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Sound predictions in an urban context

J Niesten[1,2], MJ Tenpierik[1] and J Krimm[1,3]

Abstract

Recent studies show that environmental noise in urban environments continues to be a great health risk. This noise is especially further transmitted by the hard materials that are mostly used for façades. To predict these effects it is desirable to have a reliable prediction method. There are already several ways to predict sound levels in an urban context. This paper investigates two while focusing specifically on a practical approach to show that the methods are suitable to use during an actual design project. The impact of changing a façade at a specific location is investigated using both prediction methods. A façade which reflects sound to a location where it has a smaller impact, a sound absorbing façade, and a façade which combines both are taken into consideration. These façade adaptions have the potential to improve the sound levels in the investigated area from 1.7 up to 9.3 dB(A).

Keywords

Sound reflections, façades, high-rise, environmental noise, urban context

Introduction

The World Health Organization[1] states that environmental noise is the number two health risks. In the European Union, at the end of the 20th century, 40% of the population was exposed to traffic noise levels exceeding 55 dB(A) and 20% was exposed to higher noise levels exceeding 65 dB(A). At night, the amount of people exposed to a noise level of >55 dB(A) was 30%.[2] The health effects related to high noise levels are ranging from annoyance to serious heart conditions. According to the European Environment Agency 48,000 new cases of heart disease and 12,000 premature deaths are attributed to environmental noise in 2017. They also estimated that most of these cases are related to road noise.[3] In the Netherlands a study from KpVV CROW shows that approximately 600,000–800,000 inhabitants are severely affected by traffic noise each year while an additional 300,000 people experience sleeping problems.[4] Besides the health effects, high noise levels can

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also result in high costs. A study from 2007 indicates that the social costs from traffic noise in the European Union are approximately 40 billion Euros/year.[2] This corresponds to a loss of 0.4% of the total GDP. Furthermore, exposure to higher noise levels on children was also connected to how long it would take them to learn to read. In the NORAH study a 10 dB increase in the long term equivalent noise level was found to delay learning to read by 1 month.[5] From this it can be concluded that high noise levels have effects which cannot simply be ignored, both on individuals and society as a whole.

In an urban context there are generally four ways that sound can propagate: directly from source to receiver, by reflecting against an obstacle before reaching the receiver, by bending over or past the side an obstacle (horizontal and vertical diffraction).[6,7] Based on scale models and general acoustics theory, Nijs[6] showed that sound reflections in an urban context can increase the sound pressure level by a maximum of 3 dB. Hossam El Dien and Woloszyn[8,9] investigated the impact of the shape of balconies on noise levels. They found that balconies on high-rise buildings can influence the noise levels inside the building by a variation of up to 8 dB(A) by changing the depth of the balconies, the ceiling of the balconies, or inclining the parapet. Lee et al.[10] also investigated several changes to the façade and the balconies of a high-rise building. By combining deeper balconies, angled balcony ceilings, and sound absorbing materials, they obtained a maximum noise reduction of 23 dB on the balcony directly in front of the façade. This research was conducted using both a scale model and computer simulations. Both of these prediction methods produced similar results. Lugten[11] investigated noise in an urban area on a much bigger scale. He investigated the impact of building volumes combined with gravel strips in the landscape positioned in such a way that they would reduce airplane noise coming from a nearby airport. Over a distance of >2500 m these elements reduce equivalent sound pressure levels at the receiver up to 19 dB.

In case direct sound does not play an important role in certain urban areas the influence of sound reflections will be more dominant. Techen and Krimm[12] showed that, in case the direct sound is blocked, façades consisting of hard sound-reflective materials can cause urban noise levels to be 3–8 dB higher than in a free field situation. In a study from Sanchez et al.[13] it was shown, for a variation of 2D sections, that the design of the façade of a building could reduce the average sound pressure levels up to 13 dB(A). This was investigated at the side of the noisy street near a balcony, while also looking into the geometry of the section of the street. Because the amount of reflective façades in the urban environment is not diminishing and the amount of noise sources is continuing to grow, it is important to investigate possible solutions to noise mitigation in cities. This development, driven by the migration to the big cities, is increasing the number of people harmed by noise. Recent research at the Frankfurt University of Applied Sciences[14,15] has measured parts of several façades on site as well as in a laboratory. This research shows that the acoustical situation in front of a façade can be modified using certain structures and has the potential for designing quieter cities. The façade surfaces which were investigated for example consist of individual slats under a certain angle, façade panels with incorporated angles and grooves, and perforated elements. In the mentioned research broadband level changes of 0.5–4 dB are found. The research presented in this paper also focuses on practical solutions, but has chosen a different approach by investigating and improving an existing façade in its context. Therefore not only technical aspects play an important role, but also feasibility of the solution for the specific building and location.

Nowadays, several methods to simulate sound levels in an urban context exist, which can be divided in three main groups: heuristic methods (including ray tracing), wave-based methods, and hybrid methods.[16] Most of the (software) models using the heuristic approach are simplifying certain effects like sound diffraction, weather effects, scattering of the sound in trees, etc. Instead of treating sound as waves, it is often represented using rays. There are various heuristic models, like ISO 9613-2, Harmonoise, and Nord2000, and software packages which implement them. The various models are different from each other in the way specific effects are implemented. The preferred methods can differ between countries because (local) standards are also influencing the models that have to be used, from a legal standpoint.[16–19] Wave-based acoustic models focus more on predicting the actual behavior of the sound waves instead of simplifying the prediction. Available models are for example based on the PSTD or FDTD methods. These models tend to be more accurate than heuristic models because they include more physical effects, like diffraction, weather effects, scattering, and so on. The downside of these models is that they are generally slow regarding to both calculation time and time it takes to properly setup the model. This is directly linked to the fact that these methods are more detailed, which leads to the need for more detailed models, which increases the computational load even more.[15,20,21]

Finally there are hybrid models which combine both the heuristic and wave-based approach. This approach combines the possibility to quickly calculate the acoustically more simple trajectories using a heuristic approach while adding more detail at certain parts of the trajectory. For example methods that combine a ray-tracing algorithm with solving Helmholtz equations.[16]

This paper uses two prediction methods to investigate an existing courtyard area and possible façade designs to reduce the sound levels caused by reflected sound waves. The goal is to evaluate these prediction methods and the possible designs for this specific case study location. Based on these results the application potential for comparable architectural projects is explored. During the research the available time was limited, as would also be the case during an actual design project. Therefore it was needed to simplify certain parts of the research and rely on prior studies. The two used and investigated prediction methods are scale model measurements and ray-tracing simulations (via CATT Acoustics).

Because certain prediction methods are selected and evaluated before they are being used to design a building façade this paper consists of two parts. It will first analyze the potential aspects which cause differences between the actual and modeled situation by comparing field measurements to scale model measurements and ray-tracing simulations. In the second part of this paper several theoretical façade designs, which have been developed to reduce the sound levels inside the investigated outdoor area, are discussed. These façade designs are evaluated using the chosen prediction models.

Methodology

Case description

At the start of this research project, on-site measurements were conducted on a real location in the Netherlands: the Herman Gorterhof area in Delft. This area is located near a busy road with an daily intensity of on average 6036 vehicles/day. The hourly average of passing vehicles during the day period (07:00–19:00) is 373, during the evening period (19:00–23:00) is 226, and during the night period (23:00–07:00) is 46 vehicles/h. Between 16:00 and 18:00 the traffic intensity on this road was at its highest peak with an hourly intensity of 488–539 vehicles/h.[22] Most of the direct sound transmission from this road is blocked by a building which reflects the sound to other locations not within the investigated are. This building has eight floors parallel to the street and creates an enclosed, quieter, courtyard area by reflecting the sound elsewhere. The sound enters the enclosed area through an opening of approximately 40 m between two buildings and is reflected by a high-rise building, with 18 floors, around 50 m in height. This building is positioned perpendicular to the busy road. In Figure 1 a schematic situation of the area and the noise source is shown, giving an indication of the direct soundwaves into the courtyard area in a darker shade and the reflected ones in a lighter shade. Furthermore, sound diffraction over and along the building parallel to the road will occur, as will wind-induced curving of the sound transmission path.

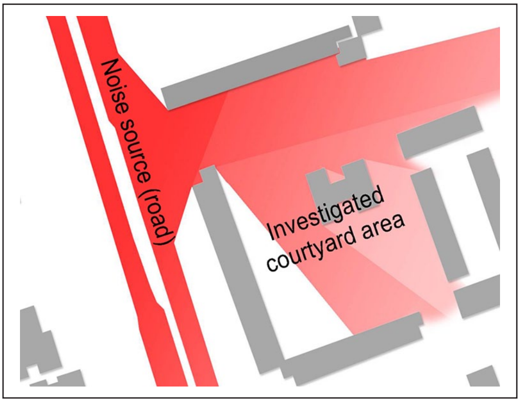

Figure 1. Schematic situation of the investigated area with shaded areas as an indication of the intensity of the direct and reflected noise that can enter the area via the small opening between two buildings.

