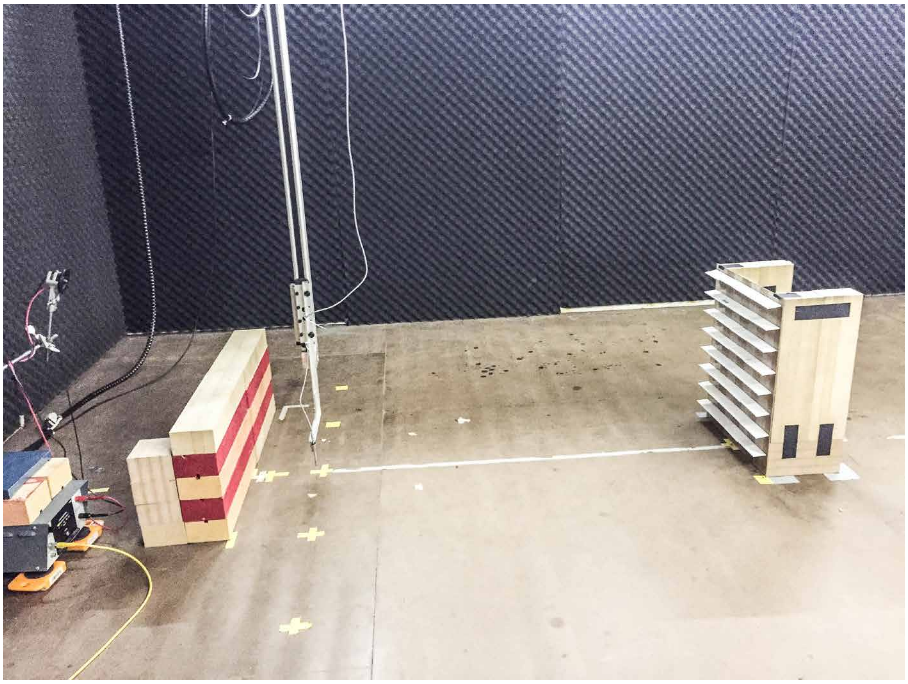


FIGURE 5.9 Model 6.5.1, a lamella type façade modification during measurement in the laboratory.

§ 5.2.2 Scale measurements – Sequence 1 - 2; Setup and data evaluation

For a comparison of scaled measurement data and on-site measurement data, sequence 1 was conducted with two microphone positions. In sequence 2, vertical and horizontal structures were measured to determine the significance of the data in relation to changing surface structures on a façade. Based on the experience conducting these first measurements and their results, a more detailed setup should be developed.

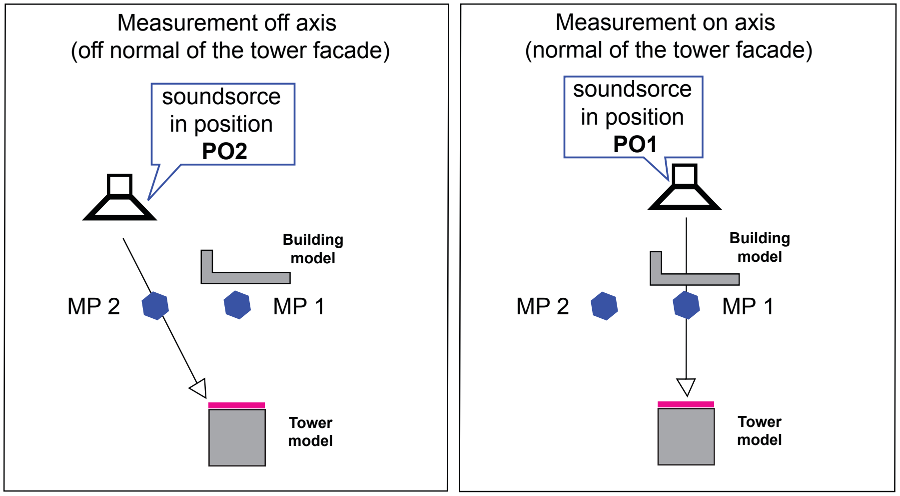


FIGURE 5.10 Scale measurement layout with two microphone positions.

A raw data set of a single measurement for one microphone position consists of frequency-distributed levels in the equipment frequency range from 1 Hz to 100,000 Hz. Only the frequency-distributed levels within the validated range of 800 Hz to 40,000 Hz were used for further calculations. In the next step the frequency numbers were scaled by the scale factor of 1:50 from 800 Hz to 40,000 Hz to 16 Hz to 800 Hz. The frequency distributed levels for the 1/3-octave frequency bands were calculated based on the frequency scaled raw data. In order to compare the on-site measurement data with the scaled measurement data, average levels of the frequency distributed levels for the frequency range of 16 Hz to 800 Hz were calculated. The calculation steps are shown in Figure 5.11.

In the following description the values for the frequencies refer exclusively to the scaled frequency values in the range of 16 Hz to 800 Hz.

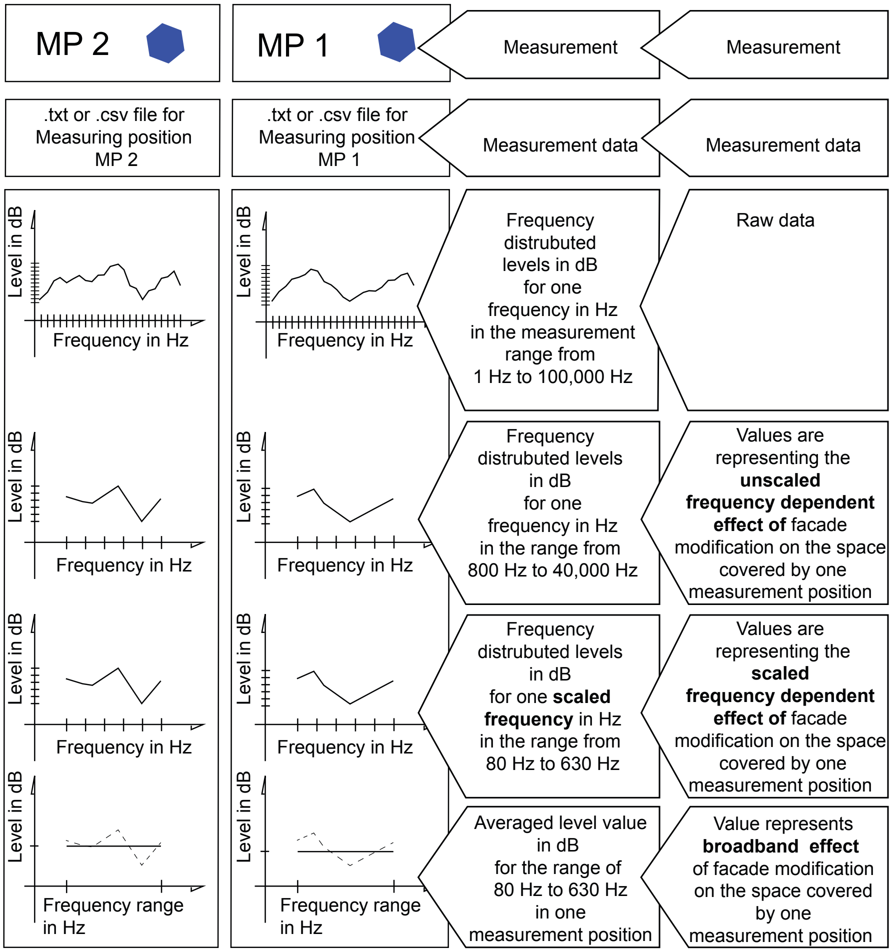


FIGURE 5.11 Data processing of two measurement positions

§ 5.2.3 Scale measurements – Sequence 1; Comparison measurement

Sequence 1 comprised two measurements. First, a measurement without the tower as a reference to the field measurements. Second, the tower model without modifications. The situation with and without the Henninger Turm was measured in the scaled setup to correlate the data captured with the on-site measurement data. Comparing the data determines the deviation of the scale measurement in relation to the field measurement. The measured models are shown in Figure 5.12

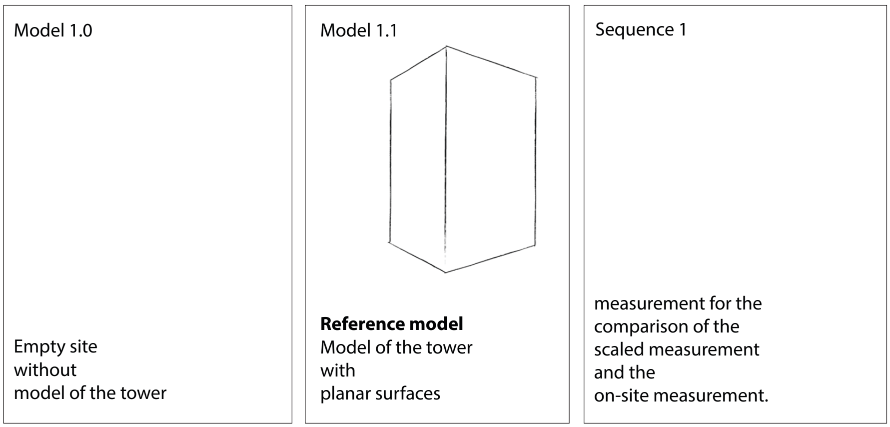


FIGURE 5.12 Measured model setups in sequence 1

The results for sequence 1 are presented and discussed in chapter 5.2.10.

§ 5.2.4 Scaled measurements – Sequence 2; Preliminary measurement

For sequence 2, three variations of façades were attached to the tower model in order to compare the achieved results with measurement data of the plane façade. Refer to Figure 5.13.

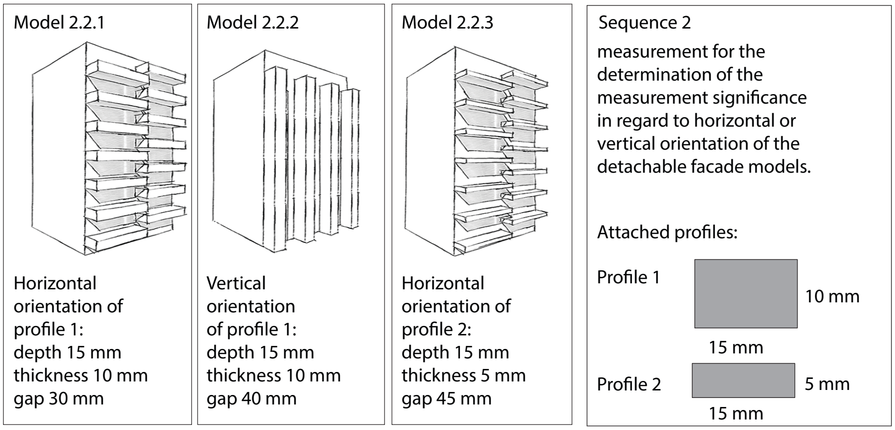


FIGURE 5.13 Measured model setups in sequence 2

The results of the sequence 2 are shown in Figure 5.14.

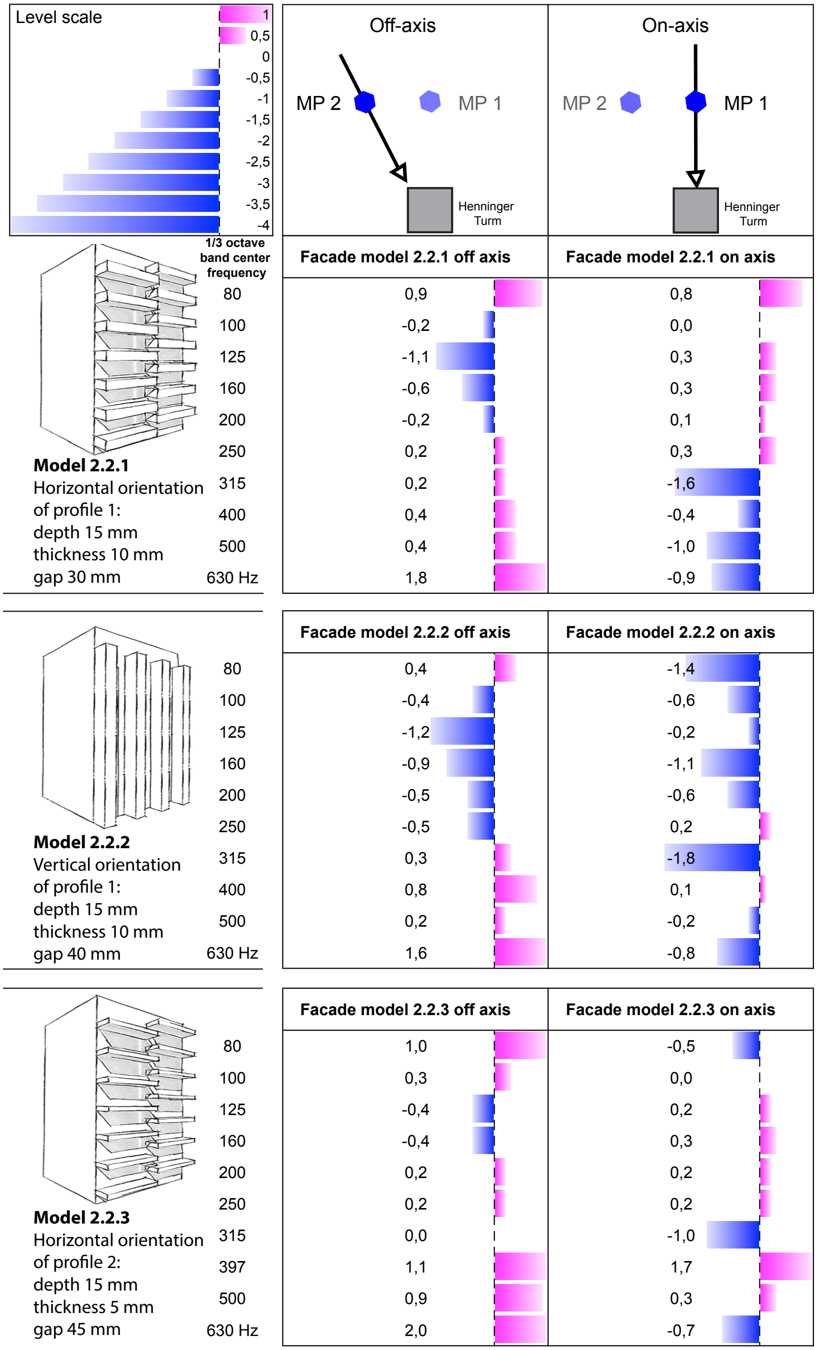


FIGURE 5.14 Results of Sequence 2

As can be seen from the results presented in Figure 5.14 there is a significant level change caused by the different setups of the façade according to their orientation. The difference between the measured models can be seen in the frequency range for the level decrease.

- For all three façade variations in both noise source settings, level decreases of -1 dB up -1.8 dB for single 1/3 octave bands were reported.
- For Model 2.2.1, a level decrease was reported on axis for 4 out of 10 frequency bands.
- For Model 2.2.2, a level decrease was reported on axis for 8 out of 10 frequency bands.
- For Model 2.2.3, a level decrease was reported on axis for 3 out of 10 frequency bands.

The results in Figure 54 also depict that a façade modification has an influence on the measurable levels of all measurement positions.

- For frequency bands with level decrease in the on-axis measurement, a level increase was reported in the off-axis measurement of model 2.2.1.
- Taking the level increases into account, model 2.2.2 affects the acoustic space in front of the building on-axis as well off-axis but in different 1/3 octave bands.

From the results the following conclusions are drawn:

- The attached geometries achieve a level reduction only to specific 1/3 octave frequency bands.
- A level reduction does not appear over the whole measured frequency range.
- The different directions of the noise source in relation to the façade model cause a wide span of variations of level reductions regarding the affected frequency band.

As this sequence was intended to deliver a rough sketch for the development of more detailed measurements no recommendations for a façade design were concluded from this data. Based on these results requirements for the models and the setup of the following measurement sequences were defined.

- For a more detailed view on the distribution of sound energy in front of the façade, more microphone positions have to be introduced.
- During one measurement sequence, only one form factor of the model should be varied.

§ 5.2.5 Scale measurements – Sequence 3 - 6; Setup and data evaluation

To obtain a more detailed view on the frequency distributed noise levels and the noise coverage of the urban space, three measurement points were introduced in the setup for the sequences 3 to 6. Position Pos 2 fills the gap between the positions MP1 (Pos 3) and MP2 (Pos 1). This extends the investigation area aiming to capture the noise events coverage spread over three microphone positions in front of the façade. Refer to Figure 5.15.

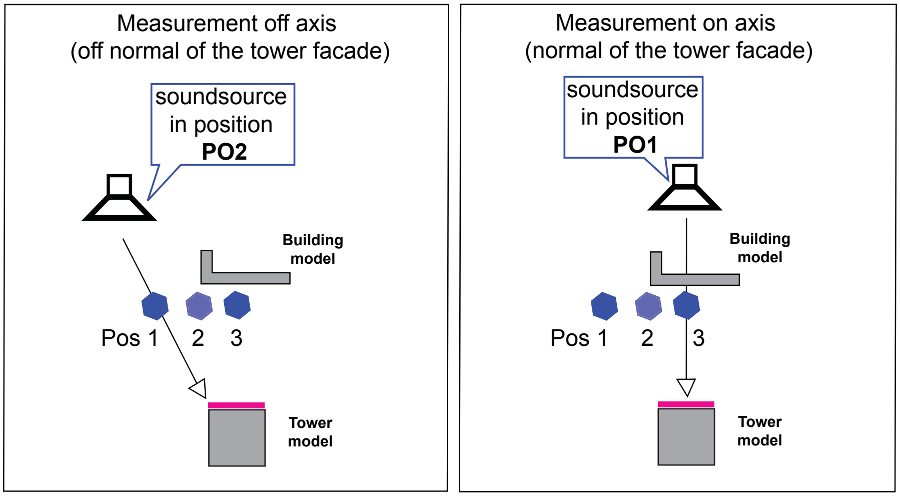


FIGURE 5.15 Scale measurement layout with three microphone positions

The three-point measurement data of sequence 3 to 6 was evaluated regarding the frequency-distributed level in each measuring point. A raw data set of a single measurement for each of the four microphone positions consists of frequency-distributed levels in the equipment frequency range from 1 Hz to 100,000 Hz. Only the frequency-distributed levels within the validated range of 800 Hz to 40,000 Hz were used for further calculations. In the next step the frequency numbers were scaled by the scale factor of 1:50 from 800 Hz to 40,000 Hz to 16 Hz to 800 Hz. As the frequency-distributed levels are not clearly readable in terms of the acoustical impact of a façade modification, the method of calculating single values out of frequency-distributed levels was used. The frequency distributed levels for the 1/3-octave frequency bands were calculated based on the frequency scaled raw data. In order to provide insight on the broadband effect of one façade model on the location of one measurement point average levels of the frequency distributed levels for the frequency range of 16 Hz to 800 Hz were calculated. The evaluation of the measurement sequences regarding the achieved accuracy revealed deviations on both sides of the defined frequency range. In order to get more precise results, the lowest and highest 1/3 octave band of the validated frequency range was excluded from calculations. All further calculations were processed for the frequency bands between 25 Hz and 630 Hz. For an evaluation of the broadband effect of a specific façade model on the space covered by four microphone positions, an average level of the four measurement positions was calculated. Refer to Figure 5.16.

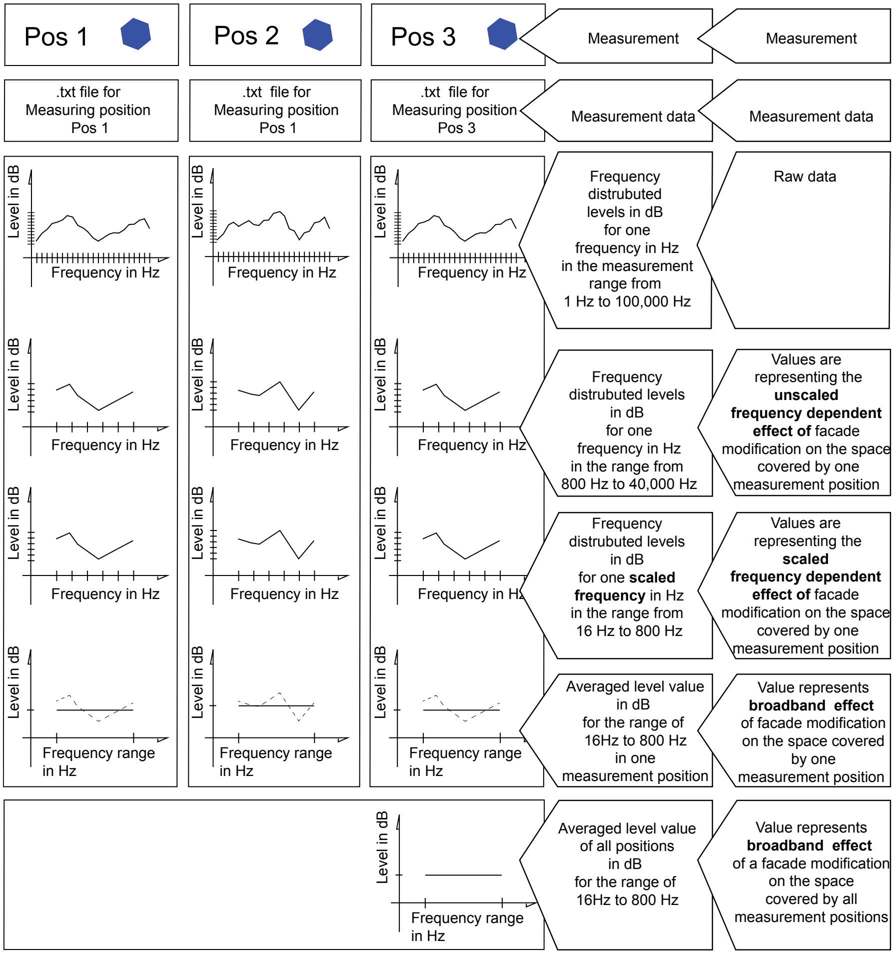


FIGURE 5.16 Data processing of three measurement positions

With these level values the acoustic potential of a façade model regarding level changes was determined. The level values of the reference model 1.1 were substracted from the level values of the façade model to quantify the level changes. Only calculation data derived from the same measurement sequence was used for a reliable result. The change of noise levels in relation to the reference model was calculated for distributed noise levels as well as for average noise level in the frequency range of 25 Hz to 630 Hz.

§ 5.2.6 Scale measurements – Sequence 3 and 6; Measured models

For sequence 3 to 6, the basic layout of the buildings in the scale model and the scaling remained the same. For these sequences the façade modifications were classified as horizontally oriented modifications and vertically oriented modifications. Attaching profile rods on a polished sheet of plywood created vertical and horizontal surface modifications. In these two classes the implemented variation of spacing in the arrangement of profile rods results in varying sizes of the front face area. Refer to Figure 5.17, Figure 5.18, Figure 5.19 and Figure 5.20.

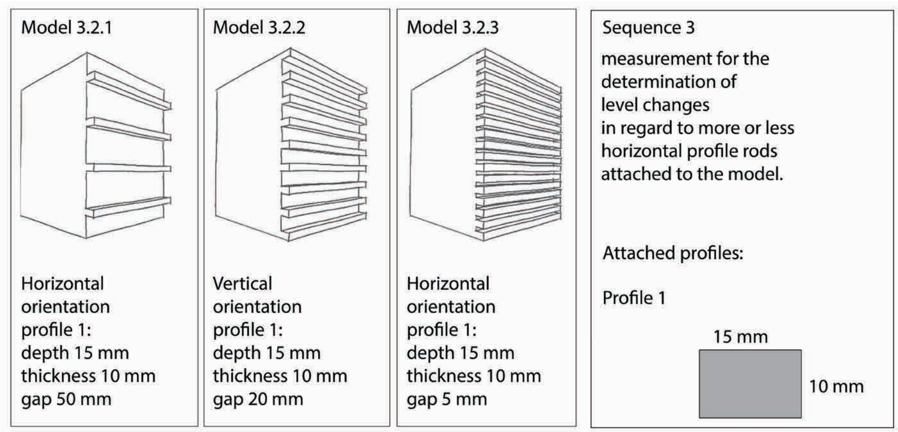


FIGURE 5.17 Variation of models with horizontal orientation in measurement sequence 3

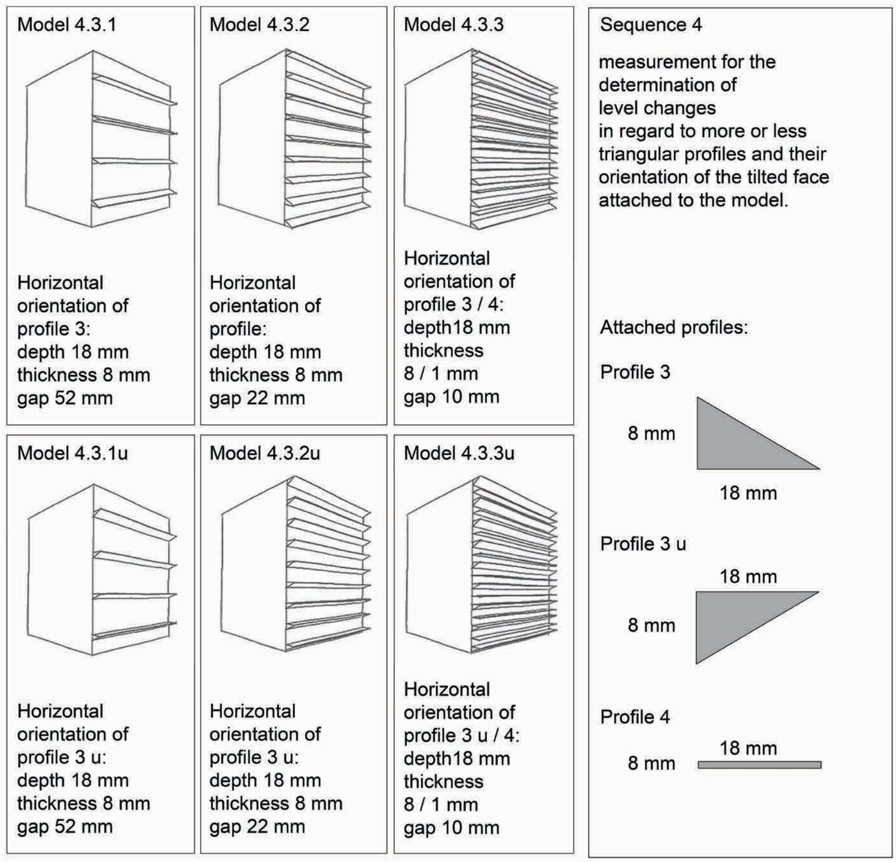


FIGURE 5.18 Surface modifications used in the measurement sequence 4

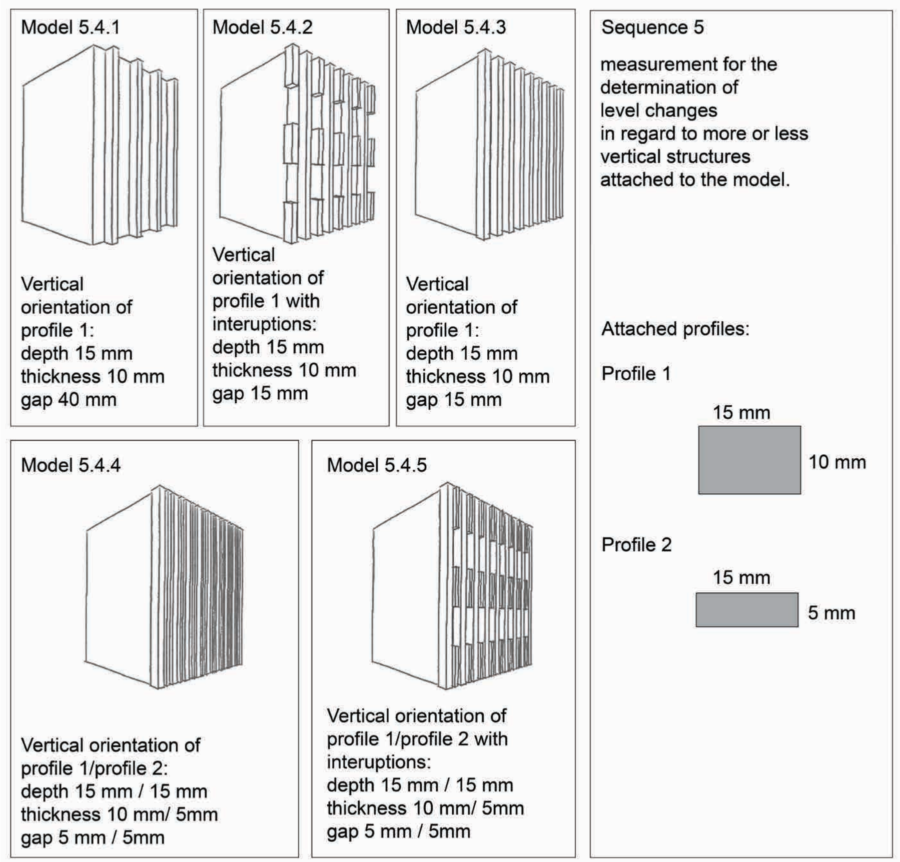


FIGURE 5.19 Surface modifications used in the measurement sequence 5

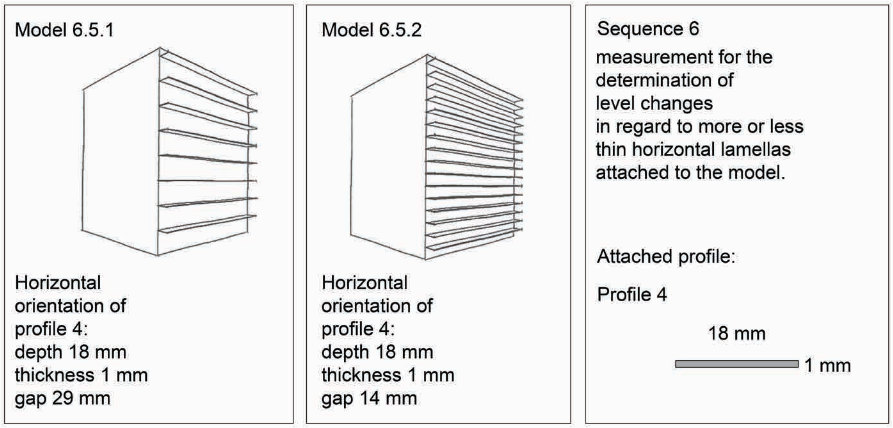


FIGURE 5.20 Surface modifications used in the measurement sequence 6

In the following sections the results of three measurement sequences are presented in detail.

