Technology Collaboration Programme
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Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

IEA HPT

Annex 51

Acoustic Signatures of Heat Pumps

Final Report – Part 11

5 Report on heat pump installation with special focus on acoustic impact

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Preface

This project was carried out within the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP), which is a Technology Collaboration Programme within the International Energy Agency, IEA.

The IEA

The IEA was established in 1974 within the framework of the Organization for Economic Cooperation and Development (OECD) to implement an International Energy Programme. A basic aim of the IEA is to foster cooperation among the IEA participating countries to increase energy security through energy conservation, development of alternative energy sources, new energy technology and research and development (R&D). This is achieved, in part, through a programme of energy technology and R&D collaboration, currently within the framework of nearly 40 Technology Collaboration Programmes.

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP)

The Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) forms the legal basis for the implementing agreement for a programme of research, development, demonstration, and promotion of heat pumping technologies. Signatories of the TCP are either governments or organizations designated by their respective governments to conduct programmes in the field of energy conservation.

Under the TCP, collaborative tasks, or “Annexes”, in the field of heat pumps are undertaken. These tasks are conducted on a cost-sharing and/or task-sharing basis by the participating countries. An Annex is in general coordinated by one country which acts as the Operating Agent (manager). Annexes have specific topics and work plans and operate for a specified period, usually several years. The objectives vary from information exchange to the development and implementation of technology. This report presents the results of one Annex.

The Programme is governed by an Executive Committee, which monitors existing projects and identifies new areas where collaborative effort may be beneficial.

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The HPT TCP is part of a network of autonomous collaborative partnerships focused on a wide range of energy technologies known as Technology Collaboration Programmes or TCPs. The TCPs are organized under the auspices of the International Energy Agency (IEA), but the TCPs are functionally and legally autonomous. Views, findings and publications of the HPT TCP do not necessarily represent the views or policies of the IEA Secretariat or its individual member countries.

The Heat Pump Centre

A central role within the HPT TCP is played by the Heat Pump Centre (HPC).

Consistent with the overall objective of the HPT TCP, the HPC seeks to accelerate the implementation of heat pump technologies and thereby optimize the use of energy resources for the benefit of the environment. This is achieved by offering a worldwide information service to support all those who can play a part in the implementation of heat pumping technology including researchers, engineers, manufacturers, installers, equipment users, and energy policy makers in utilities, government offices and other organizations. Activities of the HPC include the production of a Magazine with an additional newsletter 3 times per year, the HPT TCP webpage, the organization of workshops, an inquiry service and a promotion programme. The HPC also publishes selected results from other Annexes, and this publication is one result of this activity.

For further information about the Technology Collaboration Programme on Heat Pumping Technologies (HPT TCP) and for inquiries on heat pump issues in general contact the Heat Pump Centre at the following address:

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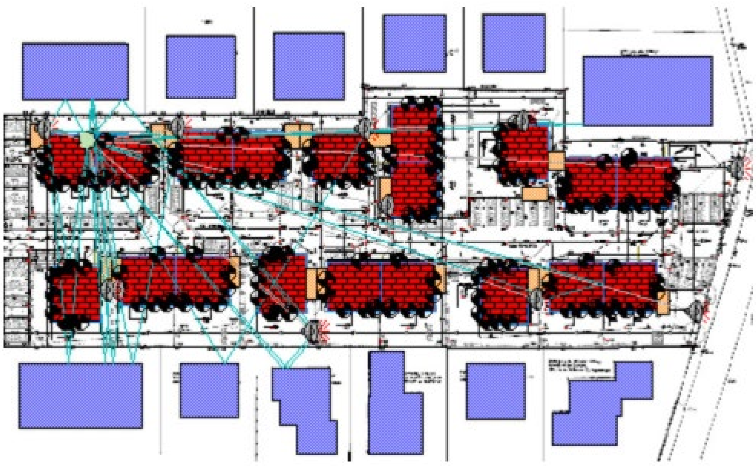
Acoustic Signatures of Heat Pumps

IEA HPT Annex 51

5: Report on heat pump installation with special focus on acoustic impact



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1 Executive Summary

Air-to-water heat pumps are also often chosen where space is limited or where there are obstacles in the building regulations. Compared to air-to-air heat pumps, water, which is more suitable for this purpose, is used for heat transfer. A permit is not required. The disadvantage of the air-to-water heat pump is its comparatively low efficiency and increased noise emissions. The latter are mainly caused by the motor of the air intake fan and by the compressor. The aim of this work thesis is therefore to select and place air-to-water heat pumps in such a way that the sound pressure level in the surrounding houses is kept low. In the following chapters, light will be shed on several topics surrounding the placement of heat pumps.

This report presents a selection of tools, which are used for calculating sound pressure levels. This includes simple formula based tools, which are often available online on websites of heat pump manufacturers or heat pump association. Examples shown include a Swiss, German and Austrian version. Two-dimensional visualization is based on the same formulas, but allows the user to see the sound pressure levels in a horizontal plane surrounding the freely placeable heat pump. All these tools neglect - apart from the corner- and wall-placement "penalties" - absorption, reflection or frequency dependencies in the calculation. The underlying formula is very ease and can be calculated by hand. To include the effects of directivity and frequency behaviour as well as absorption and reflection a much larger computational effort would have to be made. Some approaches, which try to shed light on these effects are visited next. Advanced sound propagation tools like CadnaA, SoundPlan, NoiseD3D, Mithra-SIG, IMMI, Olive Tree Lab Suite and OpenPSTD are listed. The full three-dimensional calculation of sound propagation is of course possible solving the acoustic wave equation using e.g. FEM and BEM.