A scale model and a computational model in CATT Acoustic v9 were made for this location. Using the results from all of the measurements and simulations the differences between the actual and modeled situation were investigated. Furthermore, 20 theoretical changes to the façade of the perpendicular high-rise were investigated. The impact of these changes was measured using only the computer simulations and scale model measurements. The differences between both of these prediction methods were further investigated using these measurements.

Table 1 provides an overview of some of the aspects that were or were not included in the used prediction methods.

On-site measurements

To investigate the noise levels in the area, on-site measurements of the traffic noise were conducted. These measurements were done during rush hours on a weekday from 15:50 until 18:00 h. According to traffic data from the municipality this is the busiest period of the day causing maximum noise levels. For the conducted measurements two different sound level meters were used: a Nor140 from Norsonic, which could measure both an overall sound pressure level, $L_{A;eq}$, as well as sound pressure levels per frequency band and is a class 1 sound analyzer, and a type 2225 sound level meter from Brüel & Kjær, which could measure only the overall sound pressure level. The Norsonic was set to register the measured sounds in one-third octave bands. Measurements were conducted directly near the busy road and inside the courtyard, each measurement lasting for 10 min. They were conducted on a Wednesday (27th of May, 2015) and during the measurements there was quite some wind. To reduce the effect of the wind on the measurements windscreens on the microphones of the sound level meters were used. The sound level meters were set to automatically apply a windscreen correction. However, the wind did still clearly influence some of the recorded signal from the microphone.

According to the Royal Netherlands Meteorological Institute (KNMI) the average wind speed during the measurements was approximately 3.0–5.0 m/s (3 Bft) with gusts up to 8.0 m/s (5 Bft), coming from a Southwest/West-Southwest direction. The temperature was between 15°C and 16°C with a relative humidity between 60% and 70%. This is based on one of the nearest KNMI measurement points in Rotterdam.[23] The Southwest/West-Southwest direction means the wind was coming from the road toward the courtyard area. This wind direction could have bent the soundwaves downward, potentially having influenced the measurement results.

Table 1. The several aspects which are causing differences between the actual, existing, situation, and the computer simulations or scale model measurements.

	Computer simulations	Scale model measurements
Soil properties	The effect of sound being absorbed by passing over the soil surface is not taken into account	Not included because further research was needed to determine the correct materials to use. A hard wooden floor was used.
Material properties	Included: estimation based on literature, product, and material data	Not included because further research was needed to determine the correct materials to use. Only one type of wood was used.
Trees	Not included to reduce computational load	Not included to reduce the complexity of the model
Weather effects	Not included because of limitations of the software	Not possible to include
Height receivers	2 and 4 m	4 m
Source	Stationary omnidirectional point sources, with an output based on the on-site measurements	Directional point sources, with a predefined output not based on the on-site measurements
Accuracy	Ray-tracing was used during the simulations: specific wave-based phenomena were not taken into account. However, diffraction effects are included in the software.	Actual (scaled) sound waves were used. Because of simplifications, effects like scattering would have a somewhat different effect in the model.
Uncertainties (randomness)	CATT-Acoustics uses a semi-random prediction method for scattering causing differences up to 1 dB	Because of fluctuating temperature and humidity the results slightly differed per measurement

The first measurement, conducted from around 15:50 until 16:00 h, was 3 m from the edge of the road, at the reference point. This measurement was conducted using the Nor140 sound meter to get information about the noise spectrum. The measurement setup can be seen in Figure 2. According to the method from ISO 1996-2 the expanded uncertainty for this measurement was 4.82 dB, using a coverage probability of 95%.[24]

Further measurements were taken on several locations inside the courtyard area as shown in Figure 3. The locations were chosen in such a way that they would represent points for which direct or reflected sound would play the most important role. At these points it was also possible to make sure to stay clear of certain objects that could locally influence the sound levels or reflections, like trees, cars or people present in the area. During the measurements inside the courtyard the average sound pressure level was also measured at the reference point. For each point the equivalent A-weighed sound pressure level was measured during a period of 10 min. For the measurements inside the courtyard the Nor140 sound meter was used, while the Brüel & Kjær was used at the reference point. The measurements on the two positions were recorded and processed in such a way that the gathered data has a resolution of 1 min, in such a way that there are 10 points of data per measured position. For the measured points inside of the courtyard the calculated expanded uncertainty (coverage probability of 95%) was from 4.71 to 5.08 dB.[23]

During the measurements there were also noise sources inside the courtyard area. These noise sources also influenced the measured values and thus also the difference between the sound pressure levels at the reference point and the point inside the courtyard. Because the road remained a constant and the main noise source during the conducted measurements the median of the measured data/min was evaluated instead of the average during the 10 min measurement period. This way the extreme

Figure 2. Measurement setup for the first measurement at the reference point.

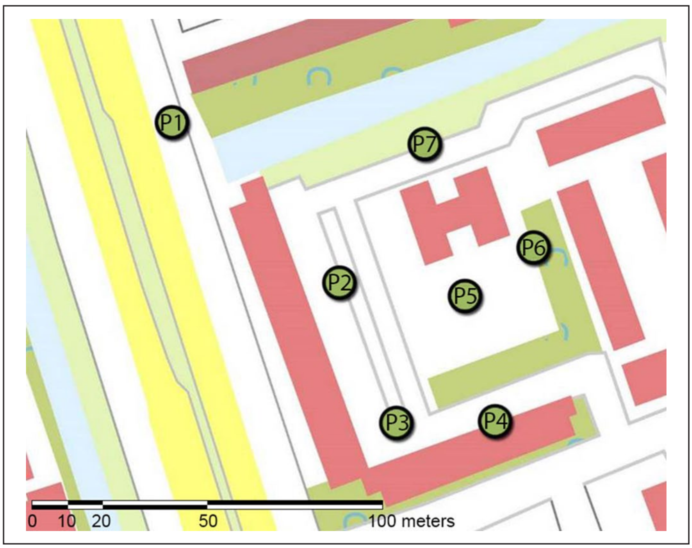

Figure 3. The measured points inside of the courtyard area and the reference point directly besides the road (A). The underlying map is from TU Delft.[25]

values, which are mostly produced by the (other) noise sources inside the courtyard area, are excluded in the final averaged sound level. Because of other effects, like the mentioned wind, this of course didn't give a perfect result, but it clearly improved the measured data, comparing them to the expected sound levels based on the perceived levels during the measurements.

Computer simulations of the case study

To simulate the influence of the sound reflective façade a computer model was made using the software package CATT Acoustics, version 9.0b, a widely used acoustic ray tracing programs. The

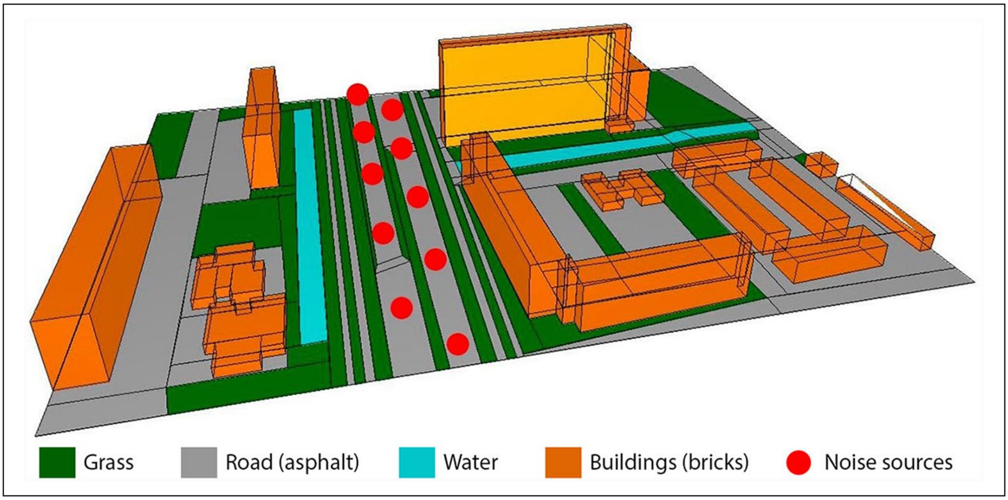

Figure 4. The used CATT Acoustics model, the red dots indicate the position of the noise sources.

Table 2. The applied absorption coefficients.