§ 5.2.7 Results for sequence 3 – Thick horizontal lamella model

The results for models 3.2.1, 3.2.2 and 3.2.3 are presented exemplarily in the following. Results from on-axis measurements as well as from the off-axis measurements are shown. In the on-axis measurement setup, the noise source was located on the normal to the façade of the tower.

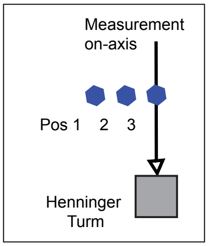
Acoustical façade parameters – Frequency distributed level changes vs. position

The results of varying measured, horizontally orientated façade models are shown in the bar graphs in Figure 5.21.

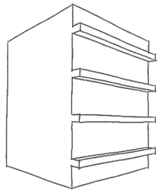
In all bar graphs, the comparison of the on-axis measurement data of the models 3.2.1, 3.2.2 and 3.2.3 and the reference model 1.1 indicate frequency dependent level increases and decreases. The level increases are below 1 dB for the models in all measured positions. From the data for Pos 3 for the noise level decrease, a dependency of frequency band and spacing of the profile rods can be derived. For the spacing of 50 mm (2,5 m) in Model 3.2.1 the maximum level decrease for 158 Hz is reported with

-1.9 db. For model 3.2.2 with a spacing of 20 mm (1.0 m) the maximum level change shifted to 397 Hz with -2.6 dB. In Model 3.2.3 with a spacing of 5 mm (0,25 m) the maximum decrease for 397 Hz is reported with 3 dB. Thus, the decrease of the spacing between the profile rods led to a higher value for the level decrease, and the affected frequency bands shifted from a lower to a higher one.

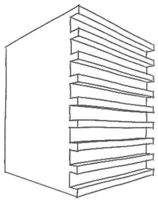
The off-axis results are shown in Figure 5.22. The bar graphs depict broadband level increases for positions Pos1 and Pos 2 for all three models. For Pos 1 a level increase of up to 0.9 dB is reported. The maximum level increase reported for Pos 2 is 0.5 dB for all three façade models. In Pos 3 broadband level decreases are reported for the three models in range of - 0.1 to - 1.4 dB. In the data of the off-axis measurement there is no trend visible, which indicates evidence for a dependency between different geometric properties. Refer to Figure 5.22.



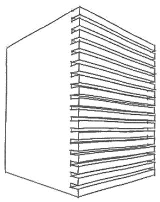
Model 3.2.1
Horizontal
orientation
profile 1:
depth 15 mm
thickness 10 mm
gap 50 mm



Model 3.2.2
Vertical
orientation
profile 1:
depth 15 mm
thickness 10 mm
gap 20 mm



Model 3.2.3
Horizontal
orientation
profile 1:
depth 15 mm
thickness 10 mm
gap 5 mm



Model 3.2.1 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	-1,1	0,9	-0,4
32	-0,6	0,2	0,1
40	0,8	-0,2	0,0
51	0,3	-0,2	0,1
63	0,1	-0,3	0,0
79	-0,1	-0,3	-0,7
99	0,2	0,0	0,1
125	0,0	-0,3	-0,7
158	-0,1	-0,8	-1,9
198	-0,1	-0,4	-1,0
250	0,0	0,1	-0,2
315	0,0	0,2	-0,8
397	-0,2	-0,3	0,1
500	0,0	0,2	0,4
630 Hz	0,3	-0,7	-0,3

Model 3.2.2 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	-0,6	-0,7	0,0
32	0,5	-0,6	-0,2
40	0,5	-0,1	-0,6
51	0,1	-0,4	-0,8
63	0,0	-0,2	-0,4
79	-0,2	-0,1	-0,5
99	0,1	0,0	0,2
125	0,0	0,0	0,7
158	0,0	-0,5	-0,2
198	-0,1	-0,1	-0,2
250	-0,1	-0,1	-0,2
315	0,2	0,1	0,3
397	-0,2	-0,7	-2,6
500	-0,1	-0,5	-0,3
630 hz	-0,1	-1,4	-1,6

Model 3.2.3 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	-1,8	-1,0	0,4
32	0,2	-0,8	0,3
40	0,4	0,4	-0,3
51	-0,1	-0,1	-0,6
63	-0,1	-0,3	-0,8
79	-0,1	-0,1	0,1
99	0,2	0,0	0,1
125	0,0	0,1	-0,3
158	0,1	-0,3	-0,3
198	-0,1	0,0	-1,3
250	-0,2	0,3	-1,2
315	-0,1	0,0	-0,7
397	-0,1	-0,4	-3,0
500	-0,1	-0,2	-1,8
630 Hz	0,0	-0,9	-2,6

FIGURE 5.21 Frequency dependent level changes for sequence 3 reported for the on-axis measurement.

TOC

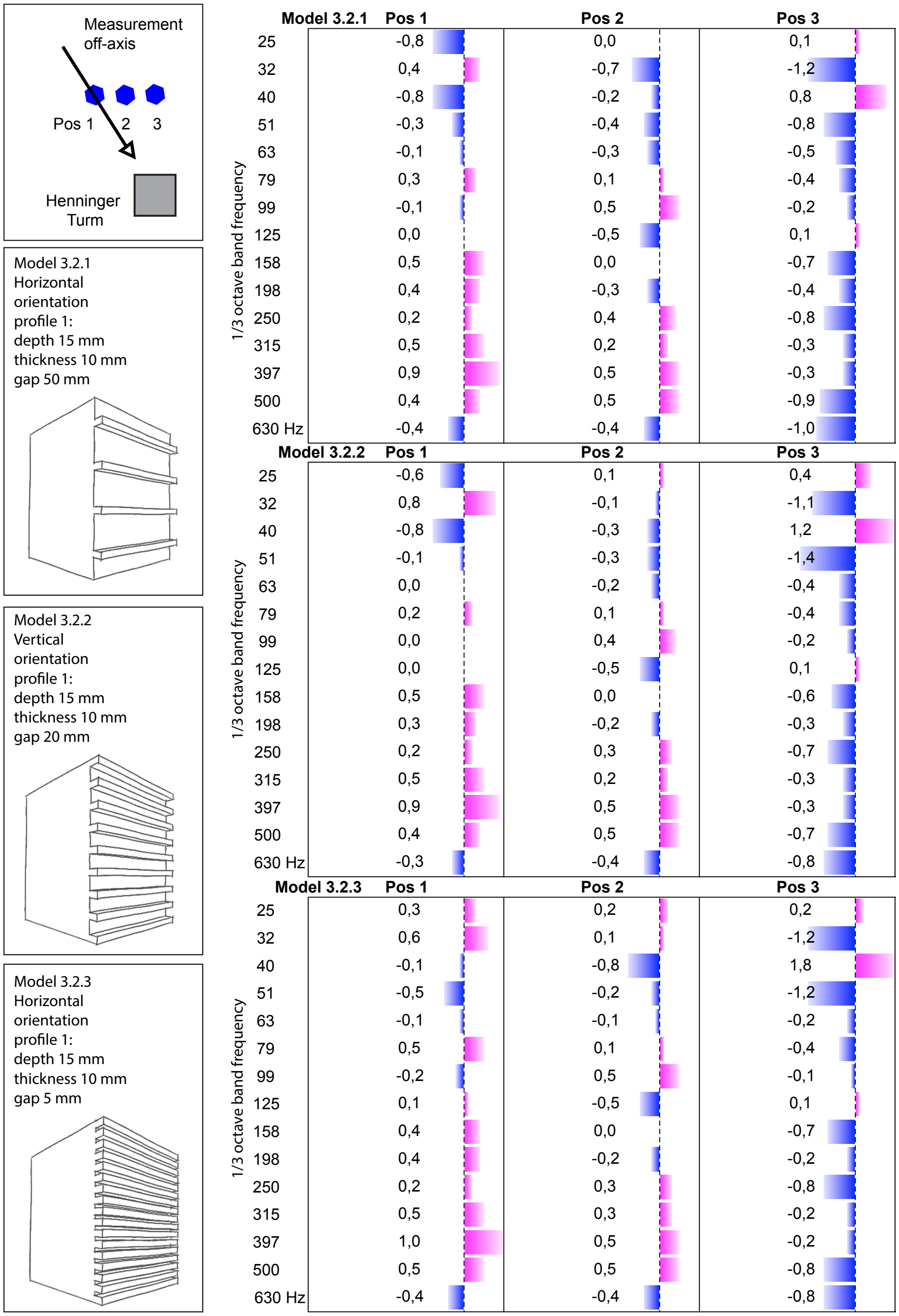


FIGURE 5.22 Frequency dependent level changes for sequence 3 reported for the off-axis measurement.

Acoustical façade parameters – Broad band level change vs. position

Calculating the average of the frequency distributed level data set for each measuring point delivers a single value on the broadband effect of one surface modification regarding one measuring point. The measurement with the noise source positioned on-axis shown in Figure 5.23 indicates level changes for the averaged noise level within the validated frequency range up to -0,7 dB. The level decrease was - 0,4 dB for the façade model 3.2.2 and -0.3 dB for model 3.2.1. Thus, the trend concluded for the frequency-distributed levels of the on-axis measurement is confirmed by the averaged values but in regard to the calculation of the average within a lower level range.

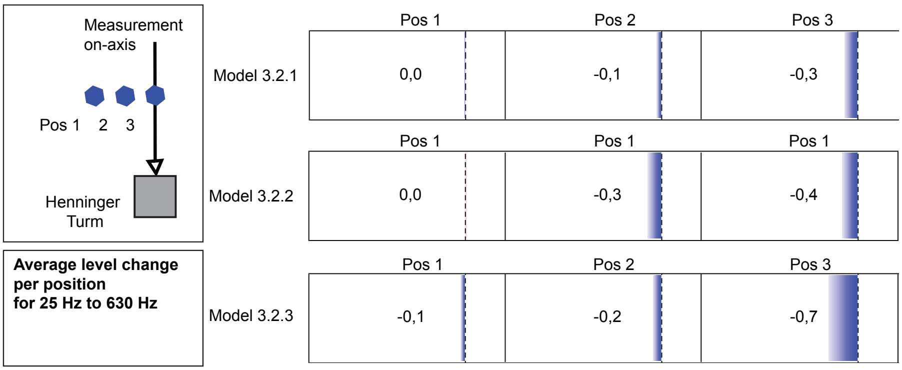


FIGURE 5.23 Level changes reported for the on-axis measurement of the façade models 3.2.1, 3.2.2 and 3.2.3.

For the single values of the off-axis measurements no trend is visible regarding the different models used in the conducted measurements. For position Pos 1 a slight level increase of 0.1 dB is reported for the three models. For these models in Pos 2 no change of level was calculated. A slight level decrease of -0.3 dB to -04 dB was observed for all models in position Pos 3.

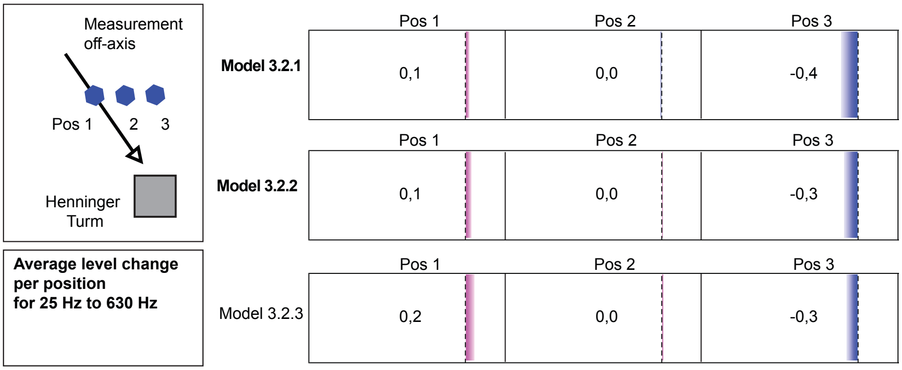


FIGURE 5.24 Level changes reported for the off-axis measurement of the façade models 3.2.1, 3.2.2 and 3.2.3.

§ 5.2.8 Results for sequence 6 – Thin horizontal lamella model

A variation of the effect of modifying the façade geometry with less or more horizontal elements added to the model is explained in the following with the results of the measurement sequence 6. The calculated on-axis level changes for two horizontal lamella models 6.5.1 and 6.5.2 in comparison to the planar façade of model 1.1 is shown in Figure 5.25.

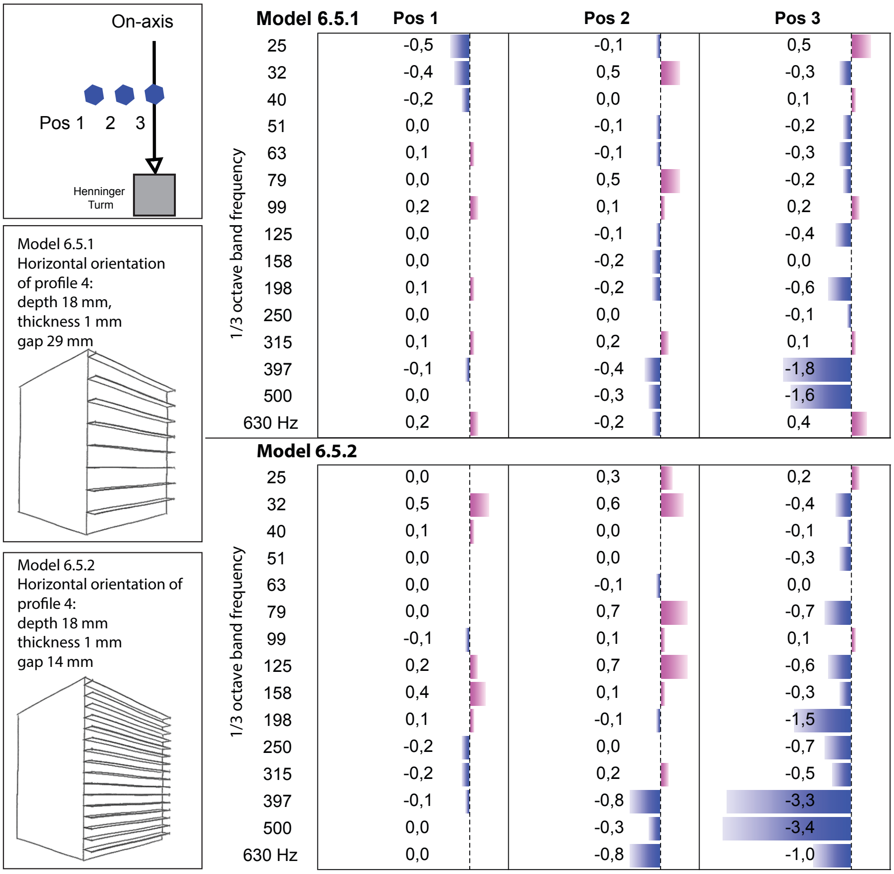


FIGURE 5.25 Frequency distributed level graphs depicting the measured level change for façade models 6.5.1 and 6.5.2 in relation to the planar reference model 1.0.

The graphs depict a decrease in noise level for position 3. For positions 1 and 2 the noise levels are slightly decreasing or increasing. For façade modification 6.5.1 the effect is less pronounced than for façade modification 6.5.2. At the measured frequency bands with a middle frequency of 198 Hz, 397 Hz and 500 Hz a significant level change can be detected.

As can be seen from the bar graphs in Figure 5.26 these trends were confirmed by the average of single values for each measurement point. In all graphs an introduction of more elements on the façade is in relation to a level change in the frequency-distributed graphs and in the single level values. But in contrast to the afore described measurement data of sequence 3, the frequency shift of the level decrease does appear for the thin lamella models 6.5.1 and 6.5.2.

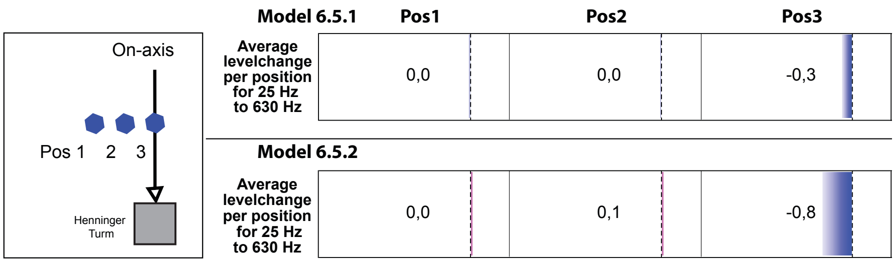


FIGURE 5.26 Average values for each measurement point reported for the models 6.5.1 and 6.5.2

§ 5.2.9 Results for sequence 5 - Vertical thick lamella model

In this sequence the acoustical effect of a step-by-step introduction of more and more vertical lamellas is documented by the calculated level changes per 1/3 octave frequency band. The bar graphs of the on-axis measurement in Figure 5.27 depict level reduction in all scenarios for varying frequency bands. In the graphs for the off-axis measurement in Figure 5.28 a level increase was calculated for nearly all frequency bands in all documented scenarios. The comparison of the data of on-axis measurement as well as the off-axis measurement reveals that the affected frequency bands in both measurements setups are close to a perfect match. The added geometry of vertical lamellas reduces noise levels caused for the on-axis noise source position while an off-axis position is causing increasing noise levels. In the on-axis data the trend is visible that more vertical elements cause more noise level reduction. With more lamellas added the maximum level reduction changes from -1.9 dB at 397 Hz to -4.4 dB at 397 Hz. In the off-axis data this trend is not clearly visible.

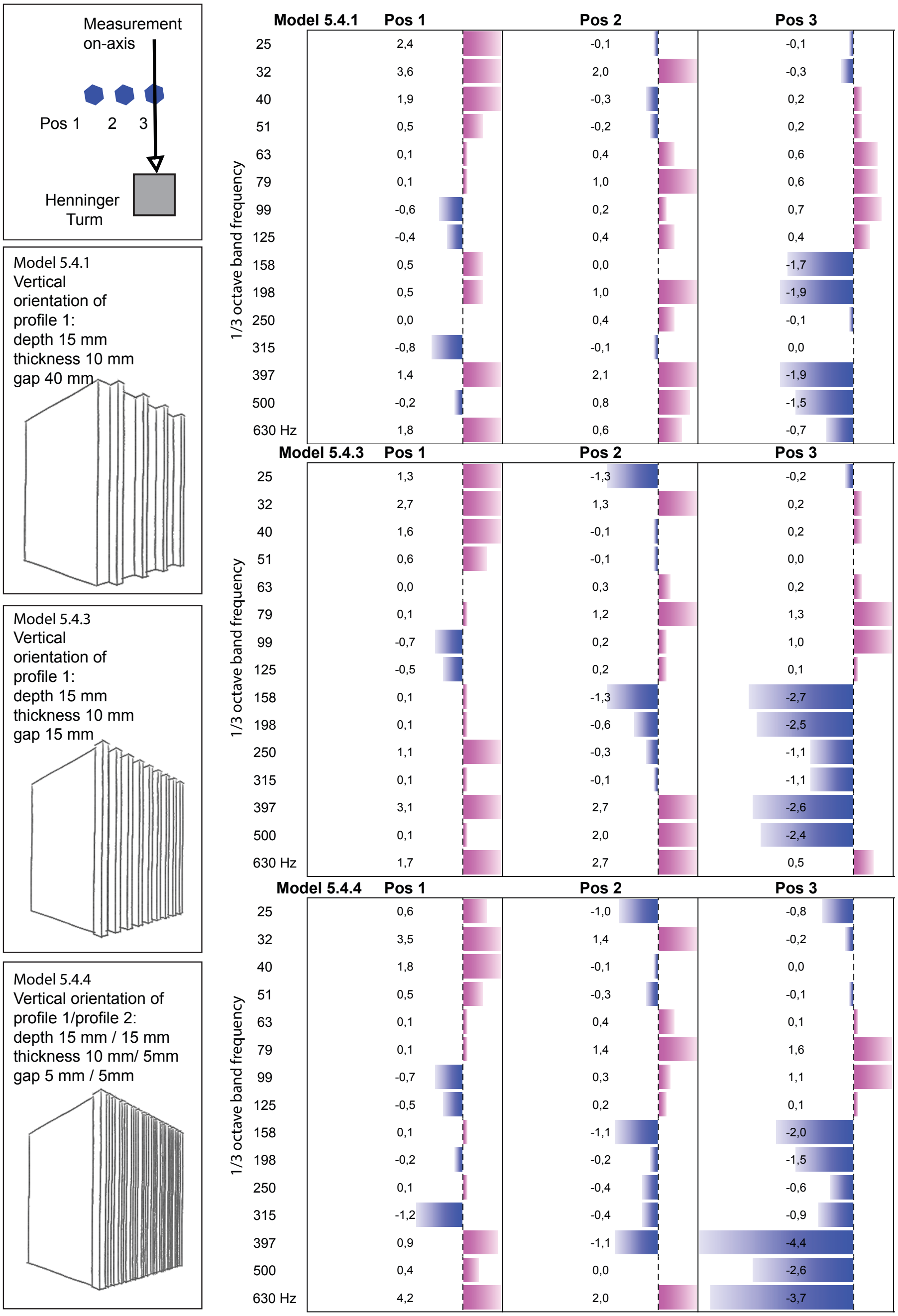
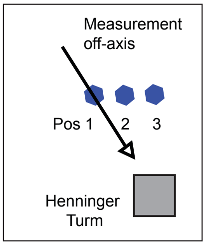
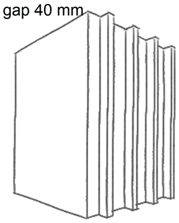


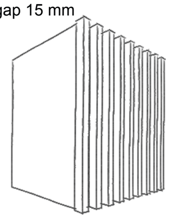
FIGURE 5.27 Measured data on-axis for vertical thick lamellas attached to the model



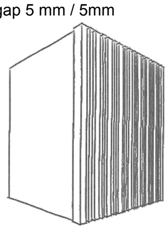
Model 5.4.1
Vertical
orientation of
profile 1:
depth 15 mm
thickness 10 mm
gap 40 mm



Model 5.4.3
Vertical
orientation of
profile 1:
depth 15 mm
thickness 10 mm
gap 15 mm



Model 5.4.4
Vertical orientation of
profile 1/profile 2:
depth 15 mm / 15 mm
thickness 10 mm/ 5mm
gap 5 mm / 5mm



Model 5.4.1 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	1,6	0,9	0,4
32	2,7	0,8	0,6
40	0,5	1,5	1,4
51	0,3	0,1	-0,1
63	0,1	0,1	0,0
79	0,3	0,1	0,2
99	0,1	0,1	0,0
125	0,0	0,1	0,1
158	0,1	0,1	0,6
198	0,1	0,2	0,3
250	0,1	0,2	0,4
315	0,1	0,1	0,3
397	0,2	0,2	0,8
500	0,7	0,4	0,8
630 Hz	0,3	0,4	0,4

Model 5.4.3 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	1,4	0,8	0,8
32	2,7	1,2	0,4
40	0,3	2,4	1,4
51	0,2	0,3	0,2
63	0,1	0,1	0,1
79	0,3	0,1	0,1
99	0,1	0,1	0,0
125	0,0	0,1	0,1
158	0,3	0,2	0,2
198	0,1	0,4	0,1
250	0,0	0,1	1,3
315	0,0	0,1	0,5
397	0,2	0,2	2,2
500	0,5	0,7	1,6
630 Hz	0,3	0,7	0,6

Model 5.4.4 (1/3 octave band frequency)	Pos 1	Pos 2	Pos 3
25	1,4	0,8	0,8
32	2,7	1,2	0,4
40	0,3	2,4	1,4
51	0,2	0,3	0,2
63	0,1	0,1	0,1
79	0,3	0,1	0,1
99	0,1	0,1	0,0
125	0,0	0,1	0,1
158	0,3	0,2	0,2
198	0,1	0,4	0,1
250	0,0	0,1	1,3
315	0,0	0,1	0,5
397	0,2	0,2	2,2
500	0,5	0,7	1,6
630 Hz	0,3	0,7	0,6

FIGURE 5.28 Measured data off-axis for vertical thick lamellas attached to the model

With vertical lamellas a level reduction of more than -3 dB can be achieved for specific frequency bands but the level reduction switches to a level increase if the noise source is changing its location from on-axis to off-axis.

Acoustical façade parameter – General level change

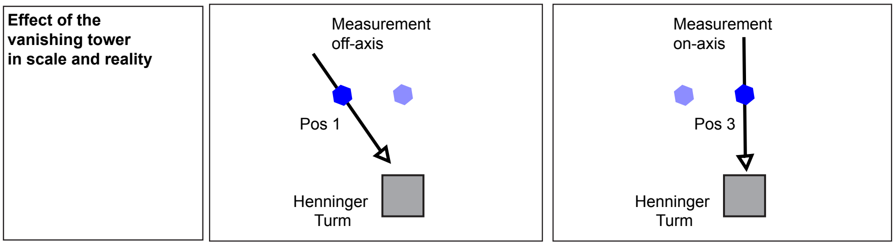
The attempt was made to achieve a specific general value for one façade model data if all three positions were used. Therefore, the three averaged frequency-distributed levels of each microphone position were averaged resulting in one level value for each surface modification within the validated level range of 25 Hz to 630 Hz for the space covered by the three microphone positions. Due to the calculation of the average, the results showed nearly similar low-level values for all measured façade modifications in the range of -0.1 to 0.3 dB. Thus, the calculation of a global value is not feasible for characterizing the effect of a façade modification on an urban acoustic space.

Only with frequency depended dB values is it possible to represent the acoustical effect of a façade on an urban space.

§ 5.2.10 Results of method suitability

A comparison of the laboratory setup and the on-site measurement at the Henninger Turm is presented in the following.

The effect of the vanishing tower was captured in two measurement setups, the on-site measurement and the scale model measurements. In sequence 1 and 3 comparison measurements with model 1.0 and without were conducted to determine the deviation between the real situation at Henninger Turm and the scale model. Subtracting the calculated average levels for the frequency bands between 25 Hz and 630 Hz for the setup with tower from the one without tower delivers values for the comparison of the effect of the vanishing tower in scale and reality. The comparison of the calculated average levels for the frequency bands between 30 Hz and 800 Hz in scale and reality is shown in Figure 5.29.



	off axis	Deviation to on-site data	on axis	Deviation to on-site data
On-site measurement 130907 (with tower) 131221 (without tower)	-2,53	0	-4,74	0
Sequence 1	-0,13	-2,4	-4,28	-0,46
Sequence 3	-0,16	-2,37	-3,67	-1,07
Deviation for scaled measurements without absorbing properties [ref]		-3		-3

FIGURE 5.29 Level decrease after the dismantling of the tower in scale and reality.

The comparison pointed out a deviation of 0.5 dB for sequence 1 and 1.1 dB for sequence 2. The off-axis measurement data comparison delivers a deviation of 2.4 dB for sequence 1 and sequence 2. One reason for the deviation between scale and reality is the simplified scale model setup. All surfaces in the scaled model setup were made out of planed or polished wood surfaces. With this simplification it is not possible to match reality 100%, as the absorbing properties were not taken into account. For models without absorbing properties in scale measurements an accuracy of matching scale and reality can be achieved with a deviation of 3 dB. In the conducted measurements a deviation of 1.1 dB or 0.5 dB was below this deviation value defined by Nijs in 1977 (Nijs, 1977). The second reason was the substitution of a linear travelling noise source in reality by a point source in scale located at two points on the travelling path. With this setup, only an approximation to the real noise source setup of a moving aircraft was feasible.

Despite the calculated deviations, the setup at TU Delft provided adequate accuracy for the planed investigation of different façade models in a simplified setup. The achieved precision in the measurement sequences was evaluated with the reference model 1.0 measured at the start and the end of each conducted sequence. The reported deviation was in the range of +/- 0.1 dB. The reported level changes within the range of +/- 0.1 dB are neither reliable nor can they be detected by the human ear.

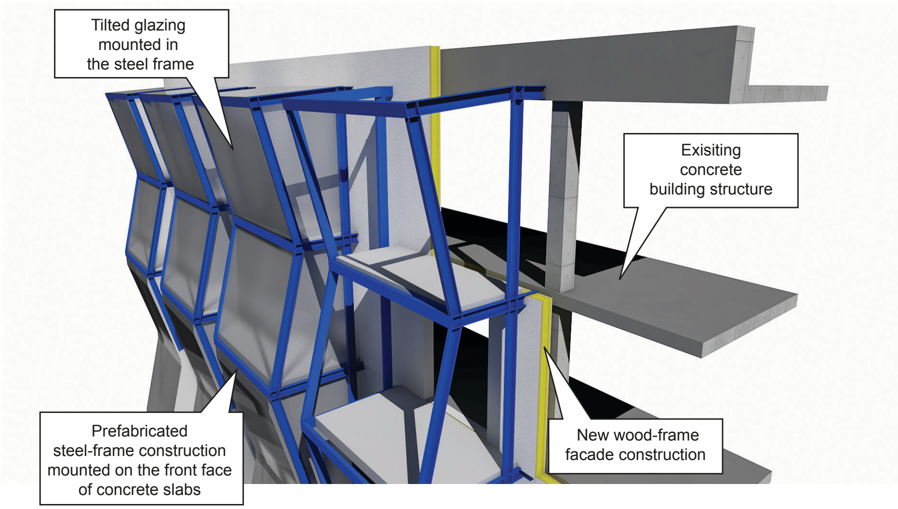
This evaluation method enclosed in the measurement and evaluation procedure proves the reliability of this scaled setup representing a scaled down reality and delivering validated results in the described range.

§ 5.3 Scale model study "Lyoner Straße 54"

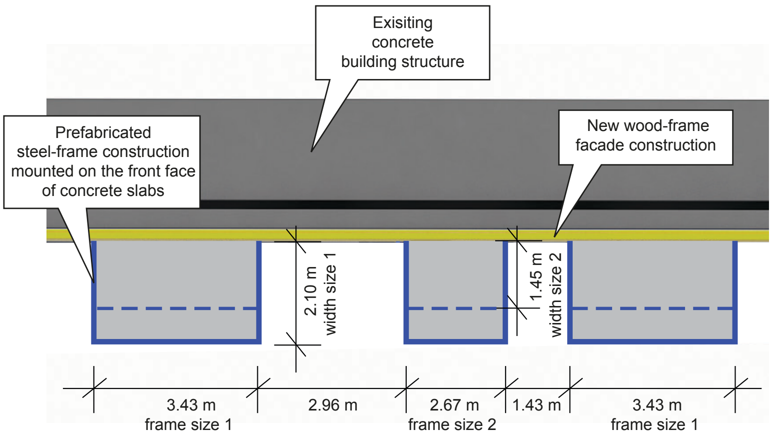
§ 5.3.1 Measurement setup at Federal Highway Research Institute (BAST), Bergisch Gladbach

In this part of the study, the building and the developed on-site measurement layout of Lyoner Straße 54, which is described in Chapter 4.5, was taken as a basis for the downscaled setup. The office building, which was documented in the on-site measurement, was part of a projected conversion area in Frankfurt/Main. In the area of the so-called "Office City Niederrad" the plan is to convert office spaces into living spaces. The project and its exposed position to noise sources are described in detail in Chapter 2.2. A refurbishment project for the conversion into an apartment building was designed for the former office building of an insurance agency. The focus of the façade design was the development of additional balcony space in front of the façade. A prefabricated steel frame construction mounted on the faces of the concrete slabs provides balconies space from 3.8 m^2 to 7.2 m^2. The steel frame is covered with a sun shading glazing, which provides an enclosed space for each balcony. The outer shape of the glazing matches the different widths of the balconies. The result is a glazing structure comprised of inclined and declined glass surfaces with an angle of 14° off the vertical. Because of its position close to flight paths the intended design should be tested regarding its acoustic performance to the outside of the building. The principle of the façade design concept is shown in Figure 5.30.

With the method of scaled measurement, it was possible to investigate the acoustical effect of this refurbishment façade design close to flight paths. The focus for this measurement was the determination of the façade effect at all measurement points under similar conditions. The scaled setup around Lyoner Straße 54 was measured in two variations to determine the acoustical effect of the façade. The first variation was the existing scaled setup; the second variation was comprised of the model with the intended new modified façade attached to the building. The existing structured façade of the office building was substituted in the scale model by a plane façade because this gives the possibility of the determination of a potential façade effect in relation to a defined zero point, a plane surface. The two setup variations in relation to the original building are shown in Figure 5.31.



Perspective view of facade concept



Top view of facade concept

FIGURE 5.30 Perspective and section drawing of the façade extension

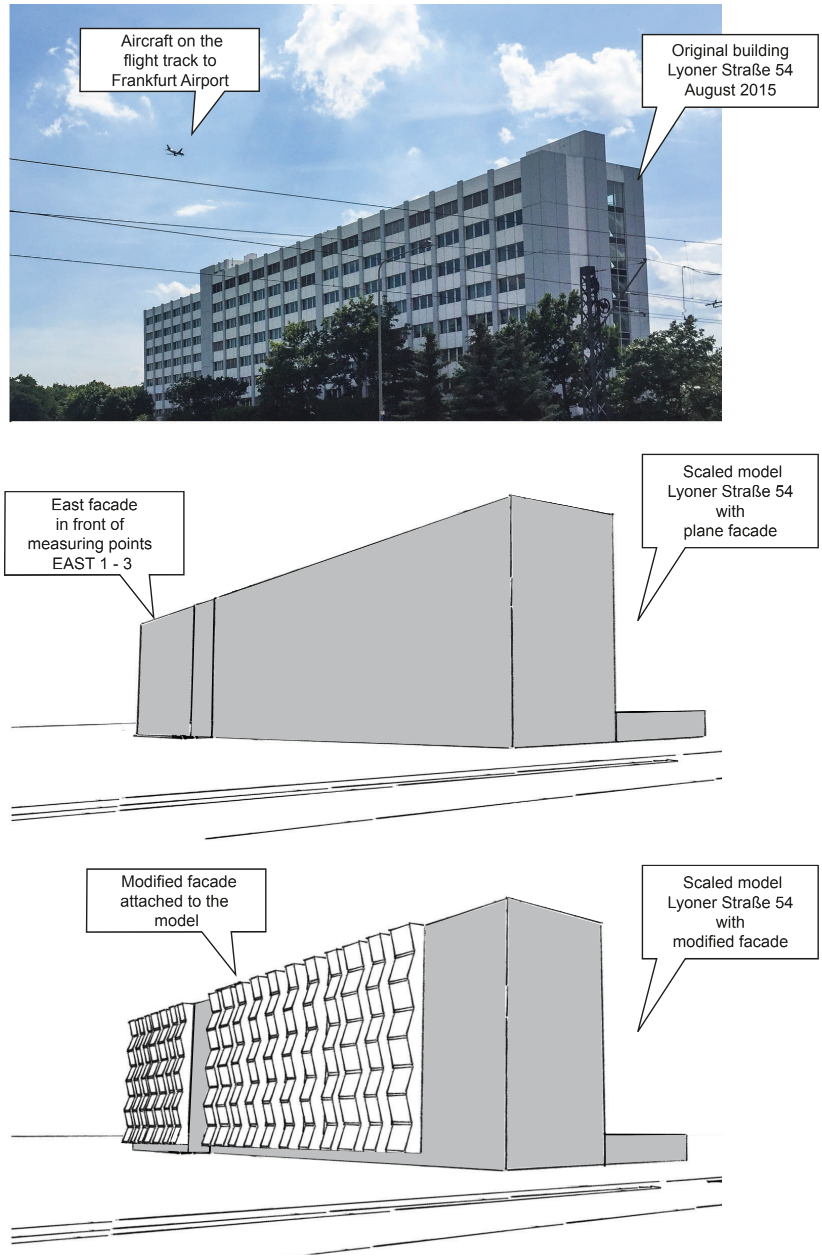


FIGURE 5.31 Measurement variations for the building Lyoner Straße 54.

A comparison of the data derived from both setup variations should provide insight into the effect of the façade on the urban space.

A third measurement was conducted with the empty measurement platform to determine the effect of the building standing or not. This measurement setup was introduced to define regions of the noise source movement where the building amplifies the sound energy in comparison to the empty site.

The measurements of this urban situation were conducted in the facilities at the German Federal Highway Research institute (BAST). There it was possible to investigate setups with dimensions around 800 m in a downscaling of 1:100 under constant conditions. The constant conditions are important for scaled measurements as in dimensions above 3 m the absorption of sound energy by the air in relation to frequencies above 6000 Hz plays an important role. The air absorption of sound energy increases with increasing humidity. And with the change of air humidity or temperature, the sound absorption of the air changes as well, and will lead to imprecise level readings.The measurement room dimension was 11 m by 12 m with a ceiling height of 4.5 m. To establish accurate measurements the room conditions were controlled.

- The walls and the ceiling were covered with broadband sound absorbing foam.
- To keep the sound absorption by air at a constant value, the air of the room was dried to 5% humidity at a temperature of 20° Celsius.

The signal path consisted of a free field 1/4 Inch condenser microphone with a matching preamplifier. To minimise the interfering influence of the microphone with regards to its size this type of microphone with a diameter of only 6,35 mm was used. The acoustical signal was converted into digital measurement data by a computer based audio interface. For the evaluation and visualisation of the results the digital data was post-processed using custom programmable software.

The sound source in use was a pneumatic point source in which an air jet moving through a small opening in a sheet of metal produced high levels in a frequency range of 1000 Hz to 100,000 Hz. By using constant air pressure at constant flow this source delivers a constant noise level. The noise source in detail is shown in Figure 5.32.

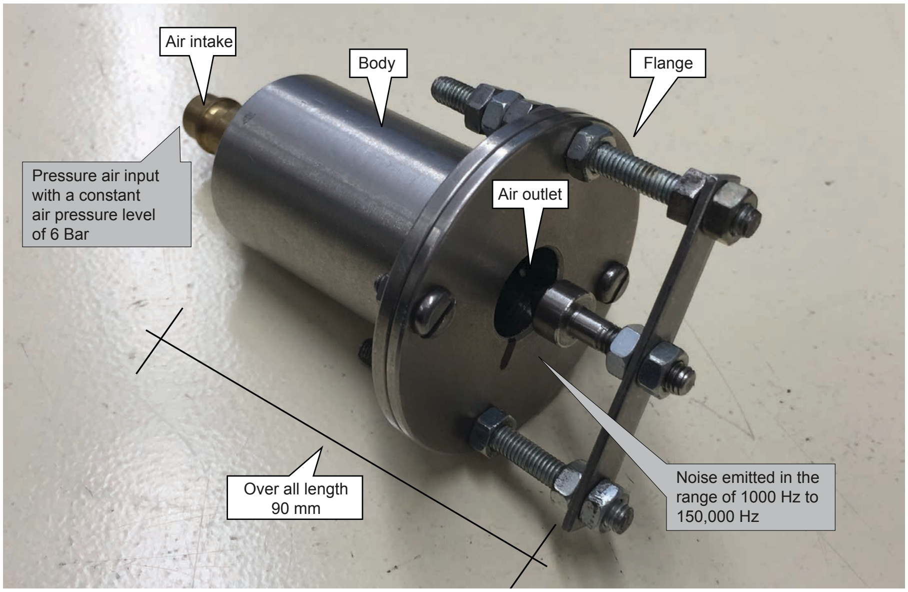


FIGURE 5.32 A pneumatic noise source with a frequency range of 1000 Hz to 150,000 Hz.

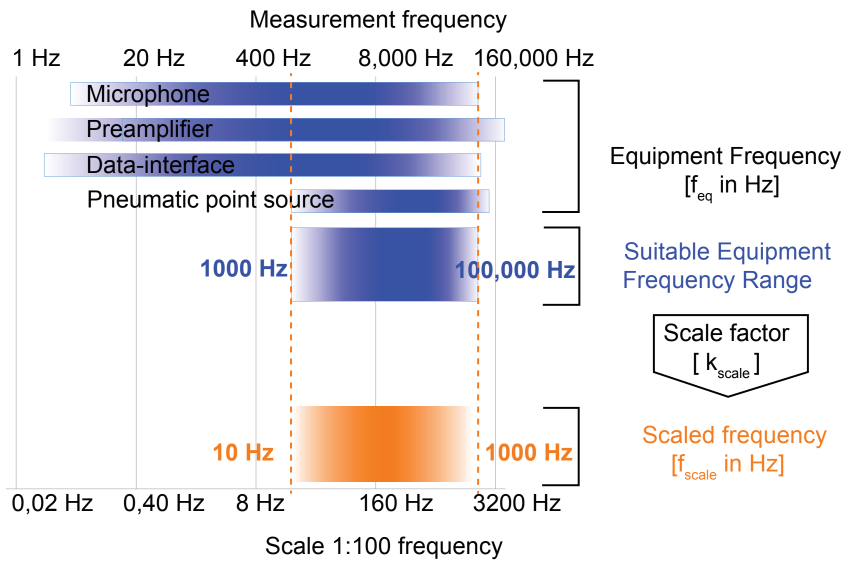


FIGURE 5.33 Equipment setup incl. relevant specifications and resulting frequency range limitation for the scaled measurement setup at BAST

With a computer controlled horizontal moving rail system the pneumatic source could be moved along a distance of 7 m, simulating a moving sound source. During the measurements an extra reference microphone attached close to the noise source was used to monitor possible irregularities of the sound source. The velocity of the moving rail in conjunction with the measurement system delivered a set of frequency-distributed levels in the range between 100 Hz and 2000 Hz at every 20 mm.

Figure 5.33 gives an overview of the measuring units and their frequency range in relation to the resulting frequency range at 1:100.

The system of the described measurement chain in combination with the air-conditioned measurement room is capable of measuring in the frequency range of 1000 Hz to 100,000 Hz. For the intended measurements at a scale of 1:100 the setup provided a frequency range of 10 Hz to 1000 Hz.

§ 5.3.2 Setup for the measurement sequence Lyoner Straße 54

The scaled urban setup consisted of the building Lyoner Straße 54 and two building façades close to it. The model of the building was built of sanded and grey painted chipboard. Sheets of sanded and clear painted chipboard represented the façades in the neighbourhood. The modified façade design was added to the model in white laminated cardboard. The surface quality of the façade modification model regarding its reflection properties remains hard reflective in the model. Different absorption properties of the surrounding ground in the real urban setup were not taken into account in order to determine the façade effect in all measurement points under similar conditions. The flooring in the measurement room, which shows similar absorption properties as grass, represented the mix of sealed and unsealed urban surfaces around the building. The grey painted model of the building with the attached façade modification in white on the flooring of the measurement room is shown in Figure 5.34.

FIGURE 5.34 Model of the building Lyoner Straße 54 in grey colour with the attached façade modification in white measured at position EAST 2. The transparent painted sheets of chipboard in the background represent the façades of buildings in the neighbourhood.

With the map data for Lyoner Straße 54, a 1:100 downscaling of the existing situation was generated. The aircraft as a moving sound source was replaced in the 1:100 downscaled setup by the pneumatic source attached to the linear moving rail. Due to spatial limitations, the distance of the noise source to the building had to be scaled down in 1:300. In order to match the real situation regarding the angle of the airplane towards the building the noise source was attached to the moving rail at 1.50 m height above ground. The measurement microphone, which was fixed on a tripod stand, was set to each of the six measurement points manually. The spatial setting of the noise source on the moving rail is shown in Figure 5.35. The underlying model layout for the measurements is shown in Figure 5.36.

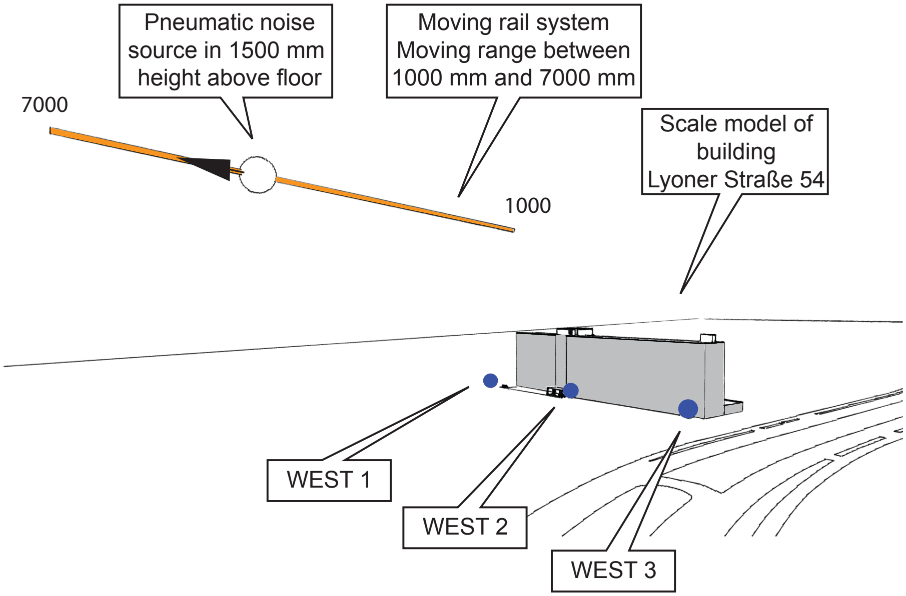


FIGURE 5.35 Spatial setup of the noise source on the moving rail system and the measurement points WEST1 - 3 in front of the east façade.

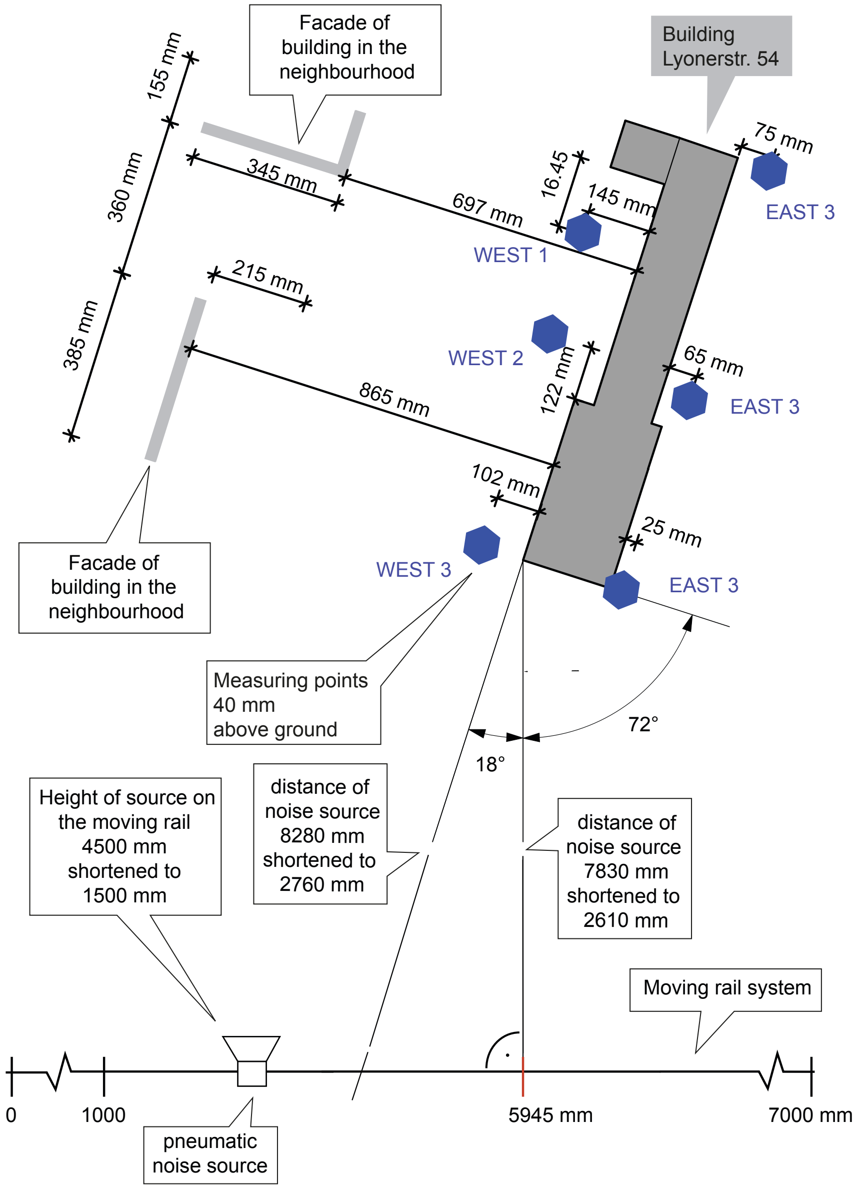


FIGURE 5.36 Model layout of the scaled measurement for the building Lyoner Straße 54 (drawing not scaled)

An overview of setup in the measurement room with the noise source in front and the model under measurement is provided in Figure 5.37.

FIGURE 5.37 Measurement room at the facilities of the Federal Highway Research Institute with the pneumatic noise source in front. The grey building model with the modified façade in white being measured is in the back.

Two measurement sequences were conducted for the building with and without the modified façade attached to the model. A third measurement sequence was conducted of the empty measurement platform, representing the empty building site. Every sequence included six individual measurements. One complete movement of the noise source along the moving rail between 1000 mm and 7000 mm defines the time duration for a single measurement. 300 data sets were recorded during the movement of the noise source on the rail. The spatial resolution of the measurement data is 20 mm, as every 20 mm a data set was recorded. For every microphone position such an individual measurement comprised of 300 data sets was conducted. With this setup it was possible to measure occurring noise levels caused by a moving noise source at the predefined points around the building. This setup makes it possible to determine the following façade related effects.

Amplifying or shielding of the noise event

Introducing a building on a building site influences the recordable noise levels at a defined position in relation to movement of a noise source. For some regions of the moving path of a noise source the perceivable noise at one defined receiver point is amplified by reflections from the façade added to the direct levels. At other points of the movement the building itself shields the direct path of the noise source. Thus, lower levels were recorded at the receiver point. H. Lyon described the definition of amplified or shielded regions (Lyon et al., 1971). Comparing the measurement data of the empty measurement space with the one of the measurement space with the basic model of building determines the amplification or shielding regions of the building in relation to one receiver point and a moving noise source. The amplifying regions of the movement of the noise source define the angles of the acoustic impact in relation to the receiver point. Furthermore, the presence of the amplification effect offers the opportunity of a modified façade.

Level reduction of the noise event caused by the modified façade

Subtracting the measured levels of the building with façade modification from the data captured without façade modification delivers the resulting level change of the modified façade at one receiver point. With the captured data the level change for single frequency bands can be calculated. This provides an insight into the transformation of the sound event at the receiver point.

§ 5.3.3 Results of the method suitability

To evaluate the matching of the scaled measurement and the field measurement a comparison of the data from the on-site measurement and the scale measurement was conducted. Measuring point WEST 3 was defined as reference point for both measurements. In relation to this measurement point the results for the deviation between both measurements were in the range of 1 dB up to 13.01 dB. Generally, the deviation increases in direction to the street. Several effects of the simplified scaled setup and the conducted on-site measurement caused the deviation.

Only one of the real existing noise sources in the vicinity of the building site was represented in the scaled measurement.

The field measurement values in EAST2 and EAST3 were significantly higher than in the scaled measurement because of their exposition to car and tram traffic noise from Lyoner Straße. For the measurement points WEST 1 and WEST 2 the deviation between on-site and scaled measurement was smaller because the car and tram traffic noise from Lyoner Straße was shielded by the 2-storey entrance building at the street. The deviation levels in relation to the measurement points are shown in Figure 5.38.