Material	Sound absorption coefficient (α) per octave band					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Standard façade: bricks[a]	0.03	0.03	0.03	0.04	0.05	0.07
Grass[b,c]	0.11	0.17	0.25	0.37	0.51	0.66
Road: standard aphalt[a]	0.02	0.03	0.03	0.03	0.03	0.02

[a]Truesdale.[27]
[b]Odeon.[28]
[c]Reethof et al.[29]

used model was not an exact rendition of the actual environment. Several simplifications were introduced in the model for various reasons. Specific elements like trees, (smaller) elements on the façades and balconies were not included. This approach of simplifying the model corresponds to many building codes in which single trees and (smaller) elements like balconies are mostly ignored or greatly simplified while this doesn't greatly affect the reliability and usability of the results.[26] Another reason for the simplifications is the need for introducing tools which can be used during the architectural design process to investigate the acoustical impact of the design. During a design process it's often undesirable to use time consuming tools which need a lot of time and data before they can be used. Designers want to be able to quickly try various design options. The simplified model can be seen in Figure 4. The applied absorption coefficients are listed in Table 2. For all materials the default scattering coefficient from CATT Acoustics were used: 0.10 for every octave band. Furthermore, water was modeled as an acoustically hard surface, using the default values for a reflective material in CATT Acoustics.

For the edges of all the objects an option in CATT Acoustics was enabled to add an extra correction for scattering by edges, other effects like diffraction could not be taken into account in this version of the software. Air absorption was enabled for the model, using the standard CATT values for simplicity, being 20°C and 50% humidity. Using these standard values instead of the actual

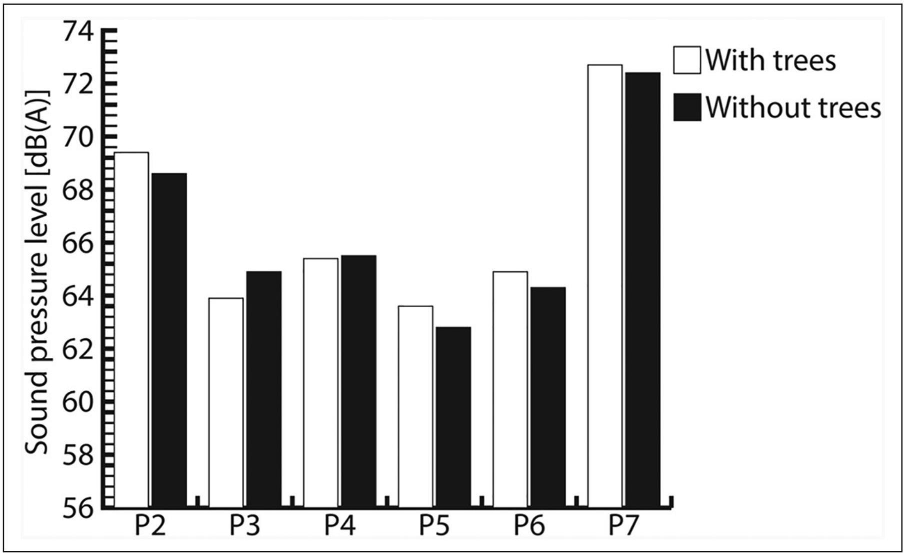

Figure 5. The difference between the simulated $L_{A;eq}$ values with and without trees.

on-site values (see before) introduced an extra margin of error. However, this margin is rather small because the investigation focused on relatively small distances, within a range of 200 m. The amount of used rays was automatically selected by CATT Acoustics based on the complexity and size of the model. The maximum length of the simulated time was set to 3000 ms, giving the rays enough time to travel approximately 1000 m, significantly more than the relevant part of the model. As for the algorithm, the “Map measures” function in CATT Acoustics was used, calculating the sound pressure levels for predefined “audience planes.”

Because CATT Acoustics cannot simulate a linear noise source several point sources were used. On both sides of the road five of those sources were positioned. The space between them is equal to the space that should be present between two cars driving at the maximum allowed speed of 50 km/h: around 45 m. The sources were assumed to be identical and their sound power and spectrum were calibrated based on the field measurements at reference point P1, as indicated in Figure 3.

As measuring positions in the acoustical model the “audience planes” were used. Using these planes the sound pressure levels in a certain area can be predicted. The height of the used planes was set at 2 m. At this height the grid for the measurement plane was generated. This height was 0.5 m higher than the height used during the on-site measurement (approximate 1.5 m) because of the way the simulation was set-up. The chosen size for the used grid was 4 m, so each measured point was placed 4 m apart from its neighboring points. Additional simulations were also conducted at a plane height of 4 m.

To analyze the error of not taking trees into account, a few simulations including trees were conducted. The trees were modeled using an absorption coefficient based on a study from Reethof et al.[29] and were greatly simplified. Only two parts were used in the model: one for the trunk and one for the leaves. To take the scattering caused by the bark and the leaves into account a scattering coefficient of 80% was used. The reason the leaves were also included in the model is that they were present during the on-site measurements, as can be seen in Figure 2. In Figure 5 the comparison between a model with and without trees can be seen. The shown values are taken from six fixed points on the used measurement grid. This figure shows that the difference between both models

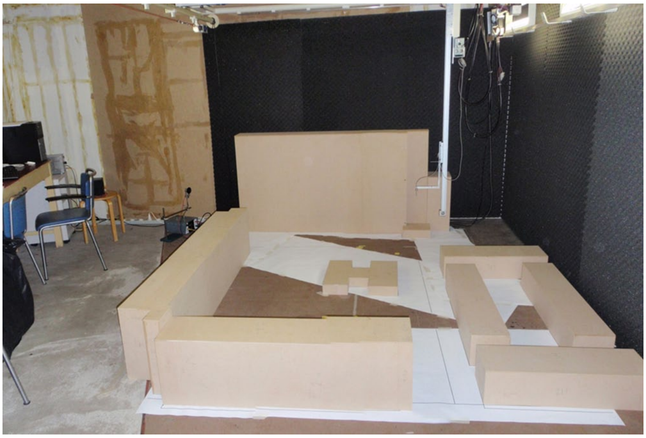

Figure 6. Overview of the semi-anechoic room with the used scale model.

was at most 1 dB(A). However, when taking all the points inside the courtyard into account it can be seen that the trees can have a big effect on certain points. Locations close to a tree can be up to 5 dB louder or down to 3 dB quieter. This is caused by the sound scattering and sound reflecting effects of the three. The amount of points affected by this is relatively small. Furthermore those points are not taken into account during the following analyses because none of the on-site measurements were conducted directly next to a tree. It was therefore decided to exclude trees. This also helped to reduce the needed computing time.

The sound power levels of the sources in the model were derived from the actual measurements that were taken at the reference point (P1) close to the street.

Scale model measurements of the case study

For the conducted scale model measurements a simplified 1:50 scale model of the investigated area was made out of MDF wood. This scale was chosen so that the model would fit in the small semi-anechoic room while the desired frequency ranges could still be measured. The used semi-anechoic room was located at the faculty of Applied Sciences at the TU Delft (Figure 6).

The following equipment was used: a 1/4″ microphone, type 4136 592785 from Brüel & Kjær (Figure 7), two amplifiers for the microphone ARIZ77 No. 81.690267 and Brüel & Kjær type 2804, a Dell OptiPlex 790 computer with Matlab version R2011b, a noise source from Tymphany, type XT25SC90-04 (Figure 8), an amplifier for the noise source, mono 60W type E60, and a rail system for both the microphone and the noise source (Figure 9). With the used equipment the frequency range which could be properly measured was 12.5–31.5 kHz. Taking into account the scale factor of the model of 1:50 this equals to 25–630 Hz. While traffic noise mostly consists of a wider spectrum, with its *A*-weighed peak between 800 and 2000 Hz octave bands, the (*A*-weighed) sound levels at the location were to great extent caused by engine (constant acceleration) noises, which are more dominant in the lower frequencies below 800 Hz.[30] This was also seen in the on-site measurements which did show a wider range of dominating frequencies than just 800–2000 Hz. Using this information the lower frequencies could be used to obtain a good estimation of the cumulative sounds levels.

The noise source was placed on a rail on which it could be moved by steps of 5 cm. With this rail the source could be easily moved between the four fixed source points (Figure 10). The positions were chosen similar to the ones used in the computer simulations, adapted to the available

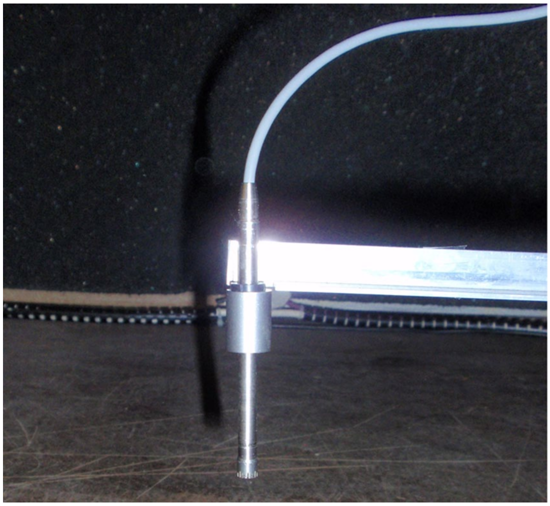

Figure 7. The used microphone.