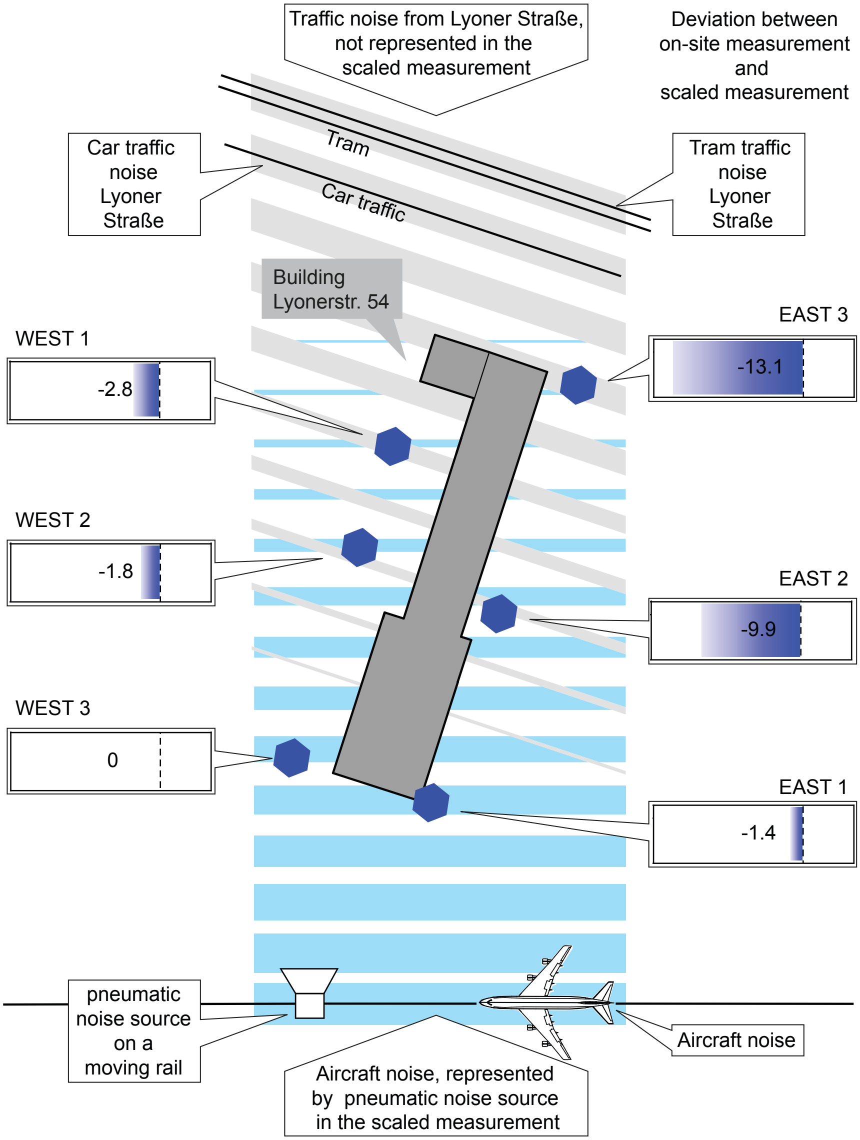


FIGURE 5.38 Evaluation of the deviation between the on-site measurement and the scaled measurement

To compare the on-site measurement data with the scaled measurement data, an average level for one measured event was calculated. This leads to uncertainties in both setups.

In the on-site measurement the start of one aircraft flight event was defined as the first audible notion of the approaching aircraft. The end of a flight event was defined when the noise of the same aircraft could no longer be perceived. These border definitions are not very precise as they were based on the human ear. Another factor for the uncertainties regarding the duration of an aircraft flight event is the variation in the height over ground of the approaching airplane. An aircraft flying high above ground is audible for a longer period of time than an aircraft flying at a lower height above ground.

In the scaled measurement, only a part of the movement of an aircraft along the building site was represented. For the calculation of the average level for one flight event the time spans of the approaching and the leaving plane are missing. The missing parts in the calculation for an average value for one movement of the noise source along the rail system resulted in lower average values for the scaled measurement. The comparison of the duration of an aircraft event and a scaled measurement event is shown in Figure 5.39.

Despite the fact of the deviation in single measurement points, the measurement setup can be used for testing façades for their effect on aircraft noise in the urban plot of Lyoner Straße 54. In the shape of the level-over-time graphs from measurement point WEST 2 and EAST 2, the similarity is evident. The graphs shown in Figure 80 and Figure 81 represent the characteristic curve for the measurement point WEST 2 and EAST 2 scaled and on-site. Furthermore, the spatial limitation of the scaled measurement is visible in the graphs. Comparing both graphs regarding their duration it can be seen that at position WEST 2, a part of the approaching airplane is missing while in point EAST 2 the part of the graph representing a leaving airplane was missing. The comparison of the level-over-time graphs is shown in Figure 5.40 and Figure 5.41.

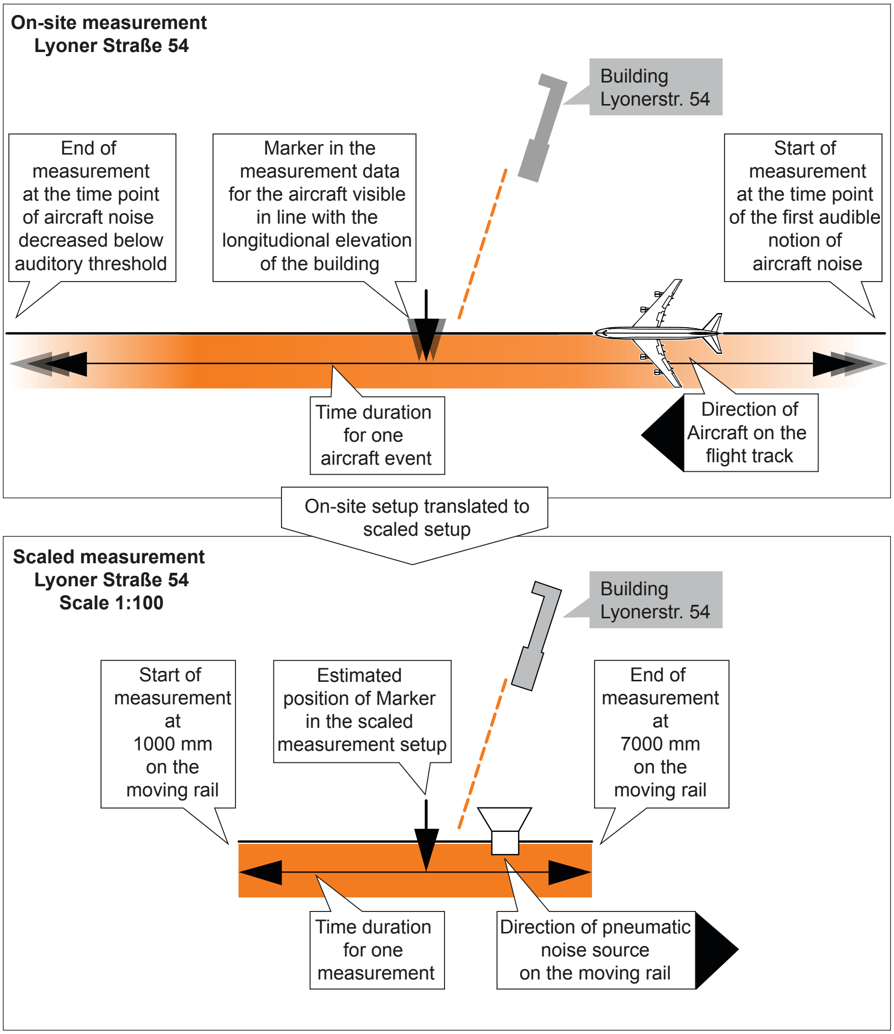


FIGURE 5.39 Comparison of the duration of an aircraft event in reality with the duration of one measurement event in the scaled measurement.

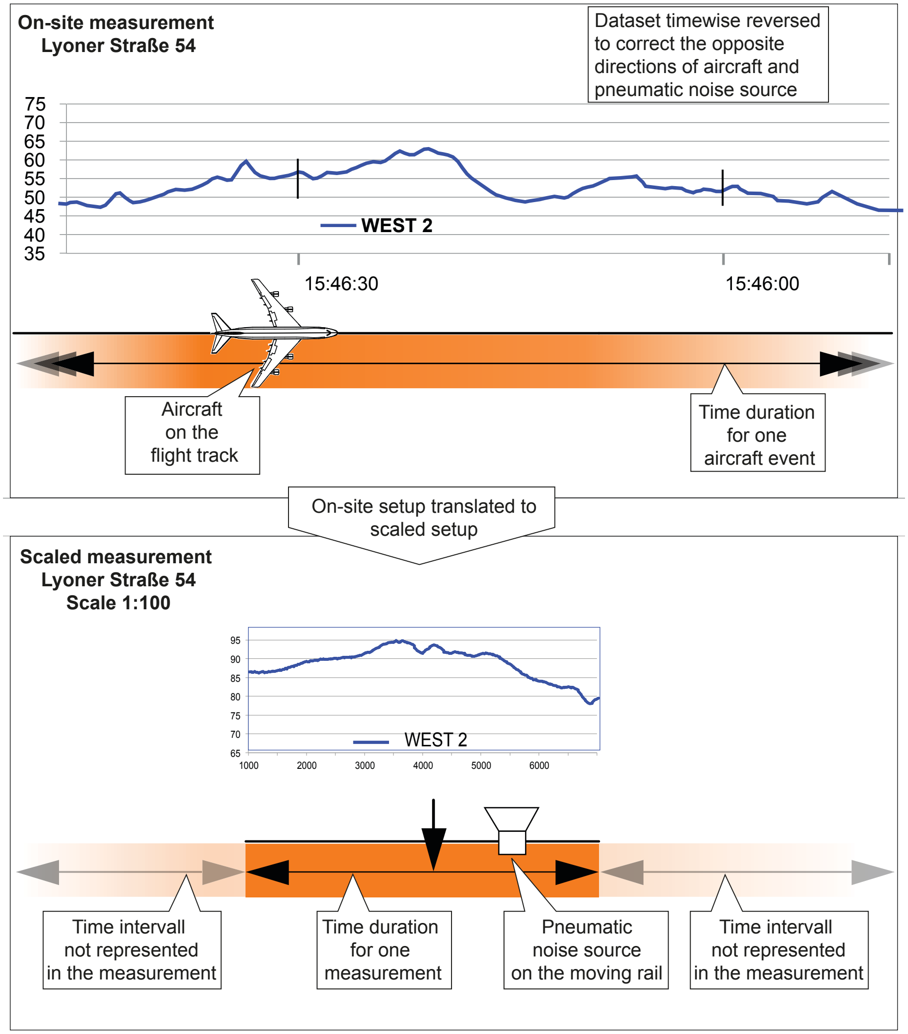


FIGURE 5.40 Level-over-time graph comparison for measuring point WEST 2

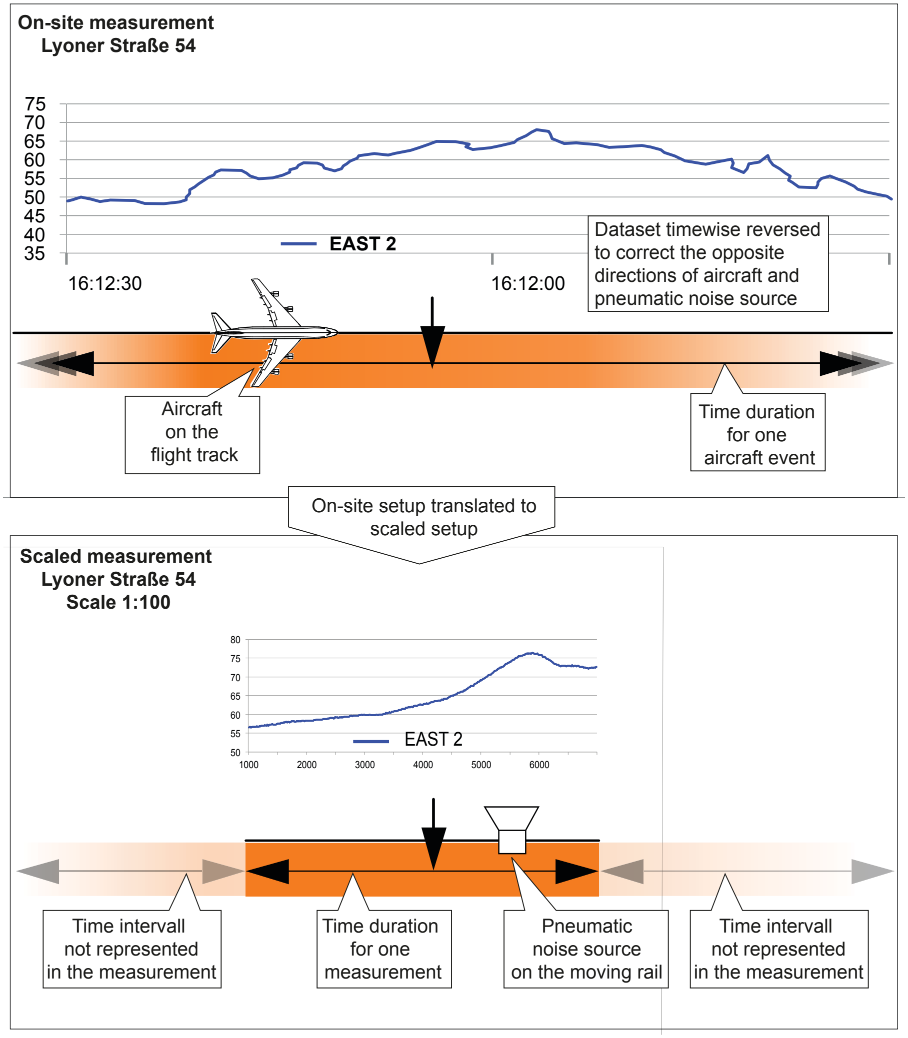


FIGURE 5.41 Level-over-time graph comparison for measuring point EAST 2

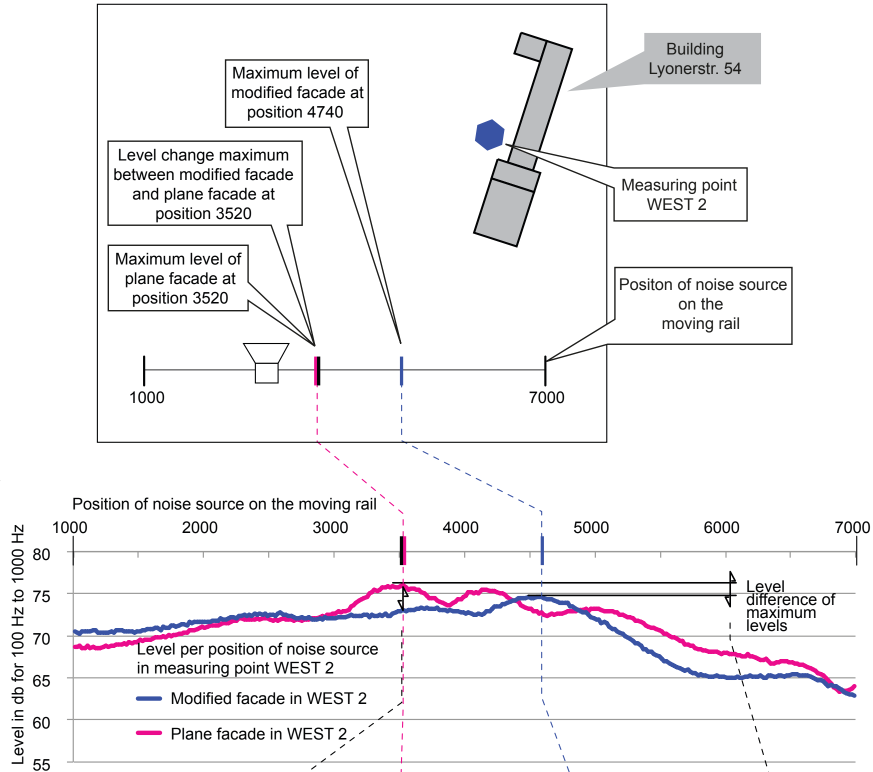
§ 5.3.4 Results of the measurements

The position-over-time graphs were inspected intensively in four cases.

- The position of the maximum level change appearing between the modified façade and the plane façade. The data of this position determins the maximum impact of the façade design.
- The position of the maximum level reported for the plane façade. The data of this position determines the maximum effect of the plane façade.
- The position of the maximum level reported for the modified façade. The data of this position determines the effect of unintended reflections contributing to a level increase.
- Supplementary, a comparison between the data sets reported for the positions of the maximum level of both façades was calculated. This comparison determines the possible change of maximum levels during one measurement.

In these four cases the difference between the modified façade and the plane façade was calculated for each frequency band between 100 Hz and 1000 Hz. A graphical ray tracing approach was conducted for the positions of the maximum levels of both façades to provide insight on the acoustical mechanism.

The results for measurement point WEST 2 are shown in the graphs in Figure 5.42, Figure 5.43 and Figure 5.44.



Frequency distributed level change modified facade - plane facade at the point of:

Frequency Hz	Level change maximum between facades	Maximum level of plane facade	Maximum level of modified facade	Level difference between maximum levels
100	-1,3	-1,3	-0,6	0
125	-1,0	-1,0	-0,2	-0,4
160	-2,3	-2,3	-1,1	-1,1
200	-3,1	-3,1	-2,3	-2,0
250	-4,5	-4,5	-4,0	-2,1
315	0,6	0,6	-5,7	0,4
400	-0,1	-0,1	-1,4	1,2
500	-3,4	-3,4	4,3	0
630	0,9	0,9	3,9	1,2
800	-1,8	-1,8	6,9	5,5
1000	-5,5	-5,5	-0,5	-6
Average	-3,4	-3,4	2,0	-1,4
Positior	3520	3520	4740	0

FIGURE 5.42 Measurement results for Lyoner Strasse 54, WEST 2, in relation to the aircraft and the building position.

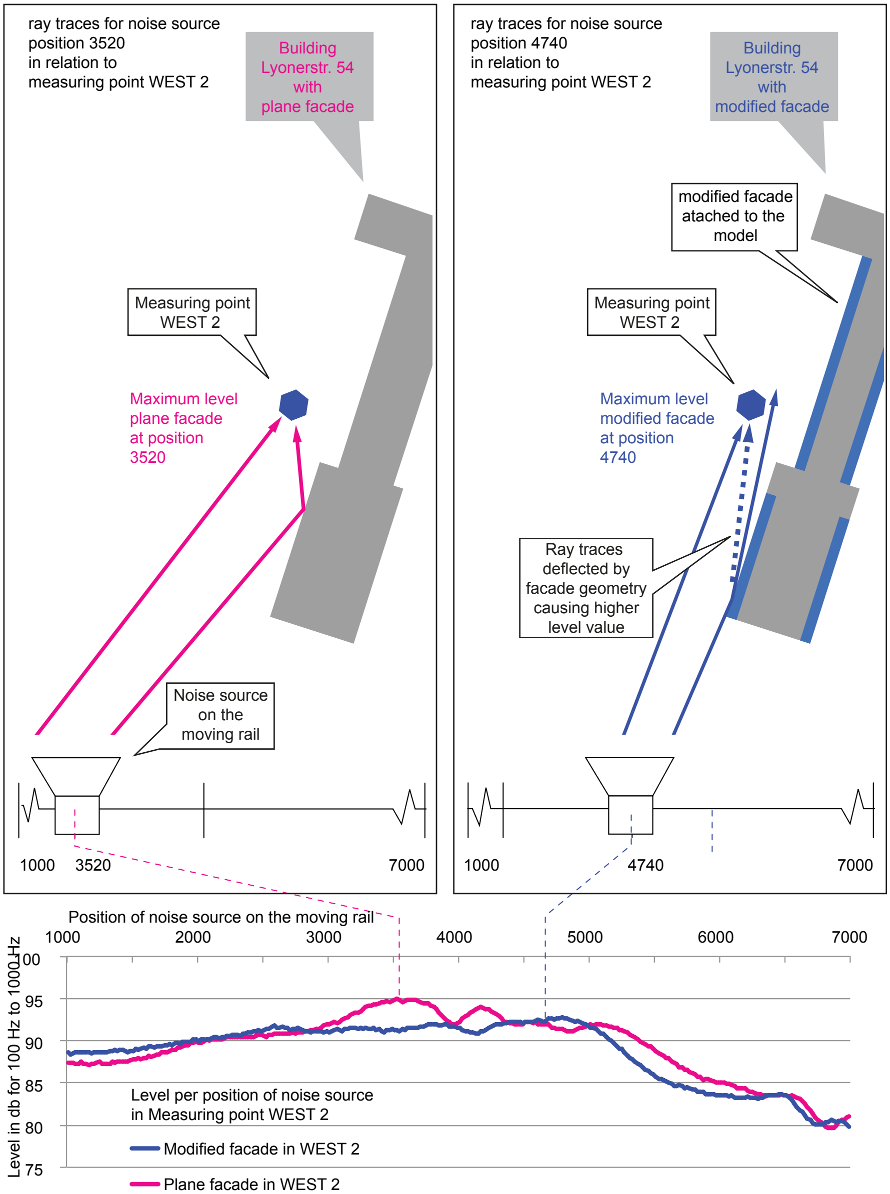


FIGURE 5.43 Graphical ray-tracing results for Lyoner Strasse 54, WEST 2 in relation to the aircraft and the building position.

The bar graphs in Figure 5.42 and the graphical ray tracing in Figure 5.43 in relation to the level-over-time graph illustrate that:

- At the position of maximum level change between both façades noise reduction occurs between -3.4 dB and -5.5 dB in the frequency bands of 250 Hz and 500 Hz and 1000 Hz. The modified façade reduces the noise level by average - 3.4 dB at this position. At this point on the rail the building itself does not block the line of sight between source and receiver. For this position of the noise source the maximum impact on changing the reflection properties of the façade can be detected. The graphical ray tracing for this position detects a façade reflection, which is added to the direct level at measuring point WEST 3. This is shown in Figure 5.43 on the left.
- The position of the maximum façade impact is similar to the position of the maximum level for the plane façade. This indicates that at this position there is no overlay by other acoustic effects such as bending or diffraction. The façade modification changed the reflection properties and caused the maximum level change there.
- At the position of maximum level for the modified façade a noise increase is reported for frequency bands between 500 Hz and 800 Hz in the level range between 4,3 dB and 6,9 dB. The modified façade is responsible for an average noise increase of 2 dB at this position. In the graphical ray tracing shown in Figure 5.43 on the right, a clear reflection in direction to the measuring point WEST 2 could not be detected. Reflections on the tilted surfaces are responsible for the increased level at measuring point WEST 2.

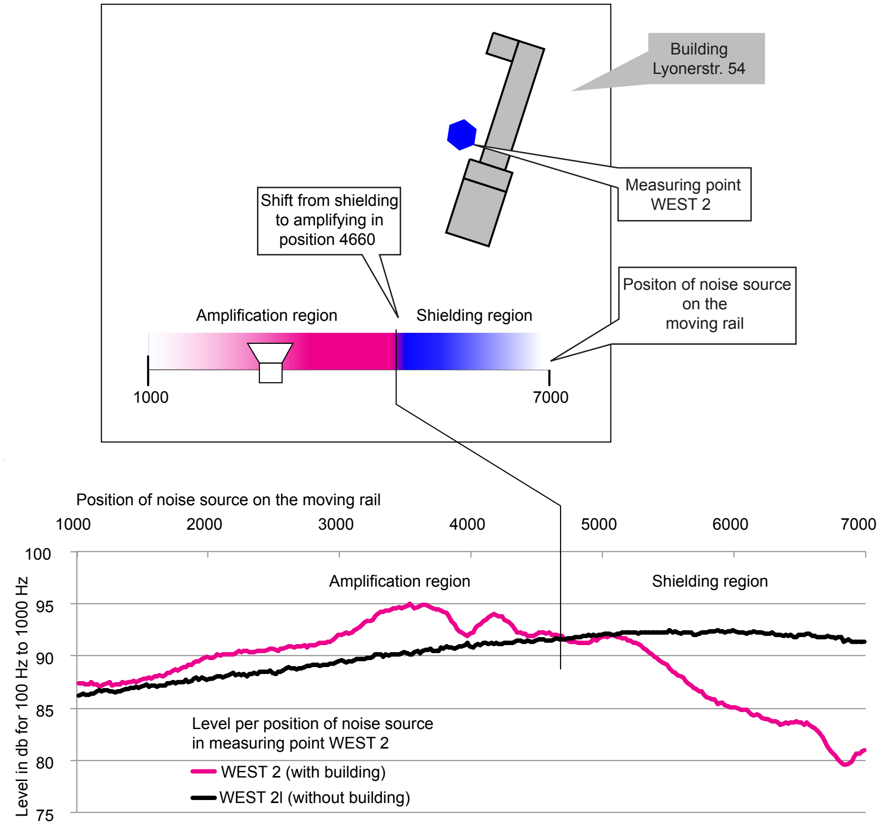
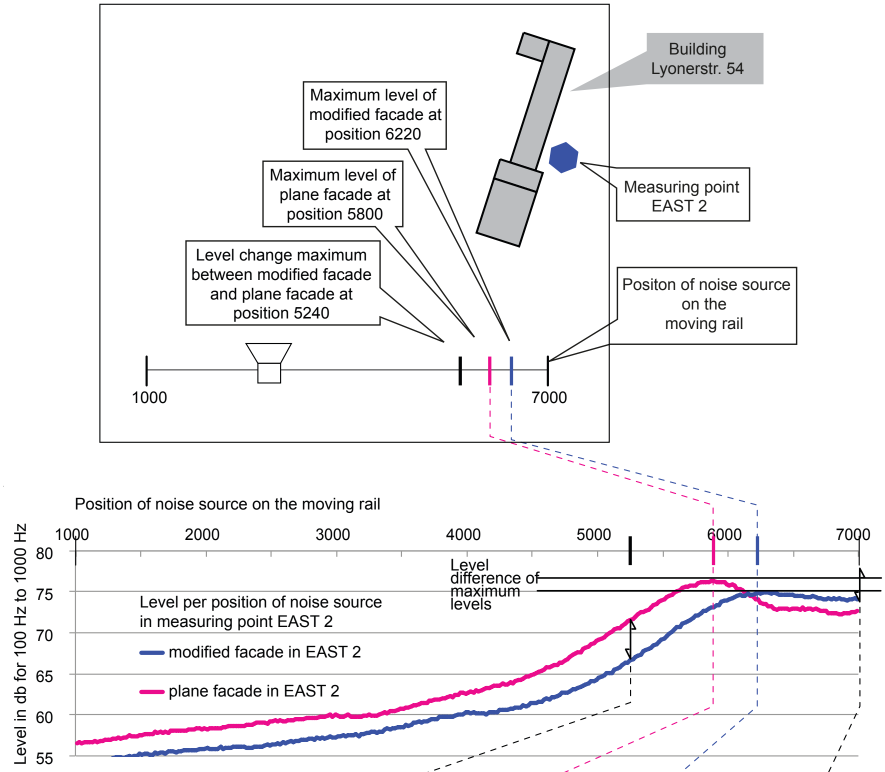


FIGURE 5.44 Comparison of the level per position graphs of WEST 2 to identify shielding or amplification regions of the noise source movement.

The results at measurement point EAST 2 are shown in the graphs in Figure 5.45, Figure 5.46 and Figure 5.47.



Frequency distributed level change modified facade - plane facade at the point of:

Frequency Hz	Level change maximum between facades	Maximum level of plane facade	Maximum level of modified facade	Level difference between maximum levels
100	-0,7	-0,1	-0,1	1,7
125	-0,3	-0,3	-0,1	1,8
160	0,7	0,4	0,6	2,6
200	1,5	1,4	1,7	4
250	4,3	3,2	3,3	5,2
315	4,2	3,8	2,3	3,5
400	-2,5	-2,3	-2,6	-0,4
500	-10,7	-9,6	-7,3	-6,6
630	-7,4	-5	0,7	-0,8
800	-4,2	-2,5	4,4	-0,1
1000	-5,4	-3,3	2,3	-2,2
Average	-5,0	-3,6	0,9	-2,2
Position	5240	5800	6220	

FIGURE 5.45 Measurement results for Lyoner Strasse 54, EAST 2, in relation to the aircraft and the building position.

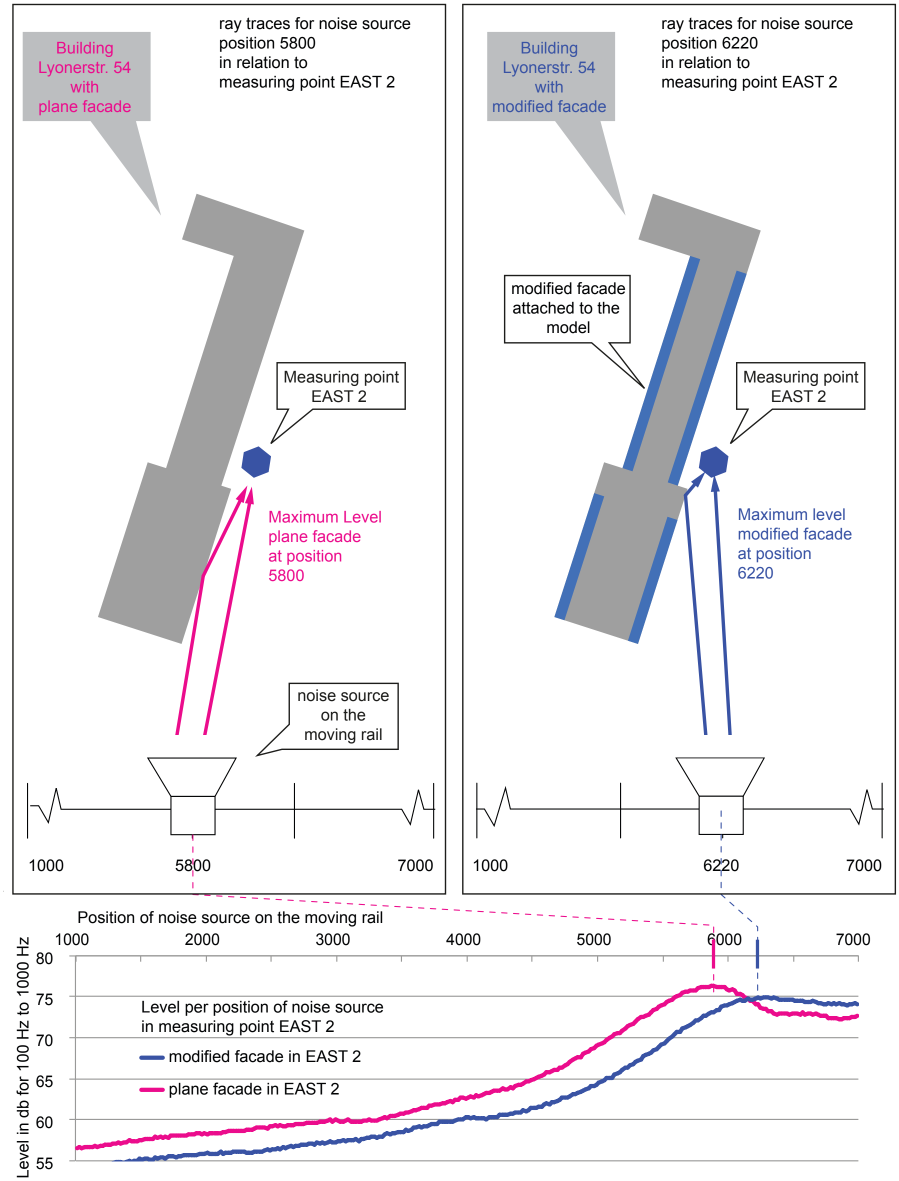


FIGURE 5.46 Graphical ray-tracing results for Lyoner Strasse 54, EAST 2 in relation to the aircraft and the building position.

The bar graphs in Figure 5.45 and the graphical ray tracing in Figure 5.46 in relation to the level-over-time graph illustrate that:

- At position of maximum level change between both façades noise reduction occurs between -2.5 dB and -10.7 dB in the frequency bands between 400 Hz 1000 Hz. The modified façade reduces the noise level by average - 5.0 dB at this position. At this position of the noise source the building itself blocks the line of sight between source and receiver. The maximum impact of the façade modification can be detected in this case for affecting the bending or diffraction of sound energy around the corner or over the roof of the building and not for the change of reflection properties.
- At position of maximum level for the plane façade noise reduction occurs between -2.3 dB and -9.6 dB in the frequency bands between 400 Hz 1000 Hz. The modified façade reduces the noise level by average - 3.6 dB at this position. The graphical ray tracing for this position detects a reflection from the façade, which is added to the direct level at the measuring point EAST 2. This is shown in Figure 5.46 on the left side.
- At the position of maximum level for the modified façade a noise increase is reported for frequency bands between 160 Hz and 315 Hz in the level range between 0,6 dB and 3,3 dB. A noise increase is also reported for the frequency bands between 630 Hz and 1000 Hz in the level range between 0.7 dB and 4.4 dB. Level decreases are reported only for the frequency bands of 400 Hz and 500 Hz in the range of -2.6 dB to -7.6 dB. The modified façade is responsible for an average noise increase of 0.9 dB at this position. The graphical ray tracing for this position shows that the part of the façade, which is not covered by metal frame balconies is responsible for the higher level there. Figure 5.46 shows on the right side that at this position a reflection from the plane part of the façade is added to the direct level at the measuring point EAST 2.

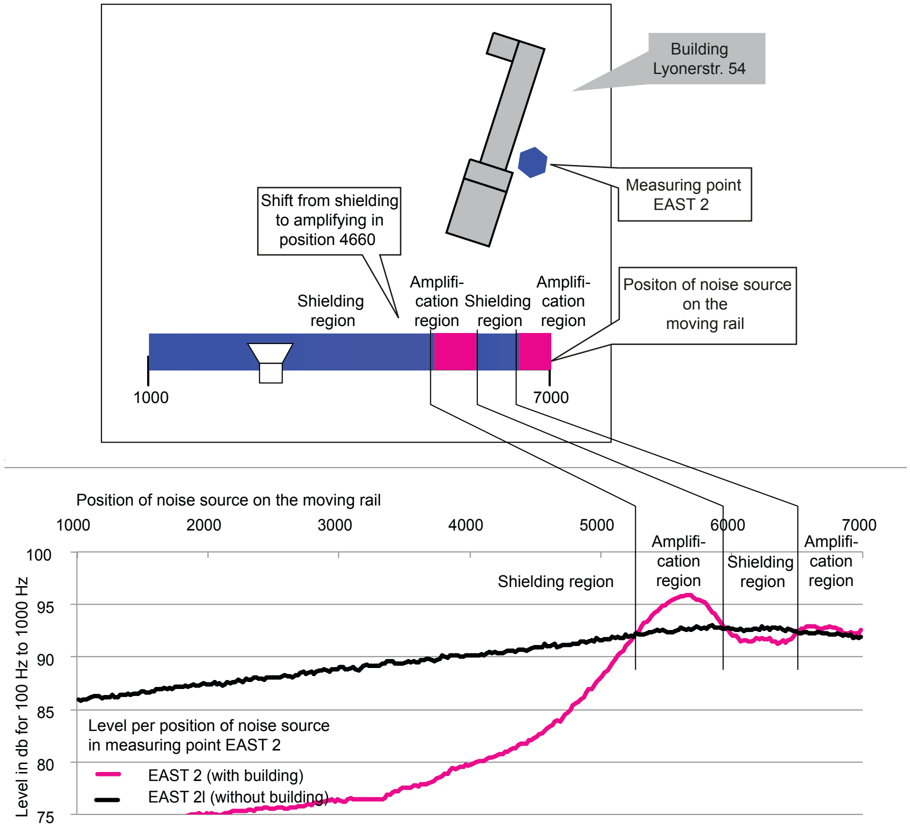


FIGURE 5.47 Comparison of the level per position graphs of EAST 2 to identify shielding or amplification regions of the noise source movement.

Evaluating the recorded measurement data gives evidence of the possibility of reducing noise levels with a modified façade geometry even in unpromising cases, for example a freestanding building located close to flight paths. From the graphs in Figure 5.42 and Figure 5.45 it can be concluded that around a solitaire building geometric façade modifications can cause averaged level changes of more than 3 dB for the frequency range between 100 Hz and 1000 Hz. At some points level reductions of -5.0 dB were reported. These level changes do not occur for the overall movement of the noise source. They only occur at certain positions of the noise source in relation to the building. Furthermore, they do not occur over the whole measured frequency range. The bar graphs for the frequency dependent levels in Figure 5.42 and Figure 5.45 reveal the potential of this façade design. For specific frequency bands the maximum achieved level reduction was -10 dB at the East side or -5 dB at the West side of the building. These level reductions were reported in the high sensitive frequency range of the human ear between 500 Hz and 1000 Hz. With this façade it will be possible to transform an unpleasant aircraft event with high-level readings in this range to a more pleasant one. The more comfortable one will show -10 dB level readings in the frequency bands between 500 Hz and 1000 Hz. This gives evidence of the possibility of transforming the impact of noise on the urban space.

For a broader view on the data, the entire time span of one measurement was evaluated for the general level change. Figure 5.48 provides the level differences between modified and plane façade for the entire time span of a single measurement, ranging from the position 1000 to 6000 of the noise source. Even in this data it is evident that a level reduction of -1.7 dB for each aircraft event is feasible with the introduction of a building envelope comprised of tilted façade panels.

Taking the level reduction of up to -10 dB in the high sensitive human hearing range into account it is impossible to express the potential of this façade design with averaged values. The potential of this façade design is the level reduction for specific frequency bands.

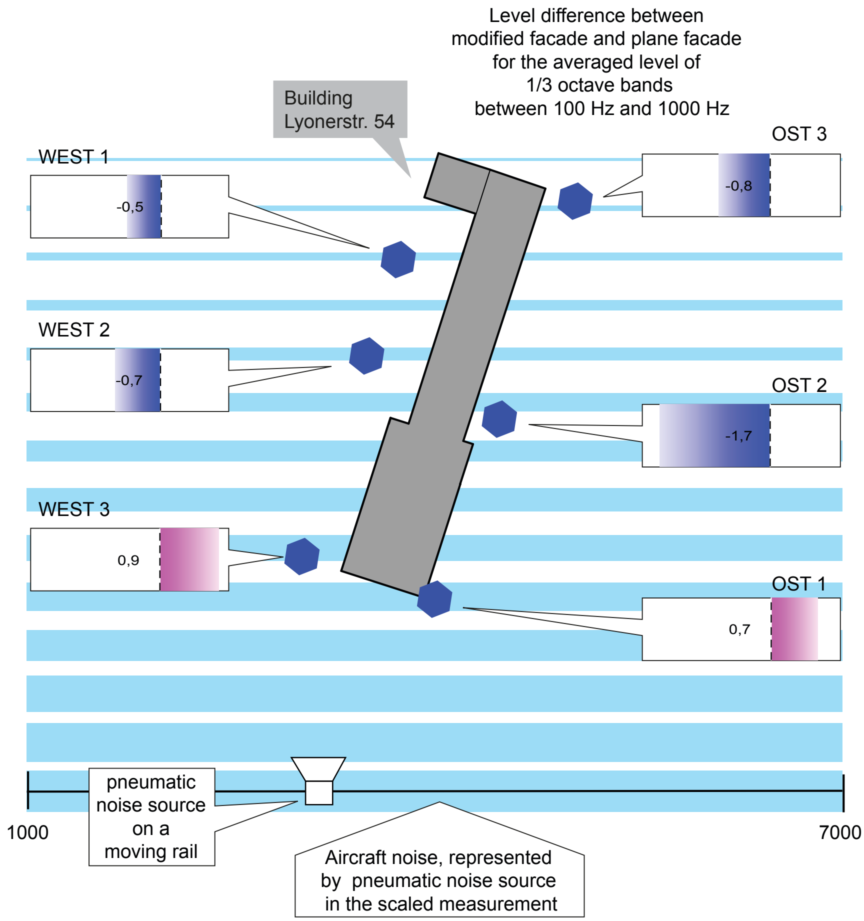


FIGURE 5.48 Level differences for the average single values for the frequency range from 100 Hz to 1000 Hz between the modified and the plane façade.

§ 5.4 Summary and conclusion

Meeting the afore defined requirements for a low-threshold introduction of acoustical investigation methods to a façade design process has achieved a close matching of reality and scaled models. The low threshold requirements were defined in chapter 3. This does not affect the obligatory investigation by ear and by on-site measurements, which deliver basic data for a promising scaled measurement of an existing urban situation. While developing and conducting scaled measurement during this research, the focus was set on fast and simplified measurement procedures delivering acceptable results. Preliminary results are needed during the early stages of a façade design. In the finishing stage all engineered designs had to be approved by highly accurate measurements conducted by specially trained engineers or researchers.

§ 5.5 Short discussion on practical applicability

In this section of the research the conducted scale measurements demonstrated that the effect of a building on the surrounding urban space could be transferred into a scale model measurement in a simplified setup, neglecting absorption properties. The use of the scale measurement method offers the possibility to introduce geometric surface modifications to a building design process whenever an acoustical approach is needed. The acoustic effects on the urban space in relation to the façade can be predicted and tuned avoiding decreased noise level at intended positions and the building site. Another advantage is the flexibility in scaling which allows the implementation according to the design stage of a project. The scaled measurement method presented here allows to investigate geometric details of an acoustic design in a 1:5 downscaling in the same way as it is possible to test a building geometry with 1:100 models. As the case studies should meet the requirements of a daily practice in engineering or architectural offices the approach to an acoustic façade intervention in both case studies was different. In the case study Lyoner Strasse 54, mainly design decisions led to a triangulated façade design. The possible acoustical qualities were considered as an extra argument in a second step. A different approach was used in the Henninger Turm study. The façade modifications there were developed for identifying the acoustical effect of adding horizontal or vertical structures to the south façade and the optimisation of them. Furthermore, the results of the conducted case studies show that architectural elements can be treated as acoustic control elements such as balconies or sun shading systems. Using these architectural elements for acoustical purposes has the advantage of not affecting air ventilation and transparency of a building. This investigation proved the feasibility of introducing acoustical parameters into future façade design for possible quieter cities. The future cities will not become quieter in terms of the entire frequency range detectable by human ears. This could not be achieved by an overall level reduction. The maximum level reduction derived from the Lyoner Strasse scaled measurements were reported in the range of -1.7 dB. This is close to the human hearing threshold of detecting the difference between two noise events. But with geometry based façade design it will be possible to transform unpleasant noise events into pleasant ones. This would be achieved with tuned geometries, which reduce the levels of specific frequency bands in the high sensitive hearing range of the human ear. With the tooling of the scaled measurement and the ability of engineers and architects in building physical models it becomes possible to design a façade in order to control defined frequency bands in the framework of a given urban situation.

General recommendation for a scale measurement setup in the framework of a building design project.

- As the scaled measurement in architectural terms must be directly linked to an on-site measurement, intensive on-site measurement is obligatory for the successful realisation of a scaled measurement.
- The scaled measurements should be conducted with moving noise sources as this delivers the best possible spatial resolution of the acoustical data.
- A minimum of three basic setups has to be measured: (1) The building site with the building comprised of plane façades. (2) The building on the building site with façades, modified with regards to their acoustical impact. (3) The building site without the building. Comparing the data of these measurements determines the effect of the building with plane façades on the noise impact on a receiver point and the possible effect of a specific acoustically driven façade design there.
- If a deviation of 3 dB between reality and the scaled measurement is acceptable in early design stages of a building project absorbing properties can be neglected. Additional to the saving of working time a simplified scaled measurement offers the opportunity to use existing cardboard models being produced in the daily architectural design process.

6 Design studies – Design proposals

§ 6.1 Introduction

The spatial setup of the interdependent elements comprising an urban space is responsible for its individual soundscape. The results of the on-site measurements presented in Chapters 4.3.5 and 4.5.3 and the scaled measurements revealed a strong connection between the position of the noise source and the measured levels. As mentioned in Chapter 1 it is not feasible for engineers and architects to influence the noise sources. The only way to influence an urban acoustic space is to modify the impact from noise sources by manipulating reflection properties of the interacting urban surfaces. Taking this hypothesis into consideration the following strategies could be evaluated regarding their impact.

- Implementation of absorbing materials in the façade surface
- Control of noise reflection by changing the angle of reflecting surfaces

According to current standards, at least 40% of a façade is needed to meet the requirement regarding the availability of daylight and transparency. Therefore, a minimum of 40% of a façade is made out of glass, which exhibits hard reflective surface properties. The remaining 60% of a façade can be used to introduce material with sound absorbing properties.

Due to these requirements, the use of sound absorbing material, which is mainly opaque and open porous, is limited to the opaque parts of a façade. The open porous structure of the currently known absorbing materials limits its implementation in a façade design. Dust and dirt could fill the pores of the material and change the acoustic properties as well as the visual appearance.

Introducing reflecting surfaces with different sizes and angles, which deviate from the angling of the plain façade changes the reflection effect of a façade. Here the material properties must be hard reflective for a maximum reflection effect of the surface. Hard reflective materials are well accepted and widely used for façades. An advantage of hard reflective materials in the context of an acoustically driven façade design is its potential use for transparent as well as opaque parts of a façade. Among others, glass, metal sheets or high-pressure laminate cladding could be listed here. A disadvantage of introducing controlled reflection surfaces is the unpredictability of noise hot spots somewhere else. The scaled measurements in Chapter 5.2.9 revealed this mechanism. The façade geometry causes a significant noise reduction for one position of the noise source. The same geometry causes higher-level readings for a different position of the noise source. To obtain a deeper insight into this mechanism future research projects are needed.

Basic considerations for a perforated façade with respect to the mandatory requirements of a façade (e.g. light, ventilation and transparency) are shown in Figure 6.1.

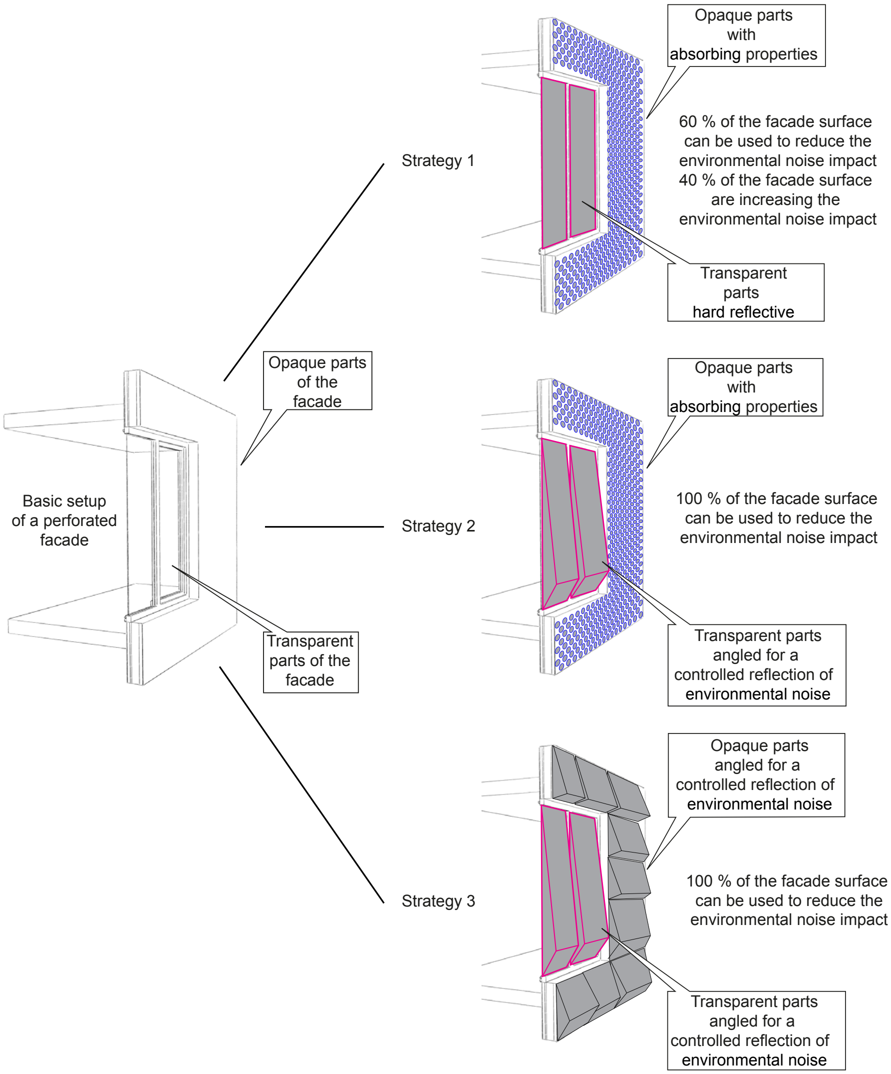


FIGURE 6.1 Basic intervention strategies for the acoustical modification of a perforated façade.

In Strategy 1, only 60% of the available façade surface could be used to control the reflection properties. Strategy 2 and Strategy 3: a façade surface can contribute up to 100% to the impact of an acoustically effective design. In the framework of this research the decision was made to set the research focus on Strategy 3, which works with controlled reflections of hard reflective façade elements. Due to afore mentioned limitations of open porous absorbing materials in façade designs as well as in the models of scaled measurements this research focused on geometry based designs. To achieve a suitability and predictability in on-site studies as well as in scaled model studies, the material and surface properties in all proposed designs remain hard reflective.

§ 6.2 Façade surface designs

The need to improve the acoustic environment of existing buildings in noisy urban settings triggered the development of acoustical façade surface design. by means of ray sketches and technical drawings, façade surfaces or façade add-ons were developed with focus on their transformation potential for the urban space. Surface designs based on the principle of introducing controlled reflection were developed and tested in this part of the research. The importance of the angle of the noise source in relation to the building led to the fundamental requirement that an acoustically effective façade surface must provide defined reflection properties for defined angles of the noise source. It is believed that with such a specific surface it is feasible to match the façade design to the type of noise source and the location of an intended silent place. As the noise source height is different between cars (0.75 m) and airplanes (e.g. 600 m for an aircraft close to the airport) both reflection paths differ in terms of their angles towards the façade. Figure 6.2 shows the different angles towards a façade.

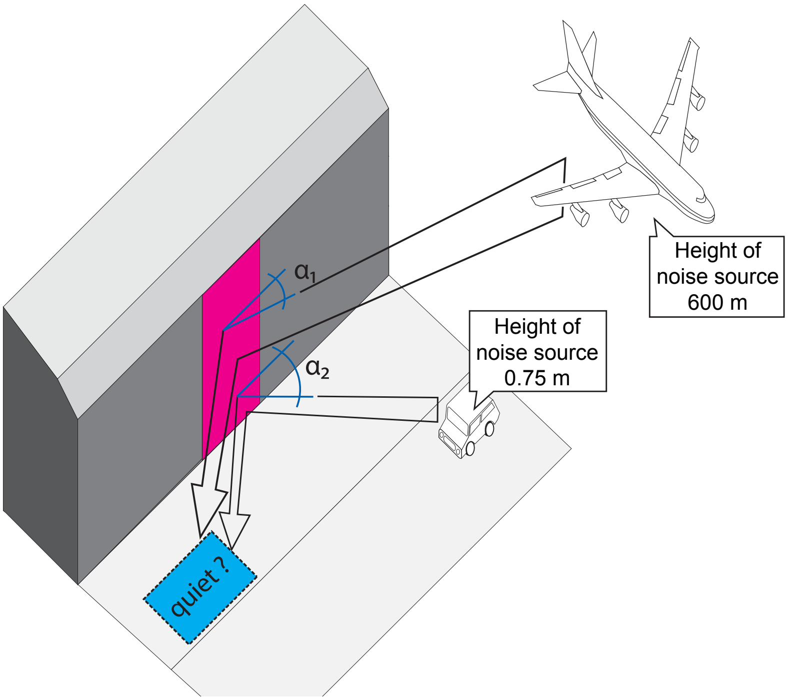


FIGURE 6.2 Different angles for the reflected sound path of cars and airplanes in an urban space.

The requirement for modified reflection properties in relation to a specific defined angle led to specific design proposals or material geometries. A selection of proposed façade surfaces or materials is shown in the following.

§ 6.3 Surface proposals

In this part of the research façade proposals were developed and tested regarding their acoustical properties. In addition to this, established architectural materials were acoustically measured in order to determine their reflection properties in relation to the sound source position.

§ 6.3.1 Perforation of metal sheets combined with folding technology

§ 6.3.1.1 Triangulated perforation of metal sheets - Type 1

This type of metal cladding is comprised of perforated metal sheets. The size of the triangular holes and the distance between them was based on recommendations of the metal working company. The triangle edges are all 2.5 cm long. The distance between the triangle corners is 1.0 cm. This offers the possibility to introduce a maximum of perforations to a metal sheet of 1.0 mm thickness. In order to obtain control on the direction of reflected acoustic energy only two lines of each triangle were cut. The filling of the triangular holes was bent towards the backside of the panel. The bent triangle improves the reflection properties of the module by reflecting sound energy to the inside of the construction at a certain angle. The detail view of the module and a simplified ray tracing drawing is provided in Figure 6.3. Figure 6.4 shows the built module.

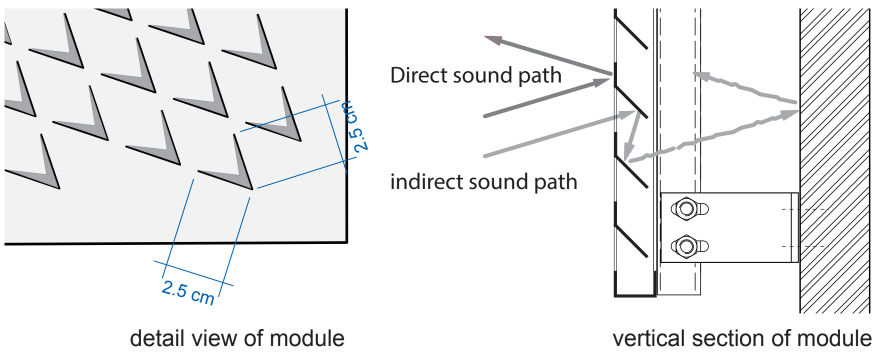


FIGURE 6.3 Detail drawing of the surface proposal triangle perforation

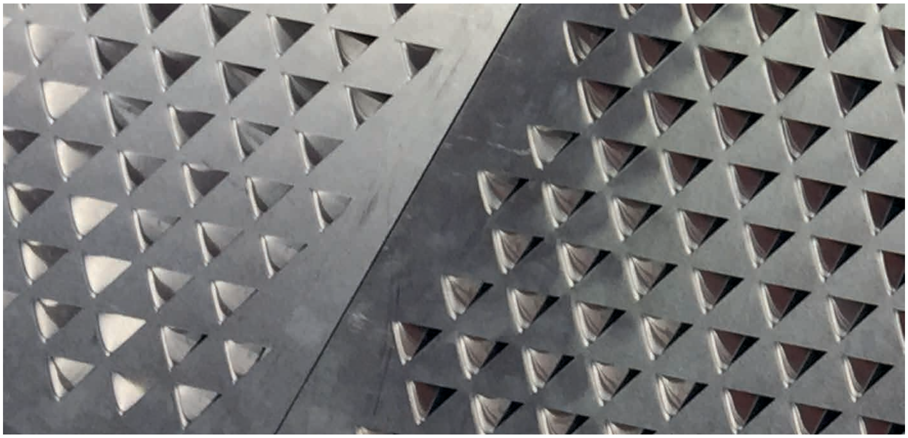


FIGURE 6.4 View of the mock-up surface

§ 6.3.1.2 Triangulated perforation of metal sheets - Type 2

This variation of a perforated metal sheet cladding with triangular apertures is comprised of multiple triangles facing in many directions. The decision for the cutting layout was mainly driven by design considerations. The tilted triangles improve the scattering properties of the module by reflecting sound energy to multiple directions at a specific angle. The detail view of the module and a simplified ray tracing drawing is provided in Figure 6.5. Figure 6.6 shows the built module.