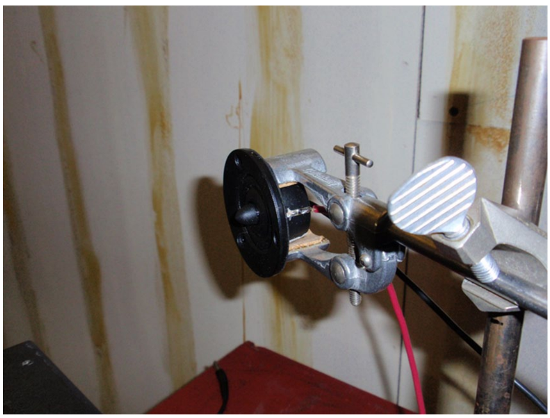

Figure 8. The used noise source.

space in the measurement room. For the positions it was also taken into account that they would give a good prediction of both closer, more direct, sources as well as sources further away, of which the reflections would be more important. Because the used source was not omnidirectional, it was rotated toward the entrance of the courtyard for each measurement position. Using this system the center of the source was placed 8 cm above the ground. The source couldn't be placed closer to the ground due to restrictions in the semi-anechoic measurement room and the positioning system of the microphone. On the used scale level this would be equal to 4 m above the ground level. This height is significantly higher than the height of the source in the actual situation and in the computer simulations, because the most predominant sound sources of a car, the engine and the wheels, are in reality quite close to the ground.

For all the measurement points inside the courtyard area (Figure 10) the sound pressure levels measured using the different source positions were (energetically) added together to determine the

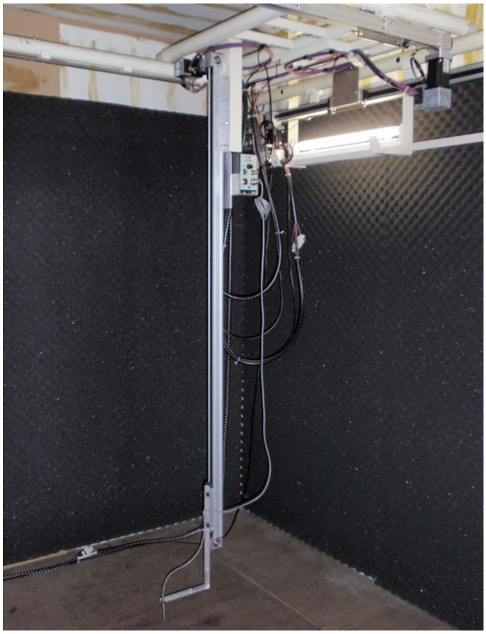

Figure 9. The rail/movement system.

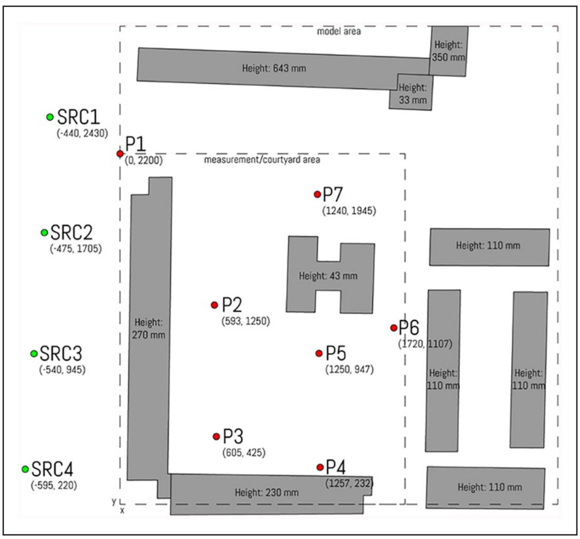

Figure 10. Scale model measurement setup with the source points (SRC) and the receiver points (P).

total sound level. While only the frequencies up to 630 Hz were measured during the scale model tests, the summed *A*-weighed sound levels were also calculated. Since the output signal of the used noise source could not be changed only the difference in the sound levels between the reference point and the points inside the courtyard were taken into account.

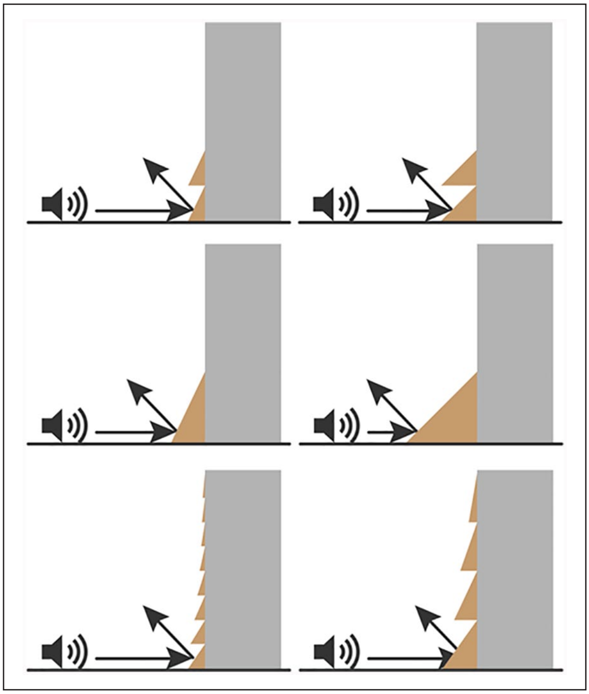

Figure 11. Sections of preliminary designs reflecting the sound upwards.

Redesign of the façade systems

The previously discussed prediction methods and models have been used to investigate the impact of changing a façade on the sound pressure levels in a nearby area. The façade of the 18-storey high-rise building, which is positioned perpendicular to the road, was changed in the models. This façade is highlighted in a lighter shade in Figure 4. The sound pressure levels inside the courtyard area are used to determine how much the sound pressure levels increase or decrease as a result of changes to this façade. Using the discussed methods, various façade adaptions were investigated like adding absorbing elements, adding scattering elements, adding elements which reflect the sound back to the road or adding elements which reflect the sound toward the sky. In Figures 11 through 14 several preliminary façade designs are shown in a simplified way. All of them could potentially decrease the sound levels in the investigated area, but some of them could not be implemented in a practical design. So during the preliminary design phase not only the potential improvement of the sound levels was taken into account, but also the feasibility.

After judging various preliminary designs and both potential improvements of the sound levels and technical feasibility, three façade designs were chosen for further investigation: the first design absorbs sound as much as possible, the second design focuses the sound upward and the third design combines both the upward reflection and the absorption of sound. In Figures 15 through 17 an schematic overview of these designs can be seen. The lowest two floors in all of the designs consist of storage spaces without many windows and are therefore cladded with a sound absorbing material in all of the designs. The higher floors contain apartments which have access to a gallery (right side) and a balcony on the side of the investigated courtyard area (left side). On the side of the balcony the façade was adapted so it absorbs or reflects sound waves.

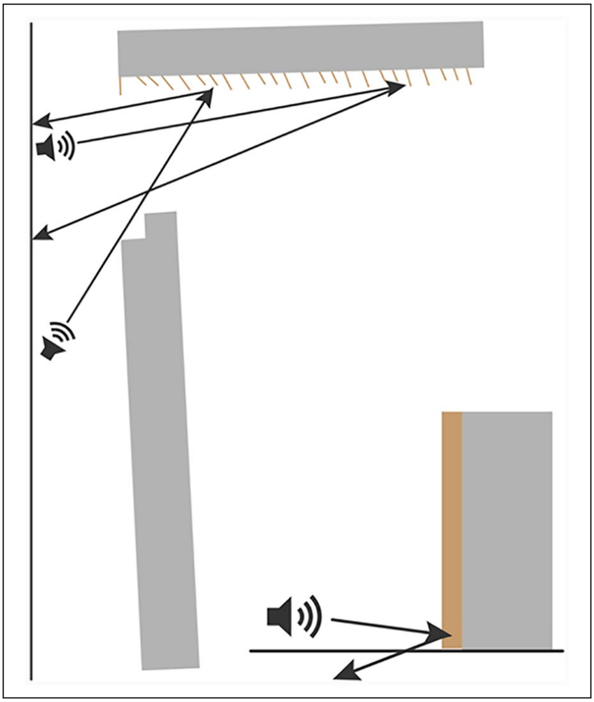

Figure 12. Topdown view and section of a preliminary design reflecting the sound back to the road.