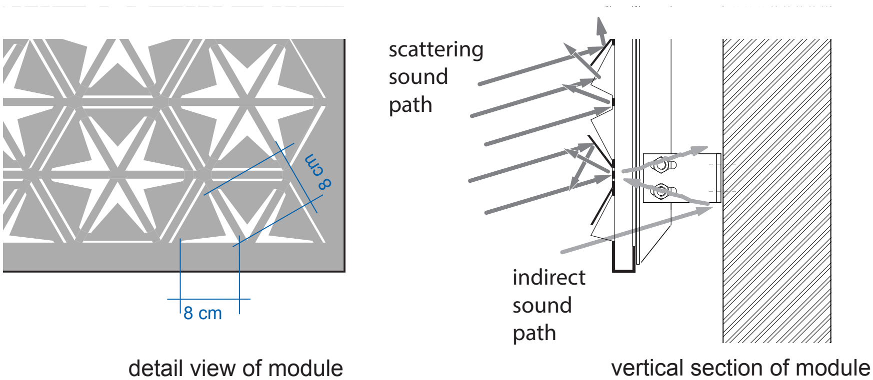


FIGURE 6.5 Detail drawing of the surface proposal triangle perforation Type 2

FIGURE 6.6 View of the mock-up surface

§ 6.3.2 Lamella structures

This surface proposal is comprised of vertical lamellas. In order not to affect the transparency of a façade this design uses very thin metal sheet lamellas. The lamellas with a thickness of 1.5 mm are of varying depth on the outside. The graphical ray tracing in Figure 6.7 shows that in direction of the lamellas the sound path is not affected. In direction perpendicular to the orientation of the lamellas the geometry has an influence on the sound paths. Figure 6.8 shows the lamella structure in detail.

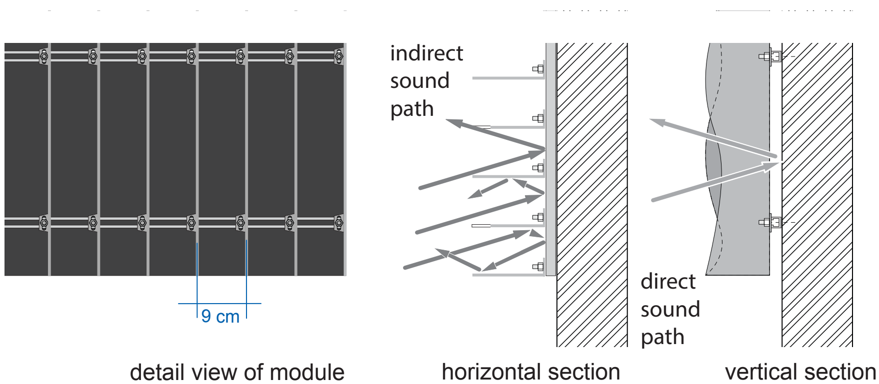


FIGURE 6.7 Detail drawing of the lamella add-on structure.

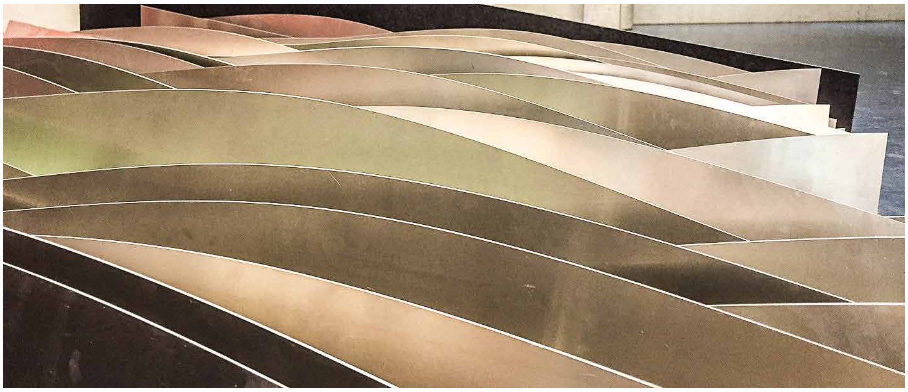


FIGURE 6.8 View of the mock-up surface

§ 6.3.3 Double layer structures of perforated materials

The intention of this proposal was to strengthen the effect of multiple reflections and absorption by introducing a second layer. Perforated HPL (High Pressure Laminate) boards were used for the outer layer. The perforation is comprised of holes with diameters between 5 cm and 50 cm. The irregular distribution of the holes intended a division in transparent or less transparent parts of the façade. For the second layer between the outer layer and the wall a transparent wave formed polystyrene roof cladding was used. Distributing through the wave formed surface will reduce the direct reflected sound energy. In addition to this, extra holes in the surface were drilled in order to improve the absorption properties of the façade element. Refer to Figure 6.9 and Figure 6.10.

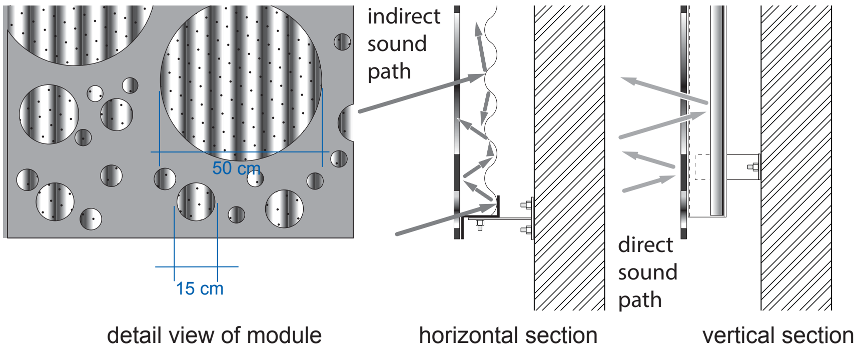


FIGURE 6.9 Detail drawing of the double layer structure.

FIGURE 6.10 View of the mock-up surface.

§ 6.4 Material proposals

Supplementary to afore described mock-ups prefabricated façade materials were considered regarding their implementation in acoustically effective façade designs.

§ 6.4.1 Trapezoidal sheet metal

For the use in opaque parts of acoustically effective façades trapezoidal sheet metal was considered. The advantage of this material is the availability of multiple geometry variations based on the technical regulations of EN 1090-2 (European Committee for Standardization, 2011). With the available variations it is feasible to match a specific frequency range by choosing a specific type of sheet metal.

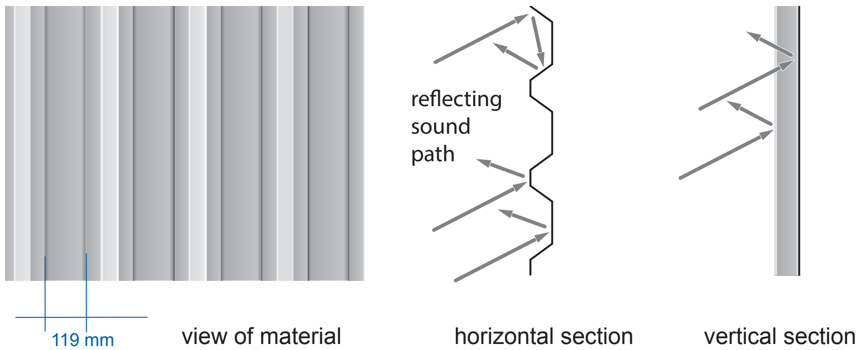


FIGURE 6.11 Detail drawing of trapezoidal sheet metal

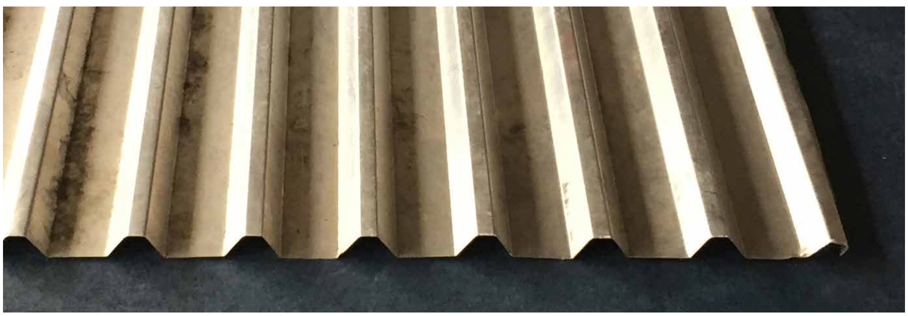


FIGURE 6.12 Trapezoidal aluminium sheet metal

§ 6.4.2 Cast glass

For the use in transparent or translucent part of façades, cast glass with a wavy surface was considered. Variations of this façade material were measured in a mock-up size of 1.5 m x 1.5 m.

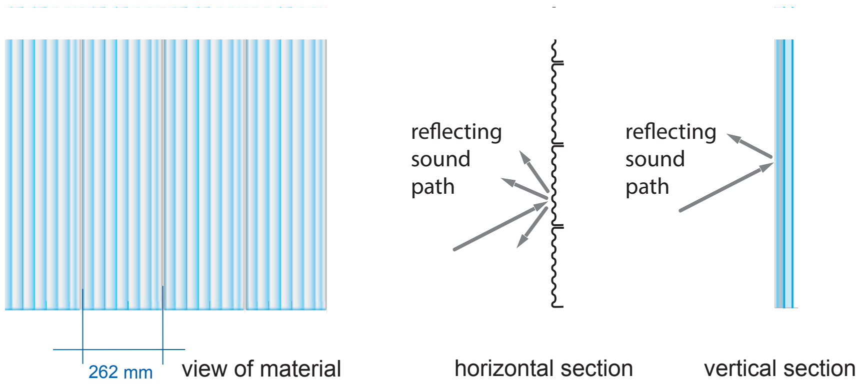


FIGURE 6.13 Detail drawing for cast glass

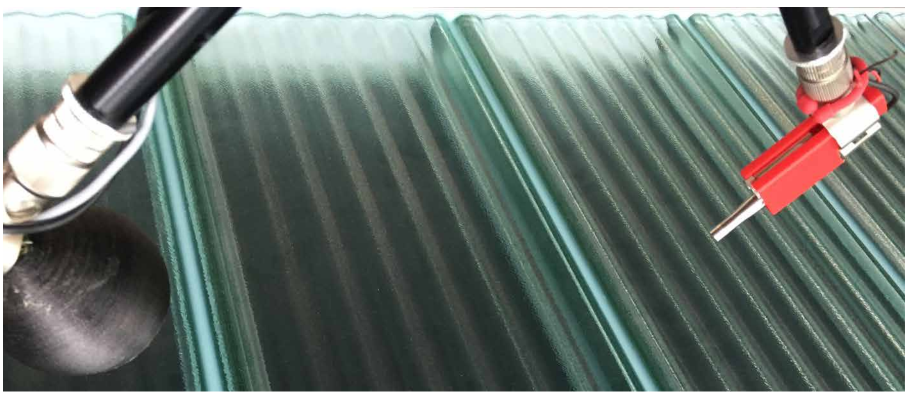


FIGURE 6.14 Cast glass mock-up under measurement. The speaker is positioned to the left. The microphone is located on the right side.

§ 6.4.3 PTFE coated glass fibre fabric

PTFE coated glass fibre fabric is already an established façade material. It offers various options to control the reflection properties of a building. Depending on the size of the holes in the fabric and its surface weight only a part of the sound energy will be reflected. The remaining part of the sound energy is transmitted through the fabric. Figure 6.15 provides a detail view of a PTFE coated glass fibre fabric.

FIGURE 6.15 Detail view of PTFE coated glass fibre fabric

7 Design studies – Laboratory methods

§ 7.1 Introduction

For the most promising façade proposals, mock-ups were built on a scale of 1:2. The mock-ups were measured with regards to their acoustical properties. Combining the acoustical measurement data and the design requirements of each mock-up led to a broad overview of the multiple possibilities for introducing acoustically effective façade designs to façades.

Facing the task of measuring the reflection properties of the mock-ups, a literature research pointed out that there is no suitable measurement procedure available delivering values for the direction of the reflection in relation to the input direction of the source and the frequency distributed level change.

The method of the impedance tube and the reverberation chamber deliver values for the reflection / absorbing properties only regarding the normal of the measured object. (Cremer, 1971).

But even for noise cancelling walls there is yet no measuring method available that provides data on the angle dependent reflection properties. For measuring noise-cancelling walls the reverberation room measurement was used to quantify the effect of noise reduction. The deviation between the reverberation room measurement data and the achieved results in the vicinity of noise cancelling walls is still under discussion. The uncertainty of the acoustical characteristics due to different angles was topic of the EU project "Reflex" in 2014. During this project reverberation room measurement data for EU regulated noise-cancelling walls were compared with the data of two different on-site measurements methods. A deviation of 10 dB was reported. The data of the reverberation room measurements could not be linked to the results of both on-site measurements methods. The results of both on-site measurement methods, (Adrienne and QUIESST Method) showed only a small deviation (Conter & Wehr, 2015).

Because of the missing information relating to different angles, alternative methods were developed and discussed. Based on the "Kurzton Methode" by Spandöck, 1932, the Adriennne Method was etasblished in 2004 (Spandöck, 1932; Cobo, Fernandez, Palacios, de la Colina & Siguero, 2004). For both methods a short signal via loudspeaker is emitted in short distance to the measurement probe. The microphone, which is positioned at the similar distance to the probe captures the reflected signal and the direct signal. Using the recorded data, it is possible to calculate the absorption coefficient of the probed material. The Adrienne method provides the option of measuring an absorption surface under several angles. Since 2016, the Adrienne method is standardised to measure noise-cancelling walls. As the Adrienne method, which requires 9 microphones does not meet the low threshold introduction requirement of this measurement method to an architectural design process, a simplified method for measuring façades was developed based, among others, on the work of C. Nocke (Nocke, 2000). The basic idea was to take the basic image of an urban acoustic space as measurement layout. The translation of the comprising elements of an urban acoustic space into a measurement layout is shown in Figure 7.1.

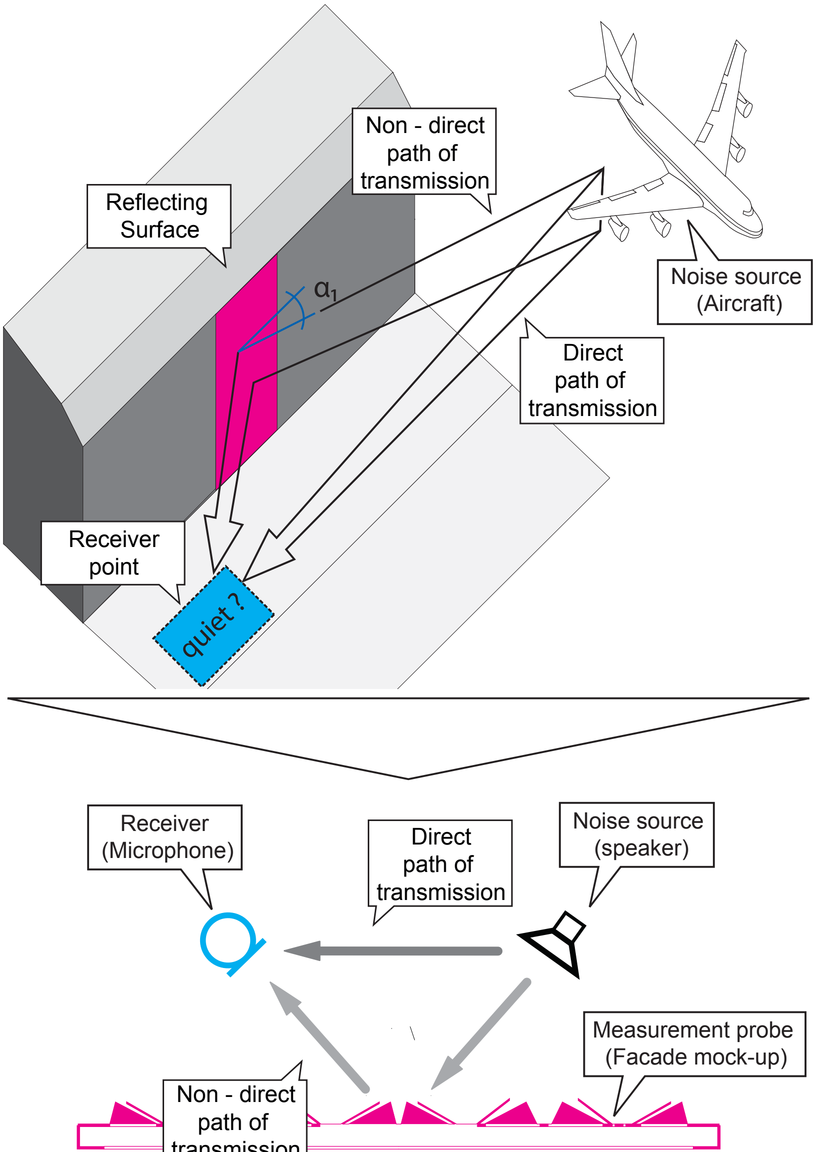


FIGURE 7.1 Translation of an urban space into a laboratory measurement setup.

The idea for the development of this setup was to include the sound energy transmitted on the direct path as this represents the acoustic impression in an urban space. This will result in low values for the level changes, as the sound energy of the direct path always delivers the major part of the captured sound energy at the receiver.

But despite the low level readings the measurement results will provide insight on the angle dependent acoustical impact of a façade surface placed parallel to the transmission path.

§ 7.2 Development of a laboratory method – Mock-up measurement

The requirements regarding suitability in an architectural design process were defined as follows:

- Measurements should be processable with freely available software and equipment at an affordable price.
- The processing of measurements should not require a specialised room like an anechoic chamber.

Following the requirements and the acoustic effects to be considered, a sketch of a setup was developed. The measurement chain should persist of:

- Source loudspeaker capable of a frequency range from 200 Hz to 12,000 Hz,
- Power amplifier,
- Laptop with a recording software installed,
- Audio computer interface e.g. an USB audio device,
- Measurement microphone fulfilling the requirements of class 2 for measurement equipment (International Electrotechnical Commission, 2002).

The input signal was defined as a logarithmic sine sweep from 200 Hz to 12,000 Hz with a durance of 0.1 s. A sweep digital audio file generated by a web based signal generator was used for the measurement (Pigeon, 2014). Following the dimension law of Rayleigh due to the scaling of objects and its properties the measured geometric principles could be tuned for differing frequency ranges by scaling them up or down. For the mock-up measurements the scale factor should be in the range of 1:1 to 1:4. Thus the sweep signal has to cover the upper range of 12,000 Hz to deliver results up to 4,000 Hz. For scaling refer to the Chapter Scaled measurements. The duration of 0.1 seconds was chosen in order to exclude wall or ceiling effects. For recording and analysing the data an open source recording software was installed on a laptop (Audacity, 2014). The software allows a recording during the playback of a track. This function is crucial for the measurement because with this function the sweep can be played over the loudspeaker and simultaneously recorded on one recording track direct while the second track captures the measurement microphone signal. With this input output configuration the calculation delay of the analogue/digital converters is included in the recordings. Thus, both recording channels are on an equal time base. The USB audio interface does the signal handling of the computer. Refer to Figure 7.2.

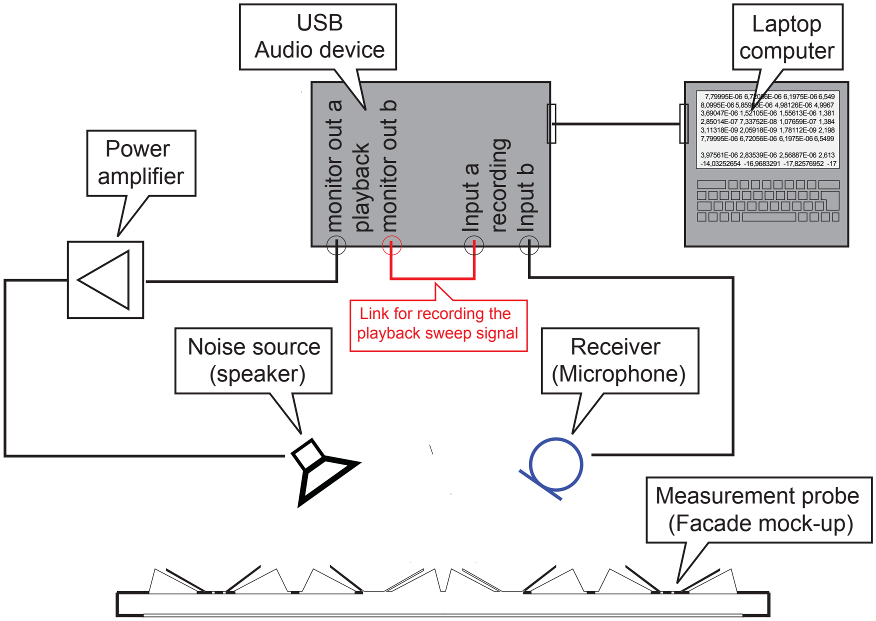


FIGURE 7.2 Measurement setup for mock-ups

The equipment in use and its specifications are provided in Table 7.1.

EQUIPMENT	Type	Model / Manufacturer	Low frequency limit	High frequency limit
Microphone	1/8 Inch condenser with power supply	MicW, i436 MicW, Pi49	20 Hz	140.000 Hz
Soundcard with preamplifier	USB soundcard with 24 bit/192 kHz	RME Babyface	5 Hz	192.000 Hz
Amplifier	Transistor amplifier	Quad 303	30 Hz	35.000 Hz
Speaker	Infinite baffle with a conical diaphragm speaker	Visaton FRWS 5R in a 3D-printed spherical housing	150 Hz	20.000 Hz
Measurement signal	Sine sweep	audio check	200 Hz	12.000 HZ

TABLE 7.1 Equipment setup incl. relevant specifications and resulting frequency range limitation for the measurement setup

The evaluation of the technical data in Table 6 proves the applicability of the intended sine sweep signal in the range of 200 Hz to 12.000 Hz in this measurement setup.

The spatial arrangement of the noise source and the microphone in relation to the probed façade proposal is shown in Figure 106. With regards to practical aspects like handling or weight of the façade materials, the mock-ups should have an elevation dimension of 1.5 m by 1.5 m. In order to exclude unwanted border effects in the measurement data the distance between the source and speaker was 5 times shorter than the elevation dimension of the probe. The source and the microphone were positioned at half the distance of the distance between source and receiver above the measurement probe.

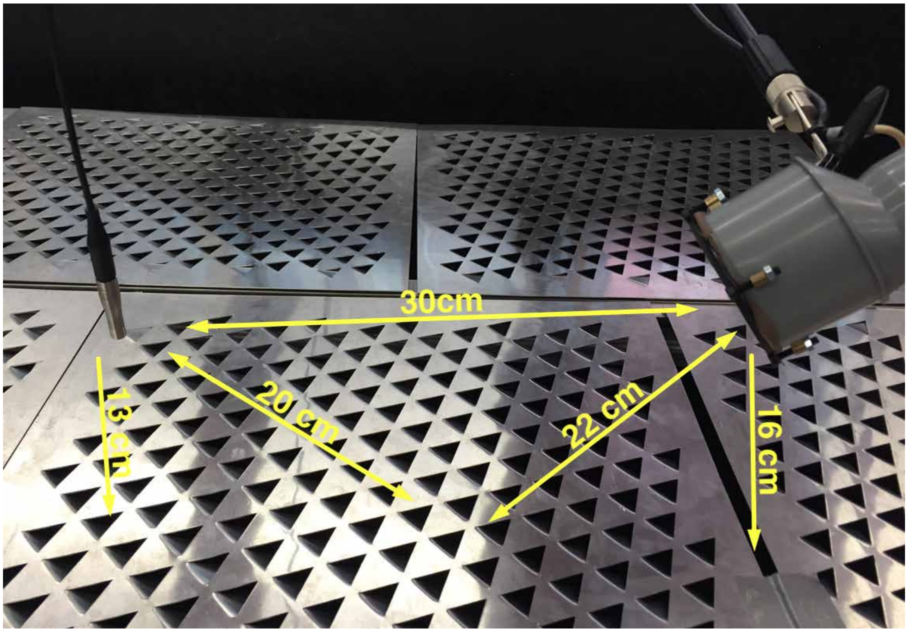


FIGURE 7.3 Mock-up under measurement. Microphone on the left, speaker on the right.

§ 7.3 Measurement operation

The mock-ups were measured with 10 times repeated sine sweeps for one position of the source and the microphone in the rotation from 0° to 360°. The source and the microphone rotate for every measurement step at a 30° angle. As the playback track consists of 10 sine sweeps with 30 s breaks in between for one measurement, 10 sine sweeps have been recorded. From the recorded track only the interval of the sine sweep duration were extricated. In order to get the transfer function of the recorded sine sweep in relation to the input sweep the recorded sweep is folded with the input sweep. This convolution, processed with open-source audio software resulted in 10-fold audio recordings (Kronlachner, 2015). Analysing the audio recording with the recording software regarding the frequency spectrum determines frequency-distributed levels for one sweep. Averaging the resulting 10 frequency spectra delivers a frequency spectrum for one 30° step. For more detailed measurement results the stepping of 30° was narrowed to 22.5° or 15° for some façade designs or materials. The results of all steps were compared in one graph with regards to their change of the measured values for each position.

§ 7.4 Results

The measuring data for the mock-up deliver results for the level change of a façade modification in relation to the direction of its geometric elements. In the following the measurement data of two façade mock-ups is exemplarily presented. The graphs in relation to the measured geometries show the dependence of angle, noise level and frequency. In Figure 7.4 and Figure 7.5, the graphs for the triangulated perforation of metal sheets are presented. The graphs in Figure 7.4 show the level change with reference to point "_-90" for the octave bands between 500 Hz and 8.000 Hz.

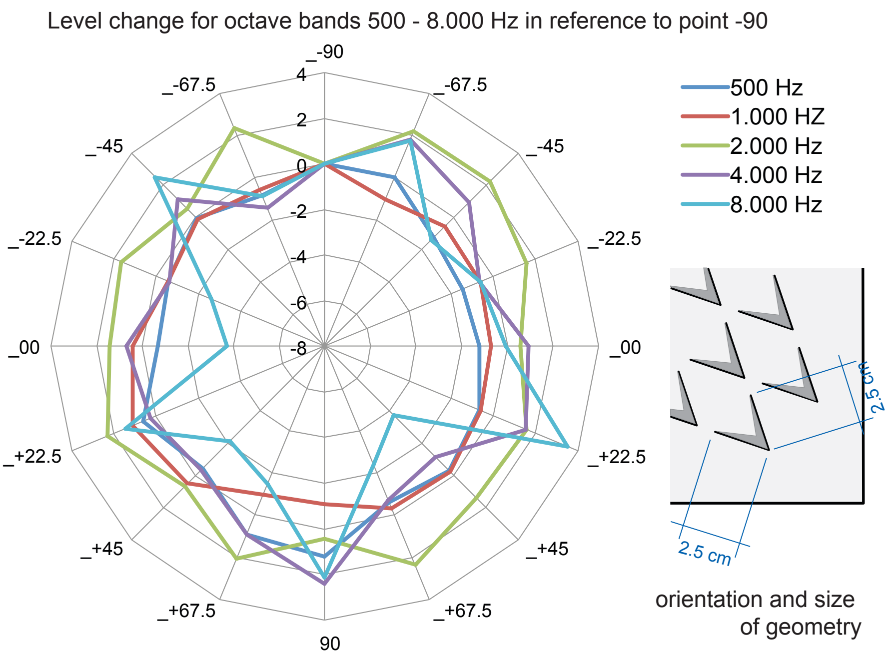


FIGURE 7.4 Measurement data for the Mock-up 1.3.1.1. shown in Figure 6.31

Figure 7.5 shows the graph for the angle dependent level change in reference to point "_-90" for the averaged level of the octave bands between 500 Hz and 8.000 Hz.

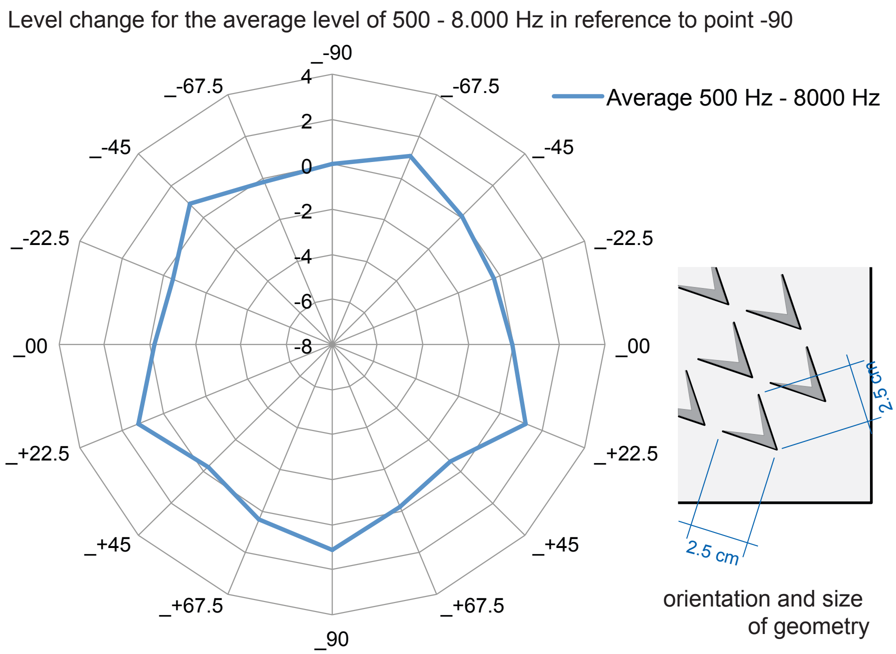


FIGURE 7.5 Measurement data for the Mock-up 1.3.1.1. presented in Figure 6.3

Figure 7.6 and Figure 7.7 illustrate the acoustical effect of the vertical lamella façade design as shown in Figure 6.7 and Figure 6.8. The graphs in Figure 7.6 show the level change with reference to point "_00 top" for the octave bands between 500 Hz and 8.000 Hz for the angles from 0° to 90°.

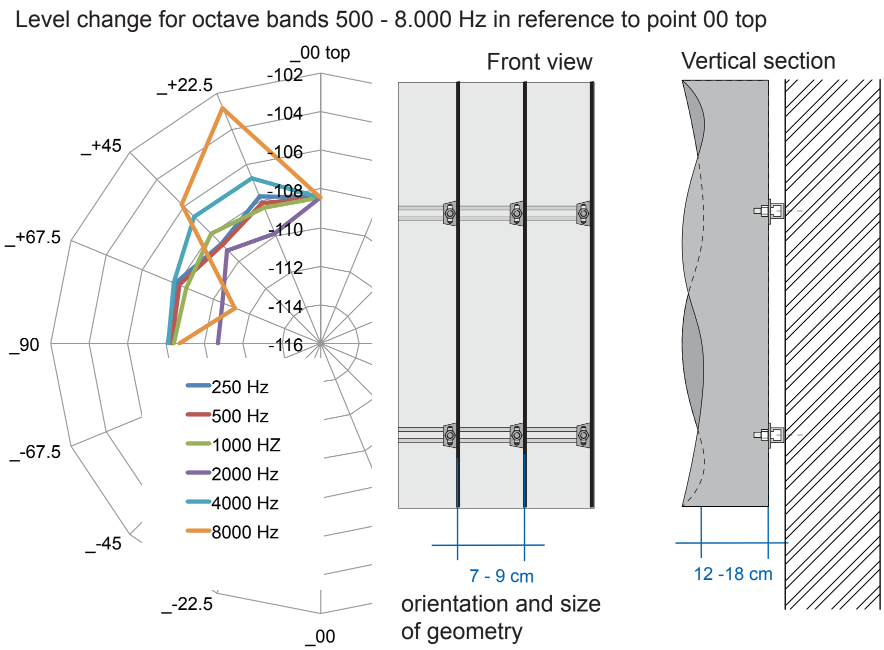


FIGURE 7.6 Measurement data for the Mock-up 1.3.

Figure 7.7 shows the graph for the angle dependent level change in reference to point „_00 top" for the averaged level of the octave bands between 500 Hz and 8.000 Hz for the angles from 0° to 90°.

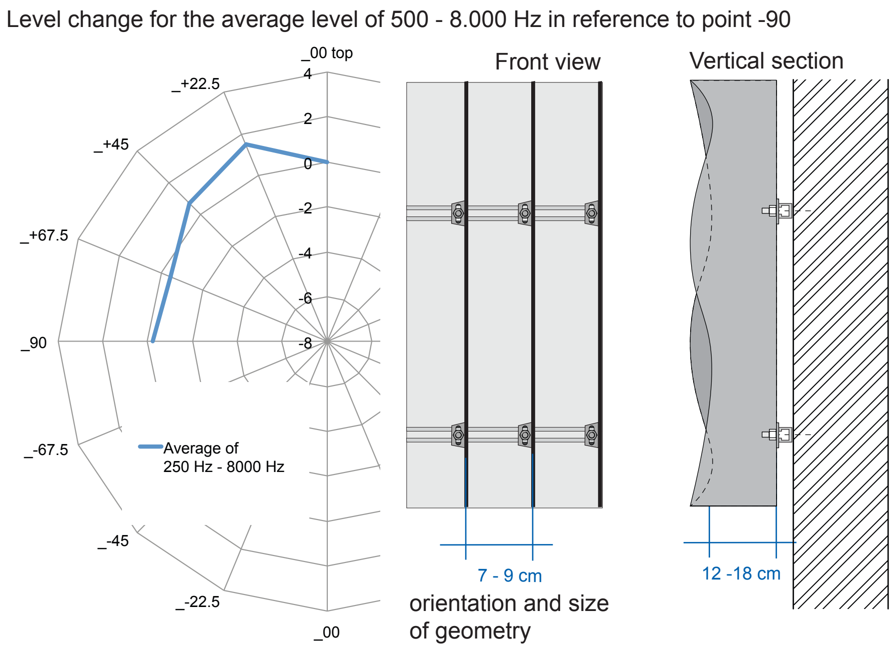


FIGURE 7.7 Measurement data for the Mock-up 1.3.2.

Figure 7.6 and Figure 7.7 depict the acoustical effect of the vertical lamella façade design as shown in Figure 95 and Figure 96. The graphs in Figure 7.6 show the level change with reference to point „_00 top" for the octave bands between 500 Hz and 8.000 Hz for the angles from 0° to 90°.

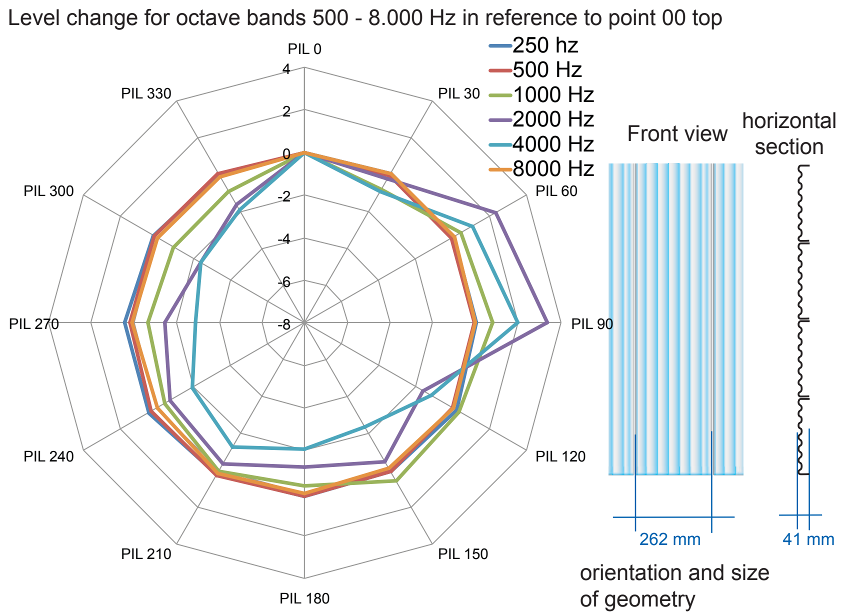


FIGURE 7.8 Measurement data for the cast glass mock-up

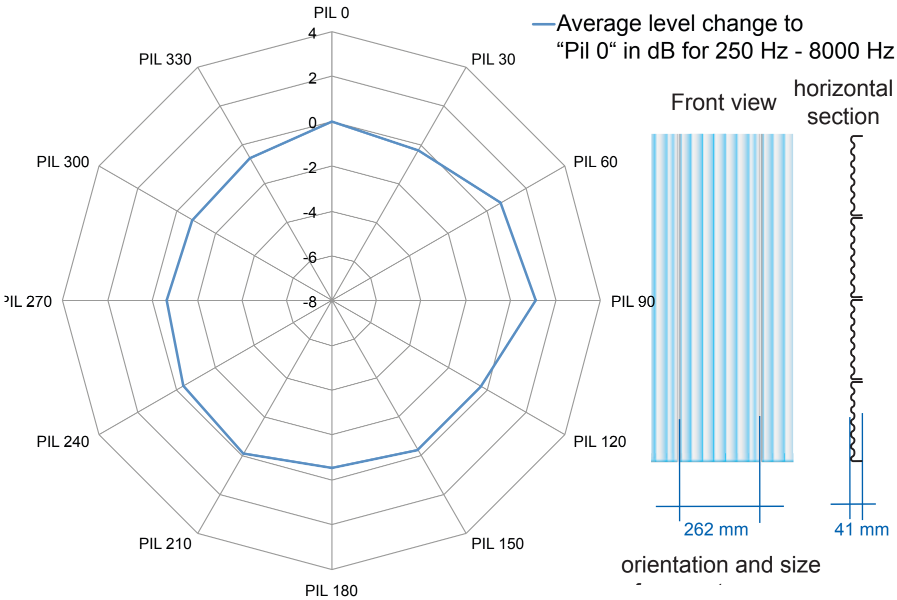


FIGURE 7.9 Single value data for the cast glass mock-up

§ 7.5 Discussion

The graph for the triangular perforation depicts an angle dependent change of frequency distributed noise levels for the octave bands 4,000 Hz and 8,000 Hz. The level change increases with the increasing frequency. For the frequencies below 4000 Hz the perforated metal sheet acts as a not perforated one. In the frequency band of 2000 Hz at all angles increased levels were reported. Below 1000 Hz only minimal level changes were documented. The triangular cut-out dimension of 2.5 cm is in the range of the wavelength of 12,000 Hz. The scaling in this context can also be applied to the size of the triangles. Changing the size of the perforation will change the effected frequency range. Considering a 1:2 scaling, the effect shifts from 4000 Hz and 8000 Hz to 2000 Hz and 4000 Hz. For a 1:4 scale, the calculated resulting frequency range will be 1,000 Hz to 2,000 Hz. Combining several sizes of triangular cuttings will result in a broadband effect of the panel. Average levels for the octave bands from 500 Hz to 8,000 Hz were calculated to determine a single level value for a façade design. The resulting graph depicts level changes of +/- 1 dB, which are not clearly readable in terms of relation to the underlying geometry. The triangular perforation can obtain control on the reflection of a narrow frequency band with a possible level change of up to 4 dB between for specific angles. With such a panel design the angle dependent control of reflection becomes feasible.

The feasibility of the angle dependent reflection control is shown for the case of a vertical lamella structure added to the façade. For 8,000 Hz the maximum level changes in relation to reference point “00 top” of +5 dB at the angle of 22.5° and -3 dB at 67.5° were reported. For the octave bands the effect regarding the documented level change decreases. An exception from this trend is the octave band of 500 Hz. For all angle dependent level changes in relation to the reference point level losses were reported. Thus, in a frequency range of six octave bands the acoustical impact of a façade design on an octave band can occur at one angle or at all angles.

The reported level changes for the cast glass mock-up depict that glass can change the reflection properties of a façade if it is produced with a wavy surface. In the case of the cast glass the angle dependent effect occurs at the octave bands of 1,000 Hz, 2,000 Hz and 4,000 Hz.

In general, from the measurement results of these design proposals it can be concluded that every material or a combination of materials produces a characteristic reflection pattern. Documenting the data of these reflection patterns in polar graphs makes it possible to arrange geometric elements in such a way on the façade that the reflection path for a place of interest is matched to the lowest level readings in the polar graph. For the surface proposals the calculation of single value levels for a broad frequency range does not provide insight on the acoustical effectiveness. The impact of an acoustically effective surface proposal could only be expressed by frequency dependent level reduction values. This is valid for the surface proposals presented in this chapter as well as for the geometric façade proposals of the scale model studies in chapter 5.2.

§ 7.6 Short discussion on practical applicability

The here presented measurement data should not be taken as absorption coefficients or material impedances. As the underlying idea of this setup was the representation of the acoustic setup close to the façade, the measurement setup and the data depict exactly only the intended setup. The reported level changes in relation to one measurement point show the changing effect for a noise source rotated over a façade mock-up, taking all possible transmission paths into account. In further research projects the measurement setup has to be proven for extended dimensions regarding the validity and the significance of the measured values. With this status of research in this project it is possible to arrange and organise a material or a façade mock-up on a transmission path of a noise source - receiver setting that a defined frequency band is affected at specific angles. It remains unclear if the acoustical effect of these façade designs occurs at bigger distances to the façade. This has to be subject of future research. Up to now the far field effects of an acoustical effective façade design can only be determined with the scaled measurement method.

The here proposed mock-up measurement procedure could become a tool for the designing of acoustic effective façade structures.

8 Research outcome

§ 8.1 Findings and conclusions

In summarising the results and the experiences of the case studies in scale or in reality, it can be concluded that it takes more than merely adding a few extra steps to conduct an acoustically effective façade design within a building design. **The disciplines of Architecture and Acoustics have to establish a new way of "acoustic project thinking" to set the basis for a fruitful collaboration in acoustic driven façade design projects.** Besides the well-known design aspects e.g. performance, aesthetics, and costs, an outdoor acoustic design aspect has to be established in the „thinking" of building projects. With regards to the acoustical performance of a building, an additional point of view has to be introduced.

For a building design, the acoustical performance of a building has to be considered for three cases of sound paths. Refer to Figure 8.1.

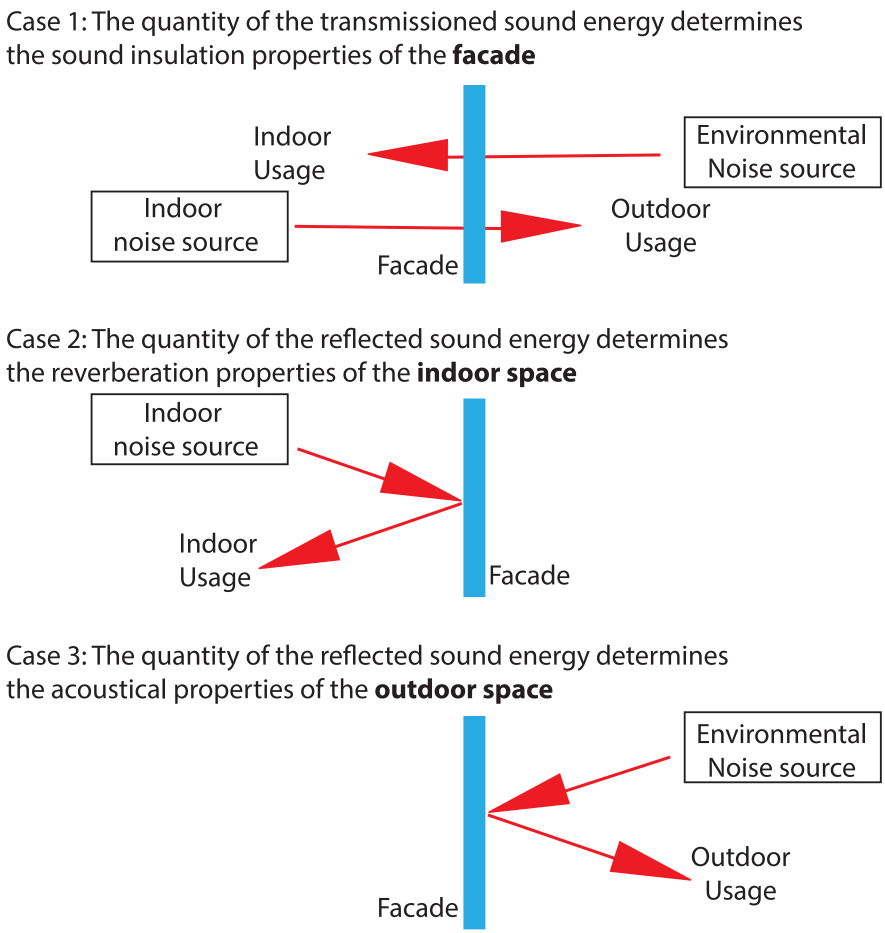


FIGURE 8.1 Three cases of sound paths in a building design

Up to now only two cases of sound paths are considered in a building project. The evaluation of the sound path from the inside to the inside determines the quality of the room acoustics. The evaluation of the sound path from the outside to the inside or vice versa determines the sound insulation properties of a façade design. This research proposes an investigation of the sound path considered from the outside to the outside. **The sound path has to be considered from the outside to the outside.**

The on-site investigation methods in Chapter 4 and the laboratory methods in Chapter 5 have shown that the investigation and evaluation of this sound path will determine the reflecting properties of a building design and its acoustic impact on urban spaces. The consequences of this fundamental change of view are emerging in both disciplines.

In the development of an underlying project plot it is the architects' task to deliver a basic design sketch. This must include defining the intended acoustical qualities for the outside spaces of a building as well as for the inside. The vicinity of a building has to be treated as a spatial setup of outdoor usages with a demand for specific acoustic qualities.

Places of interest with regards to predefined acoustic qualities have to be determined in the planning scope of projects with an intended acoustically effective façade design.

Analogously to an obligatory sub soil investigation, the acoustic urban space around a building site has to be investigated and evaluated by measurements with regards to noise sources and projected places of interest as well as for surrounding buildings.

The properties of noise sources have to be determined regarding their direction and their impact on projected places in relation to the projected façade. The analysis of the available data sources in Chapter 4.2.1 has shown that data for designing an acoustically effective façade cannot be derived from noise maps or monitoring stations.

The basic investigation method is a multipoint measurement in the vicinity of the projected building at the predefined places of interest. In order to decode the acoustical mechanism of an urban space, the simultaneously recorded data of multiple measurement positions covering the places of interest have to be compared. Therefore, one additional measurement position is needed, which is not affected by the projected façade. The data of this measurement position defines the reference zero data. The extended acoustical investigation of the building site and its surrounding noise sources in the framework of an acoustically driven façade project is described in Chapter 4.3.2, 4.3.5, 4.4.3 and 4.5.3. The comparison of the measurement data from different measurement points provides an insight into the spatial relation between them and the potential for a successful introduction of an acoustically effective façade design. The focus for the on-site measurements is not the delivery of absolute values for specific places around a building site.

If a multipoint measurement on-site is not feasible it can be substituted by the scaled measurement method described in Chapter 5.

Studies and measurements conducted in this research have revealed that for an acoustically driven façade design a set of key parameters has to be introduced. In Chapter 7 a proposal for a measurement method is presented determining the level change in relation to changing positions of the noise source. **Key parameters are mandatory to design acoustically effective façades.** Key parameters for a façade have to represent the reflection properties of a façade or material in relation to an angle of the noise incidence. The calculation of general averaged individual values for the acoustical effect of a façade is not feasible as it represents the specific effect on specific frequency bands in relation to the angle of incidence.

The effect of an acoustic façade design has to be described with a set of single noise level values for each specific angle of incidence and each specific frequency band measured.

The range of frequency bands should cover the measured frequency range of the on-site measurement. Two strategies for affecting the reflection of environmental noise were identified.

Strategy One introduces absorbing materials to a façade design. Most of the broadly applied absorbing materials exhibit an open porous structure. For example, acoustic foam, micro perforated panels, rock wool. These open porous materials are difficult to implement on the outside of a façade because of practical requirements such as cleaning capability, weather resistance, and water tightness. In this respect, a demand for the development of new façade materials appears, which is not covered by this research.

Strategy Two is based on a modified surface geometry, which controls the reflection of environmental noise towards a specific angle. If open porous materials cannot yet be used in a façade, then the intended acoustical effect has to be achieved by introducing specific surface geometries. The reflection properties of a plain façade are modified by a specific surface geometry. The investigations of scale models in Chapters 5.2 and 5.3 have shown that geometry based façade designs make it possible to achieve a noise level reduction at specific locations in their vicinity for a specific range of frequency bands. **Geometric acoustic façade designs reflect the sound energy away from the places of interest.** As sound energy does not simply disappear at the place of interest, it will reappear somewhere else next to the building. **A successful geometry based façade design for one location always implies a failure somewhere else in the vicinity of the building.** Furthermore, the scaled measurement results have shown that it is possible to introduce an acoustical effect by using established architectural elements such as lamellas or balconies.

Architectural elements can be treated as acoustically effective structures. The orientation and the geometry of elements have to be modified in relation to the noise source and the place of interest in the planning scope. **Varying the geometric dimensions of façade elements offers the possibility to tune the specific frequency range of a noise level reduction.** The investigations of various lamella structures with the scaled measurement method in Chapter 5.2.6 ff. have shown that a modification of lamellas' dimensions is linked to a change of the affected frequency band.

The best possible solution will be Strategy Three, a combination of Strategies One and Two.

For the fine tuning and the evaluation of an acoustically effective façade design, the acoustic engineer together with the architect must be in charge. The major acoustical impact of a façade design should not be tuned only to the frequency distribution of a specific noise source. In order to achieve a long-term stable effect of the façade, it makes more sense to achieve the highest possible noise reduction in the high sensitive frequency range of the human ear, i.e. between 630 Hz and 3000 Hz. This will lead to long-term stable results for the effectiveness of the façade as the human perception will not change much over the years, but the frequency characteristics of noise sources will, considering on-going developments and improvements.

For a long-term stable acoustic performance, the acoustically effective façade design must be tuned prior to a reduction of the acoustical load on the receiver's ears.

Conflicts between an acoustically effective façade design and the obligatory functions of a façade have to be solved in a redesigning process. **A compromise between the acoustic design and the functions of a façade must be developed according to the requirements of the places of interest and their spatial arrangement.** A successful overlay of all obligatory façade functions has to be proven.

Besides multiple requirements and interdependences of established design parameters, the acoustical design parameter is only one new input to a façade design process. Nevertheless, the design studies in Chapter 6.3 show the potential of an acoustic driven surface design.

The acoustic point of view can push a façade design by introducing new design patterns. In the early design stages it is the initial task of the architect to negotiate all design inputs and requirements of a façade with consultant engineers. For the task of evaluating the intended acoustic performance, a specialist acoustic engineer should be part of the team.

The performance of an acoustic façade design could not be described by absolute parameters in general, because every building project features its unique spatial arrangements of noise sources and reflecting surfaces. Development of the best possible solution for a specific location is the major underlying task of architecture. This task has to be met by an individual evaluation of the acoustical impact. **The comparison between a plain façade and the acoustically effective façade at the same location and under the same conditions will deliver precise data for the acoustical performance.**
In order to take the individual character of every building project into account,

the evaluation of an acoustically effective façade design has to be proceeded by a comparison between the intended design and the former façade design (or a plain reference surface) at the same location.

From the experience of several studies in the framework of this research it can be concluded that engaging with urban acoustics in the disciplines of architecture and acoustics will improve not only the building products but also the level and quality of collaboration between the disciplines.

Based on these findings and experiences, a general process chart for acoustically effective façades was created.

§ 8.2 Nine Steps to an acoustically effective façade design – Proposal for the façade design process in challenging urban acoustic spaces

Step 1: Defining the baseline:

Task

- Defining the location of places of interest in the planning scope.
- Defining the comfort noise level for the intended usage of the places of interest. Defining requirements for the determined places of interest.

Output

- The location of places of interest and their acoustical properties defined and fixed in the planning scope.

Who

- Client, Architect

Step 2: Preliminary on-site investigation:

Task

- Investigating the urban acoustic space in the vicinity of the projected building.
- Decoding the acoustical mechanism comprising the urban acoustic space by detecting direct sound events, mislocalisation effects and sound events not in the line of sight appearing on the building site.

Output

- Documentation of the acoustical status quo of an urban space and its comprising elements in relation to the location of places of interest.
- Basic definition for taking an on-site measurement.

Who

- Architect, acoustically specialised engineer

Step 3: On-site measurement

Task

- Developing a multichannel on-site measurement, which is based on the on-site investigation of the building site including measurement positions at the places of interest.
- Determination of specific time frames for conducting the measurements according to the activities of existing noise sources around the building site.
- Conducting a multichannel on-site measurement at the predefined positions and at the predefined points in time.
- Evaluation of the data derived from conducted multichannel on-site measurement with regards to the changing levels of moving or non-moving noise sources.

Output

- Documentation of the acoustical space and its comprising elements at places of interest sets the basis for the definition of façade requirements and the development of a suitable scaled measurement setup.

Who

- Acoustically trained engineer

Step 4: Definition of the façade requirements

Task

- Combining the on-site measurement data and the requirements for places of interest defines the requirements for the acoustically effective façade.

Output

- Definition of requirements for the façade according to the acoustical effectiveness. Definition of the location of the acoustically effective façade design in the overall sketch.

Who

- Architect

Step 5: Preliminary façade design

Task

- Developing first sketches for an acoustically effective façade design with the graphical approach, keeping track of the transmission paths between the noise source, the façade and the place of interest.