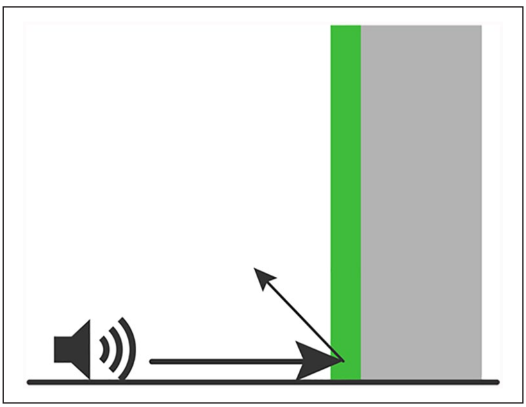

Figure 13. Preliminary design direction focusing on absorbing the sound.

The sound absorbing façade cladding at the two lowest floors is a cladding made out of porous sound absorbing tiles, for this an existing product was selected as a reference. This is a stone-like material made from recycled glass. The material is weatherproof and self-bearing, making it suitable for outdoor use. The NRC value is 0.75 for a 50 mm panel and 0.90 when adding a 25 mm cavity behind it, the values per octave band are shown in Table 3.[31] The version with the 25 mm cavity was selected for the design because of the higher absorption coefficient. This same material was used underneath the balconies in the sound absorbing and the combined designs.

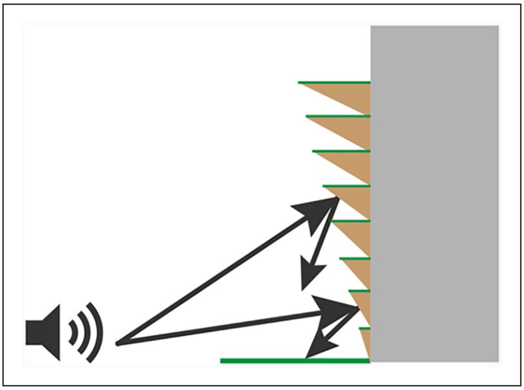

Figure 14. Section of a preliminary design reflecting the sound downwards, to an absorbing plane.

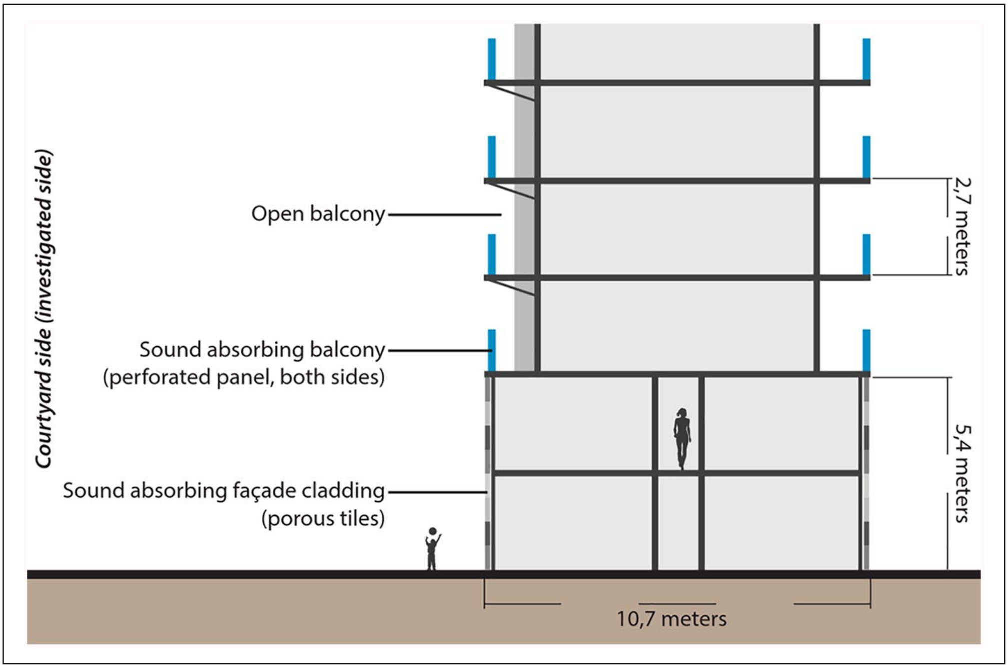

Figure 15. Sound absorbing design: the balcony parapet and façade of the lowest two floors are sound absorbing.

In both the sound absorbing and the combined designs a perforated sound absorbing panel was used as a parapet in front of the balconies. For this element, again an existing product was selected as a reference. This panel consists of perforated metal plating with absorbing material inside it. The NRC value of this product is 0.90, the values per octave band are shown in Table 3.[32]

The sound reflecting design focuses on reflecting the sound toward the sky, where it should have a lower impact on the perceived sound pressure levels in the investigated area and nearby houses. To reflect the sound waves upward acoustically hard materials were used, mostly glass and

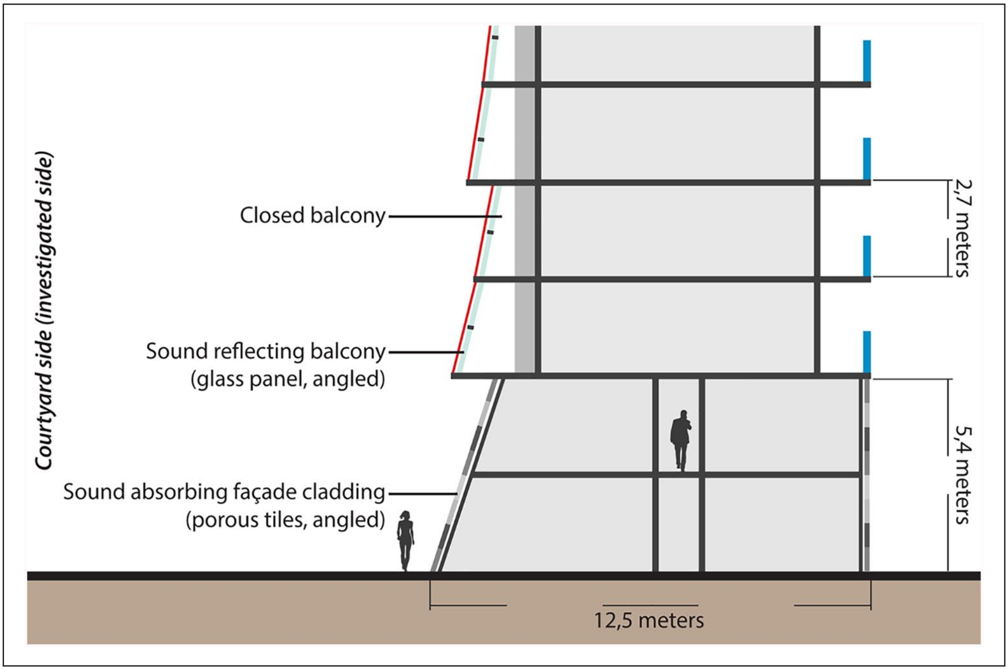

Figure 16. Sound reflecting design: the lowest eight floors are reflecting sound upward using closed balconies.

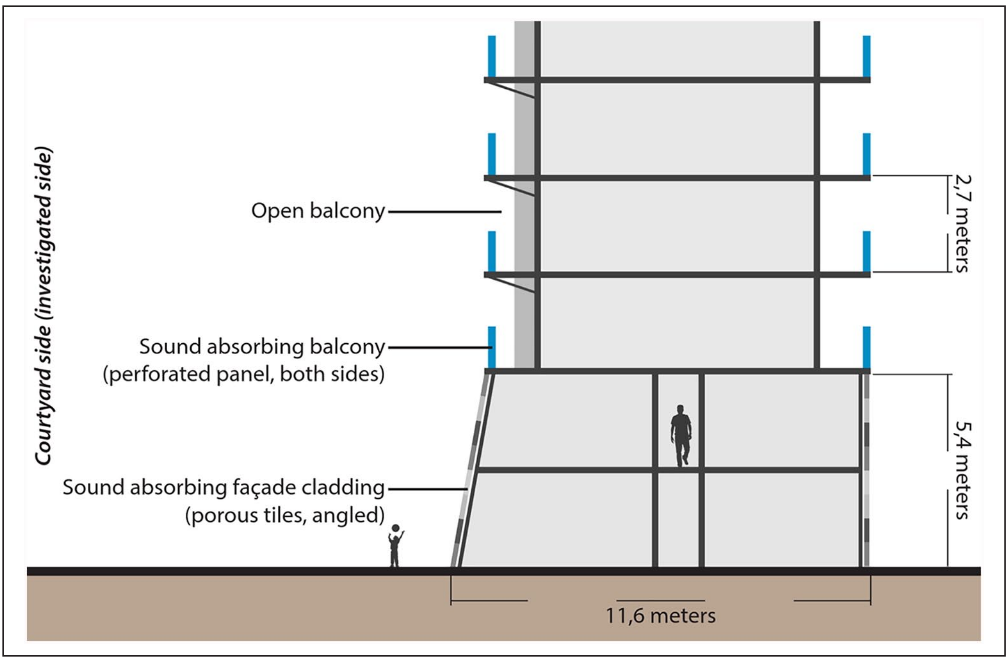

Figure 17. Combined design: the lowest two floors are reflecting and the other floors are absorbing sound.