Output

- Sketches of the preliminary façade design

Who

- Architect and acoustic engineer

Step 6: Scale model measurements 1

Task

- Transferring the on-site measurement setup in to a suitable scaled measurement setup.
- Transferring the preliminary façade design into models of the building with a detailed façade geometry.
- Conducting the measurements of the building with a plain façade and one equipped with acoustically effective façade models.
- Evaluation of the measurement data regarding the effectiveness of the intended façade designs.

Output

- Documentation of the façade effect on level changes at the predefined measurement positions.

Who

- Acoustic engineer

Step 7: Refined façade design

Task

- Finetuning the façade design based on the determining parameters derived from the scaled measurement.

Output

- Sketches of an updated façade design based on the scaled measurement data.

Who

- Architect and acoustic engineer

Step 8: Scale model measurements 2 (if necessary)

Task

- Conducting the measurements for the building with a plain façade and equipped with the refined acoustically effective façade models.
- Evaluation of the measurement data regarding the effectiveness of the refined façade design.

Output

- Documentation of the façade effect and the achieved level changes at the predefined measurement positions.

Who

- Architect and acoustic engineer

Step 9: Final façade design

Task

- Finalising the façade design based on the determining parameters derived from the scaled measurement 2.

Output

- A fully functional pre-production (mock-up) façade design meeting the requirements for the following steps in the façade production chain.

Who

- Architect, design engineer

- The nine steps to an acoustically effective façade design are presented in Figure 8.2.

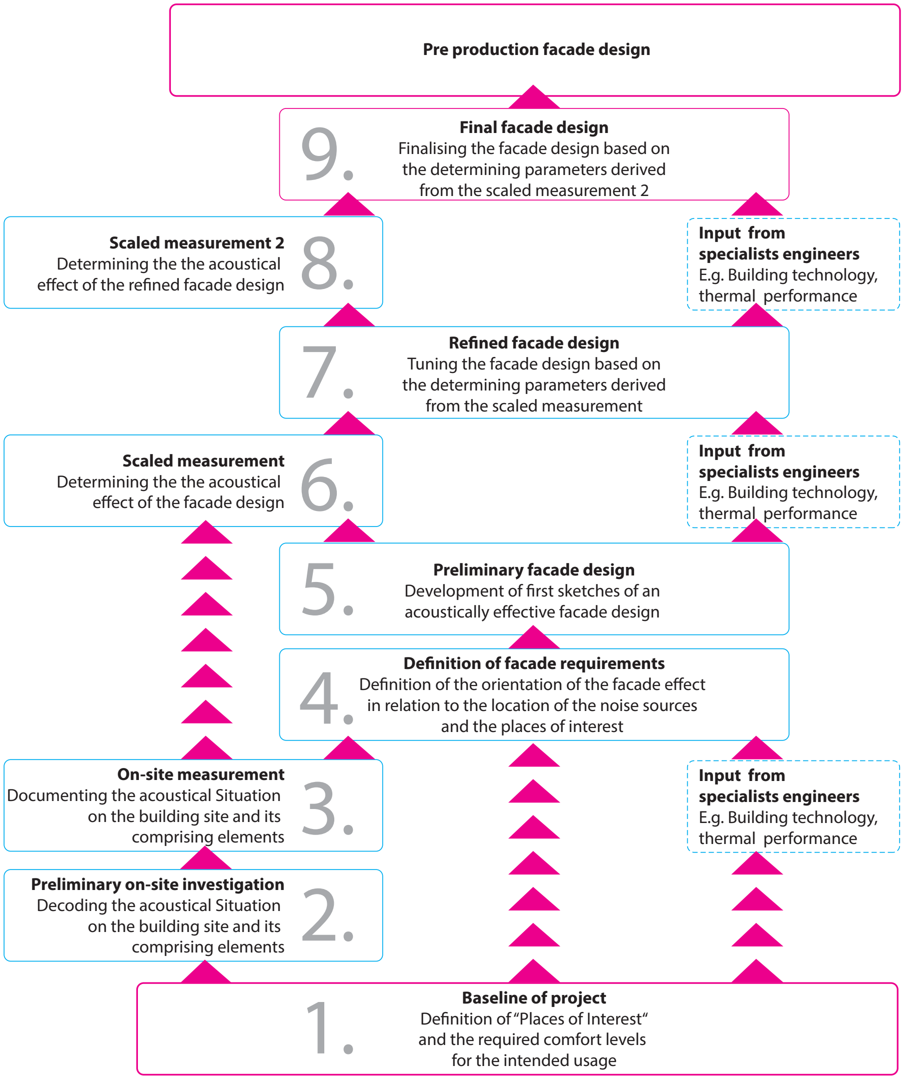


FIGURE 8.2 General process chart for the design process of acoustically effective façades

Literature

Alexico Group, (2016) global-landmark Information on the tribeca tower retrieved last from: http://56leonardtribeca.com/global-landmark/, at 171112, 23:56

Audacityteam, (2014) Audacity, retrieved from http://www.audacityteam.org

Babisch, W., Pershagen, G., Selander, J., Houthuijs, D., Breugelmans, O., Cadum, E., Vigna-Taglianti, F., Katsouyanni, K., Haralabidis, A. S., Dimakopoulou, K., Sourtzi, P., Floud, S., & Hansell, A., (2013) Noise annoyance--a modifier of the association between noise level and cardiovascular health? Science of the Total Environment 452–453, 50–57

Babisch, W., & van Kamp, I., (2009) Exposure–response relationship of the association between aircraft noise and the risk of hypertension, Noise & Health, 11(44),161–168.

Biermann, W., Beckmann, T., Wech, L., & Meier R., (2004) Analyse des Reifenabrollgeräuschs mit einem Messfahrzeug, ATZ 6 106, 564

Bullen, R., & Fricke, F., (1976) Sound propagation in a street, Journal of Sound and Vibration, Volume 46, Issue 1, 33-42

C. Steele, (2001) A critical review of some traffic noise prediction models, Applied Acoustics, Volume 62, Issue 3, 271–287

Can, A., Leclercq, L., Lelong, J., & Botteldooren, D., (2010) Traffic noise spectrum analysis: Dynamic modeling vs. experimental observations, Applied Acoustics 71, 764–770

Can, A., Leclercq, L., Lelong, J., & Defrance, J., (2008) Capturing urban traffic noise dynamics through relevant descriptors, Applied Acoustics, Volume 69, Issue 12, 1270–1280

Cheng, W. F., & Ng, C. F., (2001) The acoustic performance of an inclined barrier for high-rise residents, J. Sound Vib. 242, 295–308

Cobo, P., Fernandez, A., Palacios, R., de la Colina, C., & Siguero, M., (2004) In situ measurement of antinoise devices using pre-determined pulse waveforms, acoustica 2004, retrieved from: http://digital.csic.es/bitstream/10261/8591/1/ID22.PDF , 15-02-23, 14:47

Conter, M., & Wehr, R., (2015) Forschungsprojekt REFLEX – Vergleich der Schallabsorptionsmessung von Lärmschutzwänden nach Hallraum- und in-situ-Verfahren, Fortschritte der Akustik - DAGA 2015, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin

Cremer, L., (1971) Vorlesungen über Technische Akustik, Springer Verlag Berlin. Heidelberg: New York

de Ruiter, A., (2004) Reclaiming land from urban traffic noise impact zones, TU Delft

Deutscher Fluglärmdienst e.V, (2013) http://www.dfld.de“ provided from „Deutscher Fluglärmdienst e.V“

Echevarria Sanchez, G. M., Van Renterghem, T., Thomas, P., & Botteldooren, D., (2016) The effect of street canyon design on traffic noise exposure along roads, Building and Environment 97,96-110

Eikmann, T., zur Nieden, A., Lengler, A., Harpel, S., Ziedorn, D., Bürger, M., Pons-Kühnemann, J., Römer, K., Hudel, H., & Spilski, J. (2015). Norah Knowledge-11, NORAH Noise Impact Study Blood Pressure Study: Effects of aircraft noise on blood pressure In Gemeinnützige Umwelthaus gGmbH (Ed.), retrieved last from http://www.laermstudie.de/fileadmin/files/Laermstudie/NORAH_Knowledge-11.pdf, 170618_11:50

European Committee for Standardization, (2011), Din-en-1090-2 retrieved from https://www.beuth.de/de/norm/din-en-1090-2/144095591, at 170806,16:55

European Environmental Agency, (2014) EEA 10-2014 Noise in Europe 2014, last retrieved from http://www.bahnlaerm-mittelrhein.de/downloads/EEA 2010-2014 Noise in Europe 2014.pdf, 170618_12:39

Federal Motor Transport Authority, (2017), Jahresbilanz, Statistical data last retrieved from: http://www.kba.de/DE/Statistik/Fahrzeuge/Bestand/b_jahresbilanz.html, 170618, 14:07

Galaitsis, A. G., & Patterson, W. N., (1976) Prediction of noise distribution in various enclosures from free field measurements, J. Acoust. Soc. Am. 60, 848

Gemeinnützige Umwelthaus GmbH, (2014) http://inaa.umwelthaus.org from „Gemeinnützige Umwelthaus Gmbh“

Guillaume, G., Gauvreau, B., & L’Hermite, P., (2015) Numerical study of the impact of vegetation coverings on sound levels and time decays in a canyon street model, Science of The Total Environment, Volume 502, 22-30

Heutschi, K., (1995) A simple method to evaluate the increase of traffic noise emission level due to buildings for a long straight street, Appl Acoust, 44, 259–274
Heutschi, K., (2003) Parameter Study of the Insertion Loss Reduction in Case of a Building Façade Parallel to a Noise Barrier, Acta Acustica united with Acustica 89, Issue 5, 908-912
Hornikx, M., & Forssén, J., (2009) Noise abatement schemes for shielded canyons, Applied Acoustics 70 267–283
Hornikx, M., & Forssén, J.,(2007) Improving the shielding of road traffic noise in courtyards: Absorption treatments, INTER-NOISE 2007; Istanbul; Turkey;
Hornikx, M., & Forssén, J.,(2008) A Scale Model Study of Parallel Urban Canyons, Acta Acustica United with Acustica Vol. 94, 265 – 281
Horoshenkov, K. V., Hothersall, D. C., & Mercy, S. E., Scale Modelling of Sound Propagation in a City Street Canyon, Journal of Sound and Vibration 223 Issue 5, 795-819
Hossam El Dien H., & Woloszyn, P., (2004) Prediction of the sound field into high-rise building façades due to its balcony ceiling form, Applied Acoustics 65, 431–440
Hossam El Dien, H., & Woloszyn, P., (2005) The acoustical influence of balcony depth and parapet form: experiments and simulations, Applied Acoustics, Volume 66, Issue 5, 533–551"
Hothersall, D. C., Horoshenkov, K. V., & Mercy, S. E., (1996) Numerical modelling of the sound field near a tall building with balconies near a road, Journal of Sound and Vibration 198 Issue 4, 507-515
https://www.flightradar24.com/50.12,8.68/7, last retrieved 170804, 10:39
International Electrotechnical Commission, (2002) IEC 60651, IEC 60804, IEC 61672, Geneva
Ismail M., & Oldham, D., (2003)The effect of the scattering of sound from building facades on urban noise propagation, Proceedings of the Tenth International Congress on Sound and Vibration, Pages 1445-1452,
Ismail, M. R., & Oldham, D. J., (2005) A scale model investigation of sound reflection from building façades, Applied Acoustics 66, 123–147
Picaut, J., & Simon, L., (2001) A scale model experiment for the study of sound propagation in urban areas, Applied Acoustics 62, 327-340
Jeon, J.Y., Lee, S.C., & Vorländer, M., (2004) Development of scattering surfaces for concert halls, Appl Acoust, 65, 341–355
Jang, H. S., Kim, H.J., & Jeon, J.Y., (2015) Scale-model method for measuring noise reduction in residential buildings by vegetation, Building and Environment, Volume 86, 81-88
Kang J., (2000) Sound propagation in street canyons: Comparison between diffusely and geometrically reflecting boundaries, J. Acoust. Soc. Am. 107, 1394
Lee K. P., & Davies, H. G., (1976) Nomogram for estimating noise propagation in urban areas, Journal of the Acoustical Society of America, Volume 57, Issue 6, 1477-1480
Li, K.M. , Lui, W.K., Lau, K.K., & Chan, K.S., (2003) A simple formula for evaluating the acoustic effect of balconies in protecting dwellings against road traffic noise, Applied Acoustics, Volume 64, Issue 7, 633-764
Kinney, W. A., & Pierce, A.D., (1973) Helicopter Noise Experiments in an Urban Environment, Interim Report, Dept.Transportation, Contract DOT-TSC-93, MIT
Kirkpatrick Alberts II, W. C., & Noble, J. M., Coleman, M. A., (2008) Sound propagation in the vicinity of an isolated building: An experimental investigation, J. Acoust. Soc. Am. 124, 733
Klatte, M., Bergström, K., Spilski, J., Mayer, J., & Meis, M. (2014) NORAH Knowledge No. 4 NORAH Noise Impact Study Child Study: Impact of aircraft noise on childrenIn Gemeinnützige Umwelthaus GmbH (Hg.), retrieved last from http://www.laermstudie.de/fileadmin/files/Laermstudie/NORAH_Knowledge_4.pdf, 170818_11:55
Klein, T., (2013) Integral façade construction, TU Delft
Ko, N.W.M., (1978) Traffic noise in a high-rise city, Applied Acoustics, Volume 11, Issue 3, 225-239
Kronlachner M., (2014) joconvolver, downloaded from http://www.matthiaskronlachner.com/?p=1515
Kropp, W., & Bérillon, J., A (1998) Theoretical Model to Investigate the Acoustic Performance of Building Façades in the Low and Middle Frequency Range, Acustica 84(4):681-688
Lee P. J., Kim Y. H., Jeon J. Y., & Song K. D., (2007) Effects of apartment building façade and balcony design on the reduction of exterior noise, Building and Environment, Volume 42, Issue 10, 3517–3528
Lia K. M., & Tang S. H., (2003) The predicted barrier effects in the proximity of tall buildings, Acoustical Society of America 114 Issue 2,

Licitra, G., Van den berg, M., & De Vos, P., (2014) Good practice on quiet areas, EEA Technical Report, No 4/2014, European Envirinment Agency, last retrieved from: https://wwweea.europa.eu/publications/good-practice-guide-on-quiet-areas

Lu, K. K., & Li, K. M., (2002) The propagation of sound in narrow street canyons, J. Acoust. Soc. Am. 112, 537

Lugten, M., (2014) re-sil(i)ence, design patterns for an aircraft noise abating spatial environment, TU Delft

Lyon, R. H., (1974) Role of multiple reflections and reverberation in urban noise propagation, J. Acoust. Soc. Am. 55, 493–503

Lyon, R. H., Pande, L., & Kinney, W, A., (1971) Modeling of V/STOL noise in city streets, Washington, D.C. : Dept. of Transportation, Office of Noise Abatement

M.Jäschke, (2014) aktualisierte_Zusammenfassung, last retrieved from http://ruhige-gebiete.de/downloads/Dissertation_MARTIN_JAESCHKE_aktualisierte_Zusammenfassung_050814.pdf, at 170806, 23:09

Martin Schiff, M., Hornikx, & M., Forssén, J., (2010) Excess attenuation for sound propagation over an urban canyon, Applied Acoustics, Volume 71, Issue 6, 510–517

May, D. N., (1979) Freeway noise and high-rise balconies, J. Acoust. Soc. Am. 65, 699

Memoli, G., Kephalopoulos, S., Paviotti, M., & Licitra, G., (2006) Effect on measured noise levels of the microphone position in front of a façade, INTER-NOISE 2006, Volume 8, 5136-5145

Mohsen, E. A., & Oldham, D.J., (1977) Traffic noise reduction due to the screening effect of balconies on a building façade, Applied Acoustics, Volume 10, Issue 4, 243–257

Moleron, M., Felix, S., Pagneux, V., & Richoux, O., (2014) Low frequency acoustic resonances in urban courtyard, J. Acoust. Soc. Am. 135, 74

Myck, T., (2015). Die Lärmsituation in Deutschland nach der Umgebungslärmrichtlinie (conference contribution). Retrieved from https://www.dega-akustik.de/fileadmin/dega akustik.de/DEGA/aktuelles/symposium/9_symp_myck.pdf, p 15

Nabielek, K. et al. (2016), Cities in Europe, PBL Netherlands Environmental Assessment Agency, The Hague. ,

Nijs, L., (1977) The prediction of traffic noise levels with the aid of a scale model, Institute for town planning research, group of acoustics, Delft University of Technology, Delft

Nijs, L., & Kranendonk, F.(1979), Akoestisch optimaleoriëntering van bouwmassa's nabij verkeerswegen TU Delft

Nocke, C., (2000) In-situ Messung der akustischen (Wand-)Impedanz, Shaker-Verlag, Aachen

Ögren, M., & Kropp, W., (2004) Road traffic noise propagation between two dimensional city canyons using an equivalent source approach, Acta Acust. Acust. 90, 293–300

Picaut, J., Schmich, I., Defrance, J., Woloszyn, P., Barlet, A., & Chartier, F., (2006) Effects of diffuse reflection by building façades on the sound propagation and soundscapes in urban areas, EURONOISE 2006 - The 6th European Conference on Noise Control: Advanced Solutions for Noise Control 2006,

Picaut, J., & Simon, L., (2001) A scale model experiment for the study of sound propagation in urban areas, Applied Acoustics, Volume 62, Issue 3, 327–340

Picaut, J.; & Scouarnec, D., (2009) Using Acoustic Diffusors to Reduce Noise in Urban Areas, Acta Acustica united with Acustica, Volume 95, Number 4, 653-668

Pieren R., & Heutschi K., (2015) Predicting sound absorption coefficients of lightweight multilayer curtains using the equivalent circuit method, Applied Acoustics 92, 27–41

Pigeon S., (2014) Sine sweep generator: audiocheck.net, last retrieved from https://www.audiocheck.net/audiofrequencysignalgenerator_sweep.php at 150915; 14:20

Probst, W. , & Probst, F., (2012) Reflected sound in street canyons - Diffuse or specular?, retrieved from http://www.datakustik.com/fileadmin/user_upload/PDF/Papers/310_Reflected_Sound_in_Street_Canyons.pdf at 2017-03-15, 11:32

Probst, W., (2013) Straßenlärm bei dichter Randbebauung, Untersuchungen zur reflexionsbedingten Pegelerhöhung. Wirtschaftsverl. NW, Verl. für Neue Wiss., Bremerhaven,

Quirt, J.D., (1985) Sound fields near exterior building surfaces, Journal of the Acoustical Society of America, Volume 77, Issue 2, 557-566

Rayleigh, J.W.S., (1915) The principle of similitude, Nature 95, No.2368

Schreckenberg, D., Faulbaum, F., Guski, R., Ninke, L., Peschel, C., Spilski, J. & Wothge, J. (2015). Mental quality of life, norah studie, in Gemeinnützige Umwelthaus GmbH (Hg.) retrieved last from http://www.laermstudie.de/en/results/results-of-the-quality-of-life-study/noise-related-annoyance-and-quality-of-life-over-time/, 170806, 9:00

Schröder, E., (1973) Nachhall in geschlossenen bebauten Strassen, Lärmbekampfung 17, Springer Verlag, Düsseldorf
Schuring, D., J., (1977) Scale models in engineering, Pergamon Press, Oxford
Shaw, E. A. G., & Olson, N., (1972) Theory of Steady – State Urban Noise for an Ideal Homogeneous City, J. Acoust. Soc. Am. 51, 1781
Smyrnova, Y., Kang, J., Hornikx, M., & Forssén, J., (2012) Effect of Vegetation of noise propagation in streets and squares, Proceedings of the Institute of Acoustics, Vol. 34. Pt.1.
Spandöck, F., (1932) Experimentelle Untersuchung der akustischen Eigenschaften von Baustoffen durch die Kurztonmethode, retrieved from: http://zs.thulb.uni-jena.de/servlets/MCRFileNodeServlet/jportal_derivate_00154973/19344120307_ftp.pdf, 15-02-23, 15:00
Steenackers, P., Myncke, H., & Cops, A., (1978) Reverberation in town streets, Acustica Volume 40, Issue 2,115-119
Tang S. H., & Li K. M. , (2001) The prediction of façade effects from a point source above an impedance ground, J. Acoust. Soc. Am. 110, 278
Tang, S.K. , & Piippo, K.E., (2011) Sound fields inside street canyons with inclined flanking building façades, Proceedings of Meetings on Acoustics, Volume 12, Article number 040004, 7p, 161st Meeting Acoustical Society of America 2011
Tang, S.K., (2010) Scale model study of balcony insertion losses on a building façade with non-parallel line sources, Applied Acoustics, Volume 71, Issue 10, 947–954
Technical comittee ISO/TC43/ SC Noise, (2014) ISO 12913-1:2014(E), Acoustics - Soundscape, Definition and conceptual framework, Genevie
The European Parliament and the Council of the European Union, (2002), European Noise Directive, Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002, The European Parliament and the Council of the European Union, Official Journal L 189, 18/07/2002 P. 0012 - 0026,
Van Renterghem T., (2014) Guidelines for optimizing road traffic noise shielding by non-deep tree belts, Ecological Engineering 69, 276–286
Van Renterghem T., Attenborough K., Maennel M., Defrance J., Horoshenkov K, Kang J., Bashir I., Taherzadeh S., Altreuter B., & Khan A. (2014) Measured light vehicle noise reduction by hedges, Applied Acoustics 78 19–27
Van Renterghem, T., & Botteldooren, D., (2008) Numerical evaluation of sound propagating over green roofs, Journal of Sound and Vibration, Volume 317, Issues 3–5, 781–799
Van Renterghem, T., & Botteldooren, D., (2009) Reducing the acoustical façade load from road traffic with green roofs, Building and Environment, Volume 44, Issue 5, 1081–1087
Van Renterghem, T., & Botteldooren, D., (2010) The importance of roof shape for road traffic noise shielding in the urban environment, Journal of Sound and Vibration, Volume 329, Issue 9,Pages 1422-1434
Van Renterghem, T., & Botteldooren, D., (2011) In-situ measurements of sound propagating over extensive green roofs, Building and Environment, Volume 46, Issue 3, 729–738
Van Renterghem, T., Forssén, J., Attenborough, K., Jean, P., Defrance, J., Hornikx, M., & Kang, J., (2015) Using natural means to reduce surface transport noise during propagation outdoors, Applied Acoustics 92, 86–101
Van Renterghem, T., Salomons, E., & Botteldooren, D., (2006) Parameter study of sound propagation between city canyons with a coupled FDTD-PE model, Applied Acoustics, Volume 67, Issue 6, 487–510
Walerian, E., & Janczur, R., (1998) Noise shielding in an urban system, Journal of Sound and Vibration 212(2), 187–214
Walerian, E., & Janczur, R., Czechowicz, M., (2001) Sound level forecasting for city-centers. Part 1: sound level due to a road within an urban canyon, Applied Acoustics 62, 359-380
Walerian, E., Janczur, R., & Czechowicz, M., (2001) Sound levels forecasting for city-centers Part III: a road lane structure infuence on sound level within urban canyon, Applied Acoustics 62, 493-512
Walerian, E., Janczur, R., & Czechowicz, M., (2001) Sound levels forecasting for city-centers Part IV. Vehicles stream parameters influence on sound level distribution within a canyon street, Applied Acoustics 62, 645-664
Wang B., & Kang J., (2011) Effects of urban morphology on the traffic noise distribution through noise mapping: A comparative study between UK and China, Applied Acoustics 72 556–568
Wang, B., Kang, J., & Zhou, J., (2008) Comparison of traffic noise distribution between high and low density cities, Proceedings of the 36th international congress on noise control engineering, Shanghai, China

WHO, (2011) Burden of disease, last retrieved from http://www.euro.who.int/__data/assets/pdf_file/0008/136466/e94888.pdf, 140311, 11:32

Wiener, F. M., Malme, C. I., & Gogos, C. M., (1965) Sound Propagation in Urban Areas, J. Acoust. Soc. Am. 37, 738

Wong N.H.,Tan A. Y. K., Tan P. Y., Chiang K., & Wong N. C., (2010) Acoustics evaluation of vertical greenery systems for building walls, Building and Environment, Volume 45, Issue 2, Pages 411-420,

Wutzke M., (2017), Information on projected Highrises retrieved last from: https://www.skylineatlas.de/portfolio_type/geplant/ at 170618_16:03

Bibliography

Krimm, J., (2011), *Akustische Unsichtbarkeit* in Über Grenzen, Frankfurt High rise symposium 2011, Frankfurt am Main

Techen, H. **Krimm, J.**, (2013) *Fassaden Stadtraum und Akustik* in XIA 07-09/ 2013, Alexander Koch GmbH, Leinfelden-Echterdingen,

Techen, H., **Krimm, J.**, (2014) *Die akustisch wirksame Fassade,* in Fortschritte der Akustik - DAGA 2014, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin,

Techen, H., **Krimm, J.**, (2014) *Acoustically effective facade design, in* J.Schneider, B.Weller (Eds) Engineered transparency, Glasstec 2014, TU Darmstadt

Techen, H., **Krimm, J.**, (2015) *Mit Hochhausfassaden den Stadtraum gestalten,* Fortschritte der Akustik - DAGA 2015, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin

Knaack, U.,Techen, H., **Krimm, J.**, (2015) *Hochhausfassaden und akustische Stadraumgestaltung* Lärmbekämpfung Nr. 3 2015, Springer - VDI - Verlag GmbH & Co. KG, Düsseldorf

Techen, H., **Krimm, J.**, 2015, *Acoustical invisible envelopes*, Future Envelope 9 Unobtainium, Delft University of Technology, Delft

Knaack, U., Techen, H., **Krimm, J.**, (2016) *Transformationspotentiale von Hochhausfassaden,* Fortschritte der Akustik - DAGA 2016, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin

Knaack, U., Techen, H., **Krimm, J.**, (2016) *Tuning acoustical facade designs aiming for a controlled influence on the urban soundscape,* Proceedings of the INTER-NOISE 2016, 45th International Congress and Exposition on Noise Control Engineering, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin

Knaack, U., Techen, H., **Krimm, J.**, 2017 *Updated urban facade design for quieter outdoor spaces,* in Knaack, U., Klein, T., (Eds) Journal of Facade Design and Engineering - TU Delft Open, Delft

Knaack, U., Techen, H., **Krimm, J.**, (2017) *Der urbane Raum in der Akustik als architektonische Gestaltungsgrundlage für leisere Städte,* Fortschritte der Akustik - DAGA 2017, Deutsche Gesellschaft für Akustik e.V. (DEGA), Berlin

Curriculum Vitae

Dipl.-Ing. M.A. Jochen Krimm

1968
Born in Lohr/ Main, Germany

1994 - 2008
Professional occupation in field of event design and electro-acoustical systems

2000 - 2008
Teaching event design, electro acoustical design,
Friedrich Ebert School, Wiesbaden

2007
Teaching building design, computer aided architectural design and construction design, Department of Architecture, Frankfurt University of Applied Sciences

2010
Founder of Struktursuper Office for (electro) acoustical architecture Design, Offenbach

2011
Master Degree Architectural Design, HfbK Städelschule Frankfurt

Since 2013
Research assistant, Department of Architecture Frankfurt University of Applied Sciences

Contact
jochen.krimm@gmx.de