Table 3. The applied absorption coefficients for the absorbing materials.

Material	Sound absorption coefficient (α) per octave band					
	125 Hz	250 Hz	500 Hz	1000 Hz	2000 Hz	4000 Hz
Porous tiles, 50 mm, no cavity[a]	0.10	0.35	0.85	0.95	0.85	0.85
Porous tiles, with 25 mm cavity[a]	0.20	0.60	1.00	0.90	1.00	1.00
Perforated absorbing panel[b]	0.22	0.77	1.12	1.00	0.78	0.57

[a]Quietstone UK Ltd.[31]
[b]Kinetics Noise Control Inc.[32]

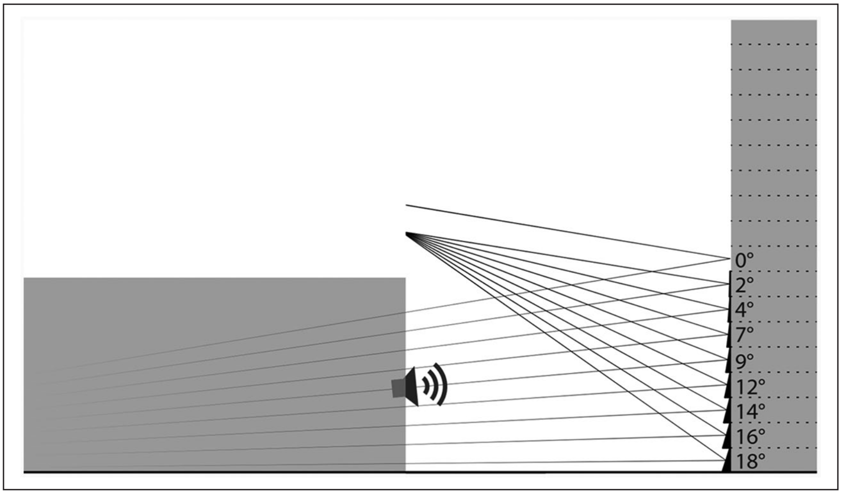

Figure 18. Manual ray trace (in a 2D/vertical plane) to define the "optimal" angles of reflection.

metal so that the inhabitants can still look outside. An exception for this can be found at the two lowest floors because those floors only contain storage spaces. The previously described sound absorbing tiles are applied on these façades for some extra sound reduction at the street level. For the lowest two floors of the combined design the same sound reflecting approach was used. To determine the angle which the façade should have to reflect the sound upward, a very simplified manual ray trace approach was chosen. The source was positioned on a distant point on the nearby road and an angle was chosen in such a way that the sound waves would always be reflected over the nearby building, as can be seen in Figure 18. While this simplification is partly incorrect because it does not take scattering, diffraction, and other similar, wave-based, behavior of sound waves into account and because the source is not a fixed position in reality, it was still used as a starting point for this design.

Computer simulations of the redesign

The impact of the three different façade designs on the sounds levels inside the investigated courtyard area was investigated using the same computer model and software as discussed before. Changes were made to the model of the existing situation to include the proposed façade systems, including the mentioned absorbing materials. In Table 3 a sound absorption coefficient of >1.00

can be seen the third material. This is based on the information from the supplier and can be explained by the used standardized measurement method. It is known that this method can give theoretical values which exceed one.[33] Since an absorption coefficient of 1.00 or more couldn't be used in the simulations using CATT Acoustics, these values were instead set at the maximum value of 0.99.

Scale model measurements of the redesign

Scale model set-up A. Besides using the computer simulations to investigate the impact of the proposed façade designs on the sound levels inside the courtyard area, a scale model was also used. The same scale model setup as discussed before was used. To determine the changes to the sound pressure levels inside the courtyard area, the measured sound pressure levels are compared to the sound pressure levels which were found in the situation without changes to the façade. For the sound absorbing materials a fleece plaid was used during the initial scale model measurements. It turned out that using this material did not produce the expected results. Within the scope and available time of the research it was not possible to further investigate and solve this problem. Therefore the scale model measurements were conducted without using sound absorbing materials.

Scale model set-up B. An important factor which should be taken into account when reflecting the sound waves upwards is that they can bend down again over nearby buildings (diffraction). To investigate the effects of diffraction for the different façade designs a second setup was used during the scale model measurements. This setup consisted of the building with the adapted façade and a second, lower building, placed in front of it. The noise source was placed in between both of the buildings and the sound levels were measured behind the second, lower, building. Using this measurement setup four different situations were measured. Two building volumes with different heights were used, which were both placed at two different positions. The setups can be seen in Figures 19 and 20. The results from these measurements were used as an indication of the diffraction effect. The measured sound levels for the different designs are compared with the measured sound levels without any changes to the façade.

Part I: Comparison of two urban acoustics research methods

Results

In Figure 21 the comparison between the computer simulations, scale model measurements, and the on-site measurements is shown. The values in this graph are based on the difference between the equivalent sound levels ($L_{A;eq}$) at the reference point and the points inside the courtyard. The absolute sound levels weren't used because the sound pressure level produced by the source used during the scale model measurements wasn't set to the same level as the actual on-site noise source, the cars on the nearby road.

The bar chart shows that the simulated differences in sound pressure levels are close to the on-site measured differences; the biggest difference that is 2.9 dB(A) while most differences are <2 dB(A). For the scale model measurements the biggest difference was 6.5 dB(A) while the difference is <2 dB(A) for only two measurement positions.

In Figures 22 through 24 the computer simulations and the scale model measurements were compared for the octave bands of 125, 250, and 500 Hz. These values were not available for the on-site measurements because only the average A-weighed sound pressure level differences were measured. In the graph it can be seen that the differences in sound pressure levels found using the

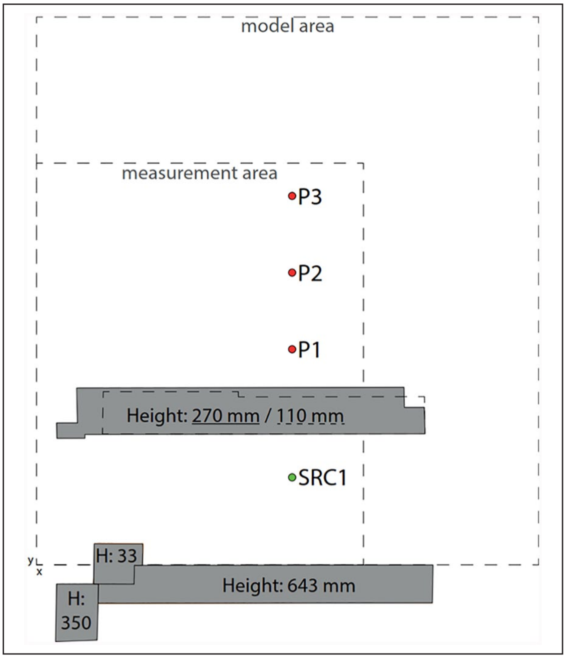

Figure 19. First scale model setup for the diffraction measurements, two different building volumes are used: building A is drawn with a continues line, building B is drawn with a dashed line (used scale factor: 1:50).

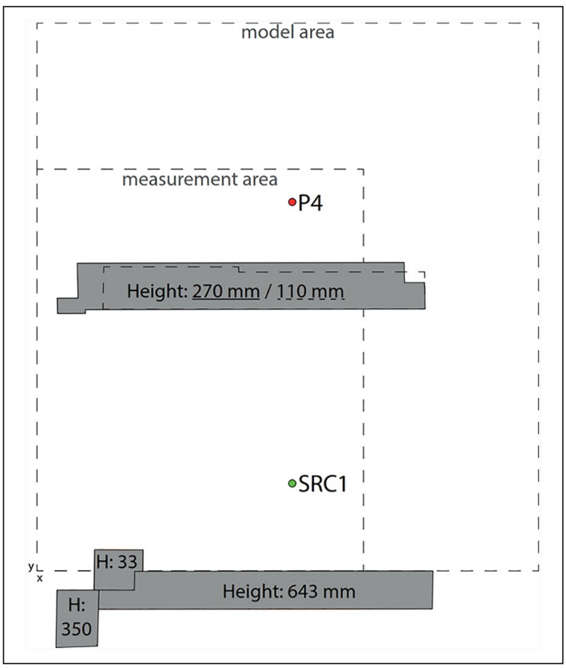

Figure 20. Second scale model setup for the diffraction measurements. Compared to the first setup this setup uses a doubled distance between both of the buildings: 1430 mm instead of 715 mm (used scale factor: 1:50).

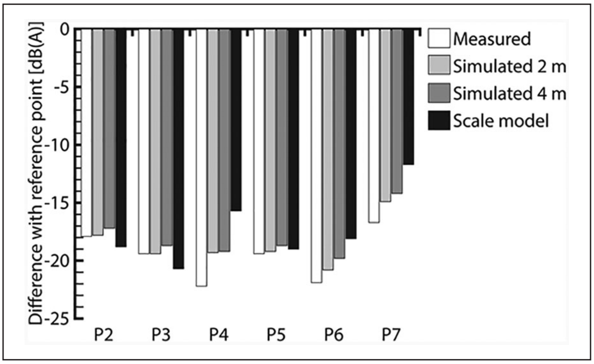

Figure 21. The differences between the reference point and the points inside the courtyard area.

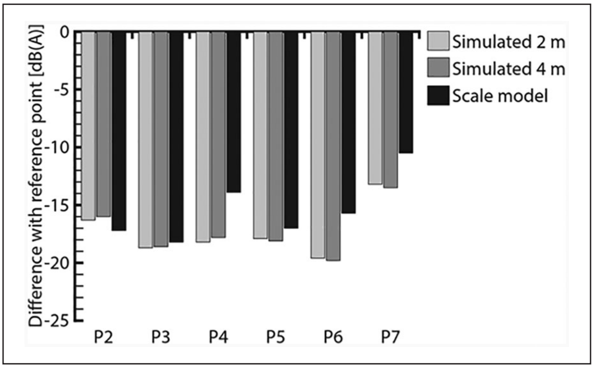

Figure 22. The differences between the reference point and the points in the courtyard area, only for the 125 Hz octave band.

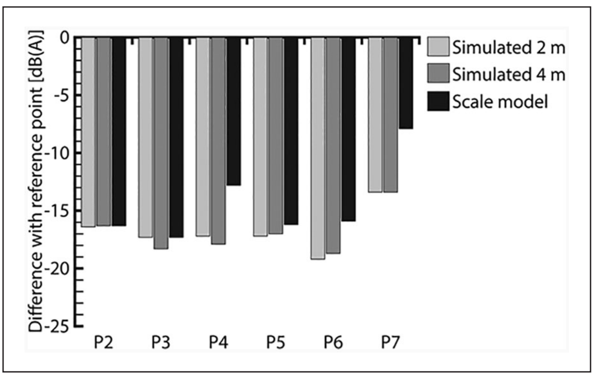

Figure 23. The differences between the reference point and the points in the courtyard area, only for the 250 Hz octave band.

scale model were higher instead of lower for the 500 Hz band than the values found using the computer simulations. The values for 125 and 250 Hz were comparable with the differences found when looking at the A-weighed levels.

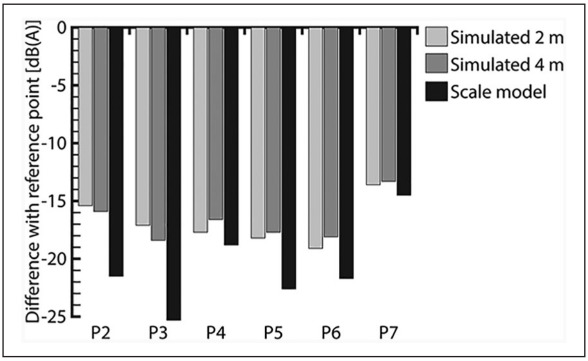

Figure 24. The differences between the reference point and the points in the courtyard area, only for the 500 Hz octave band.

Discussion

From the results it can be seen that the differences in sound pressure levels found using the on-site measurements, computer simulations, and scale model measurements are not similar for every measurement point. For certain locations the found differences between the three methods were >2 dB. This level of 2 dB was chosen as acceptable difference because it can occur when using certain simplifications in (scale) models according to Nijs[6] (p. 55). It also equals twice the just noticeable difference for sound pressure level (1 dB for the measurement point and 1 dB for the reference point). The differences are most likely caused by the used simplifications and certain aspects that could not be taken into account, from which several are also shown in Table 1.

When looking at the results from the computer simulations these differences (compared to the on-site measurements) can possibly be explained by not taking the trees, balconies, and the moving of the sources into account. The used parameters for the different materials might play an important role as well. Because most of the materials in this urban environment were acoustically hard, especially scattering, diffraction, and effects caused by the soil (ground effects) can be important in the actual situation. These effects could not be taken into account in the used computer model since a ray tracing method was used or precise values were unknown (as for scattering coefficients). Furthermore, weather effects like wind and diffraction of sound waves around the buildings were not included in the simulation model.

For the scale model measurements the properties of the materials were not included. The reason for this was that a more detailed study would be needed to determine the correct sound absorbing materials to apply at the used scale. This applies to materials on the façade and the ground. Furthermore, in the scale model measurements neither trees, balconies, the moving of sources, or weather effects were included. Diffraction was included in the scale model because actual sound waves were used.

From the results it can also be seen that the simulated sound pressure levels, levels measured using the scale model and the sound pressure levels which were measured on-site differ the most at points 3, 5, and 6 (P4, P6, and P7). This could imply that the scale model measurements and the computer simulations were both influenced by similar factors. This difference might be caused by the fact that the used stationary noise sources didn't produce an accurate (enough) approximation of the actual source of moving cars, for which a different approach per frequency even might be needed (depending on the speed). The fact that especially the measurement positions that have a (more) direct line of sight toward the road are affected by this seems to support this explanation. However, the scale model and the simulations used a different setup for the sources, one directional and the other omnidirectional, which could already cause differences in the results in the first place. Besides this, it has to be noted that in the scale model the height of the small building in the courtyard is lower than the height at which the microphone is measuring. With the used scale model measurement setup it was not possible to add more noise sources over a longer distance to compensate for this effect. This is caused by the available space in the semi-anechoic room where the measurements were carried out.

Another possible explanation for the differences can be given when looking at the height of the microphone position. During the actual measurements this height was about 1.5 m while the computer simulations use 2.0 and 4.0 m. For the scale model measurements the used height was only 4.0 m. This increased height means that the values measured in the scale model are influenced less by the various ground effects. To investigate the possible impact of this effect the simulations with a height of 4.0 m can be compared to the scale model measurements. It can be seen that they are only slightly lower than the levels which are found at 2.0 m height. This would indeed indicate that the height influenced the measured levels, but based on the simulations this would only explain a very small part of the differences. It is however possible that the effects potentially causing this difference are having a bigger impact for the scale model measurements because diffraction of sound over the buildings might play a role. The used height at which the measurements are conducted should be harmonized in future research.

The results in Figures 22 through 24 give a fairer comparison between the various methods, showing the 125, 250, and 500 Hz octave bands. The reason for this is because of the fact that the average A-weighed values for the scale model measurements are determined by only using the frequencies up to 630 Hz (due to the fact that frequencies are scaled and the equipment could only measure accurately up till 31.5 kHz). For the computer simulations and the actual measurements this average has been determined using the frequencies up to 16,000 Hz. For the 125 and 250 Hz octave bands it can be seen that the differences between the models are comparable to the differences found for the equivalent sound levels. When comparing the results from the 500 Hz octave band it can be seen that the found differences using the scale model were bigger. The difference might be partly explained by certain diffraction effects, caused by the fact that the points are mostly shielded from direct sound and the computer simulations (ray tracing) only give a simplified approach for diffraction.

Furthermore, the on-site measurements were also influenced by several unpredictable variables like the wind and local or fluctuating noise sources. Without a more detailed investigation the impact of these variables on the sound levels inside the investigated location cannot be determined.

Finally, some of the differences in the scale model measurements could also be caused by variations in the temperature and humidity in the measurement room. These variations are caused by the fact that there was no climate control available in the room and that there always had to be a person inside the room to conduct measurements. Because measurements in a scale model are conducted using high frequencies, fluctuations in the air absorption can play an important role.

Part II: Exploration of the impact of façade designs

Results

In Figure 25 the sound reduction inside the investigated courtyard area caused by the various façade adaptions can be seen. These results are produced by the computer simulations. The results

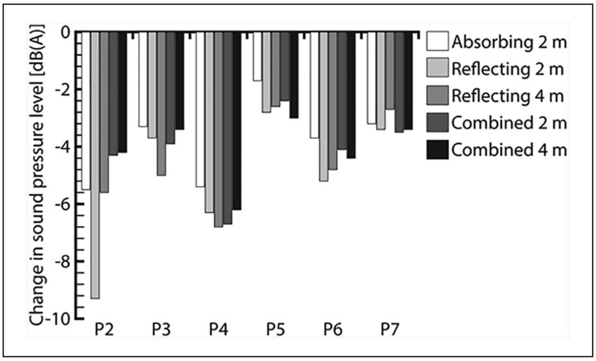

Figure 25. Simulated improvements inside the courtyard area from the different façade designs measured at an height of 2 and 4 m using the computer simulation.

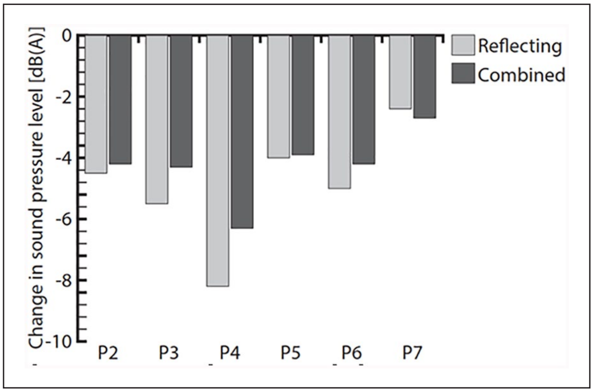

Figure 26. Measured improvements inside the courtyard area from the different façade designs using the scale model.

shown in Figure 26 are the ones which were found using the scale model measurements. Detailed results can be seen in Figures 27 through 29. The results found during the "diffraction measurements" are shown in Figure 29. All the results are shown as values compared to the situation of the original unaltered the façade. A negative value means a decreased sound pressure level while a positive value means an increased sound pressure level. As mentioned before, the scale model measurements did not include sound absorbing materials. This was done because it was not possible within the scope and time constraints of the research to determine the correct absorbing materials which should be used in the model. Sound absorbing materials were only included in the computer simulations, in which the actual known absorption coefficients of the selected materials could be used.

From the results it can be seen that the sound absorbing design would reduce the sound pressure levels inside the courtyard area with 1.7–5.5 dB(A) according to the computer simulations. Since no absorbing materials were used in the scale model measurements this design wasn't included in the setup used to investigate the effect of diffraction.

The improvement of the sound pressure levels inside of the courtyard area found for the sound reflecting design varies from 2.7 to 9.3 dB(A) according to the computer simulations and from 2.4 to 8.1 dB(A) according to the scale model measurements (without absorption). During the diffraction

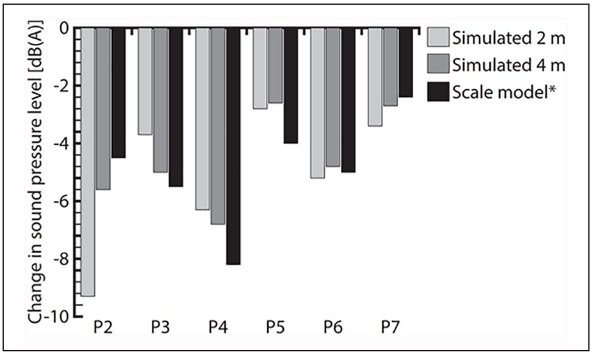

Figure 27. Detailed results from the sound reflecting design. Results marked with an asterisk don't take the sound absorbing materials into account.

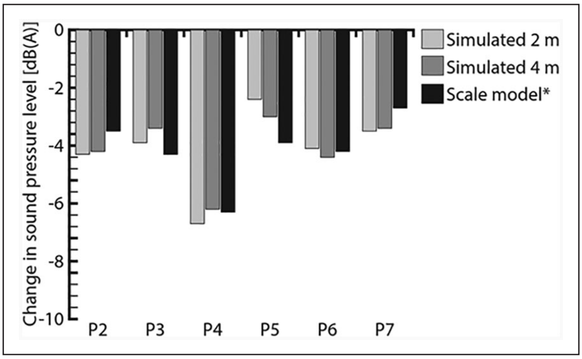

Figure 28. Detailed results from the combined façade design. Results marked with an asterisk don't take the sound absorbing materials into account.

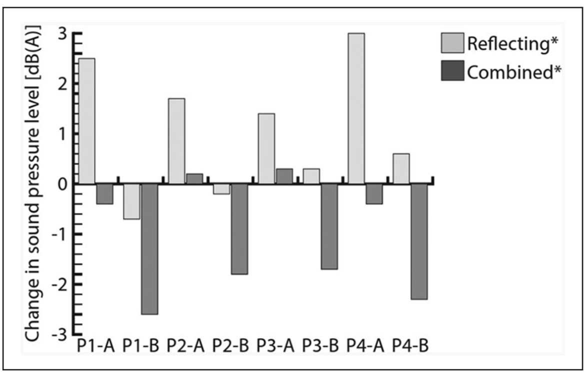

Figure 29. Detailed results from the diffraction measurements, for both building A and B. The results don't take the sound absorbing materials into account.

measurements the biggest decrease of the measured sound pressure levels was 0.7 dB(A). However, at most positions from the diffraction measurements an increase in the sound levels was found. The highest measured sound level was 3.0 dB(A) higher than the measured reference values.

Finally, the sound pressure levels inside of the courtyard area measured for the combined design improved from 2.4 to 6.7 dB(A) according to the simulations and 2.7–6.3 dB(A) according to the measurements (without absorption). The values measured during the diffraction measurements mostly showed reduced values compared to the situation without changes to the façade. The found reduction was up to 2.6 dB(A). At two measurement positions a small increase of the sound levels, up to 0.3 dB(A), was found.

Discussion

Comparing the results it can be seen that there are quite some differences between the used prediction methods. This can partly be explained by the fact that the computer simulation did take the material properties into account and that the scale model measurement mostly did not. Furthermore, the façade adaptions used in the scale model measurements were crafted by hand, while the façade adaptions for the computer simulation were all placed straight and without imperfections. Finally the previous discussed differences between the two prediction methods also apply here.

From the results it can be seen that especially the sound reflecting design reduces the sound pressure levels inside the courtyard area: up to 9.3 dB(A) at the measured points. However, a problem of this façade adaption is that it potentially increases the sound pressure levels elsewhere because sound waves are being diffracted over nearby buildings and may bend due to wind. When using the combined design this effect is reduced since the sound waves are only reflected at the lowest floors and are being absorbed as well. In the investigated courtyard this façade reduced the sound levels at the measured points up to 6.7 dB(A). Reductions like these can greatly improve the perceived sound pressure levels and make certain areas more comfortable for people to be in.

At the investigated location it was preferred to reduce the risk of increasing the sound pressure levels elsewhere. The reason for this was that some of the nearby areas were quieter and are not being influenced by direct noise from the nearby road. In a situation like this the diffracting sound will have a bigger impact than at noisier locations. Therefore the preferred façade design would be the one combining sound absorption and sound reflection. At other locations it might be preferable to use only absorption or reflection depending on the desired and acceptable sound levels in de nearby areas.

Conclusion

The first goal of this paper was to discuss the differences between two prediction methods and the actual sound pressure levels on a certain site. From the results it can be concluded that the investigated prediction methods give an acceptable approach of the actual situation but not a perfect one. The biggest difference between the actual situation and the scale model measurements was found to be 6.5 dB. While this is a significant difference it only occurred locally and the results were useable to get a basic understanding of the sound pressure level differences inside of the investigated area.

To reduce the time to conduct the computer simulations and to build the scale models these models were simplified. From existing literature it was concluded that these simplifications could lead up to differences of at least 2 dB. However, since several simplifications were combined this expected difference was bigger in the investigated situation.

Besides the mentioned difference in the previous paragraph, the research shows that the simulated sound pressure levels did approach the actual sound pressure levels. Comparing the scale model measurements and the computer simulations, the computer simulations produced the results with the smallest difference between the simulated and the actual situation. However, since the applied ray tracing simulations only take some of the more detailed effects of sound into account, like diffraction (around edges) and weather effects, it cannot be concluded this is the most reliable method for urban acoustics modeling. Both the simplified computer simulations and simplified scale model measurements can be used to get a basic idea about the sound pressure levels in a certain area within a limited amount of time. When there is a need for more detailed results simplifications should be avoided as much as possible and more advanced urban noise prediction models like Nord2000 and Harmonoise or wave-based models, which include these effects, should be used. This will however increase the required time to build a more detailed prediction model.

Using the investigated prediction methods it is possible to investigate various façade adaptations which can be used to reduce the impact of sound reflections. At the investigated location the sound pressure levels inside the courtyard area can be reduced up to roughly 9 dB(A) when using a façade design which reflects sound waves upward. These reductions can greatly improve the perceived sound levels, making an area more pleasant for people to be in.

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