Figure 1-1: Simple web based calculation tools

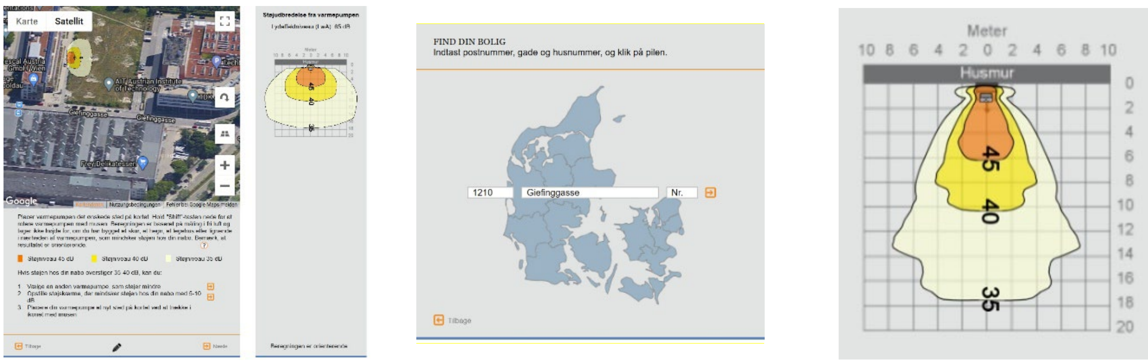


Figure 1-2: Two-dimensional visualization of sound pressure levels

The virtual placement of heat pumps using augmented reality is presented. This includes a description of acoustic measurements of noise sources, the aurealisation approach and the methods for calculation sound propagation. The app is realized by a modelling and mapping approach and hardware and software for visualization and acoustics are described.

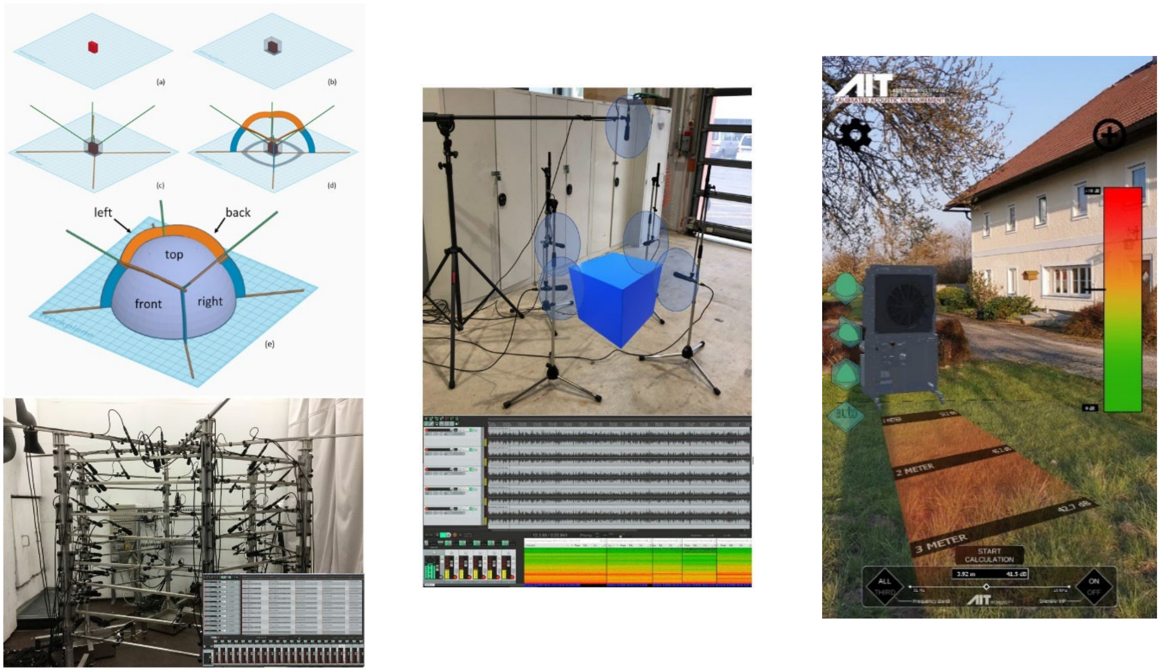


Figure 1-3: Augmented reality and acoustic app

The acoustic interaction of multiple heat pumps including reduction measures is analysed using primarily the tool IMMI. First, the terraced housing estate chosen for a exemplary study is presented including the description of heating load, hot water provision, heating demand and the analysis of the neighbouring sites. The maximum sound propagation is calculated using IMMI following ÖNORM ISO 9613-2:2008 and ÖNORM S 5021:2010. Several scenarios have been compared: One heat pump per household, one heat pump per house and a local heating supply scenario. In all cases heat pump selection and placement are outlined. Results are compared using a method introducing penalty points on all defined immission points (doors, windows, borders). For a promising case, calculations have been repeated introducing noise barriers into the calculation. Time of day dependent sound propagation have been visited to introduce user profiles of the different buildings. Alternative tools like OpenPSTD and Olive Tree Lab Suite and the involved options are described.

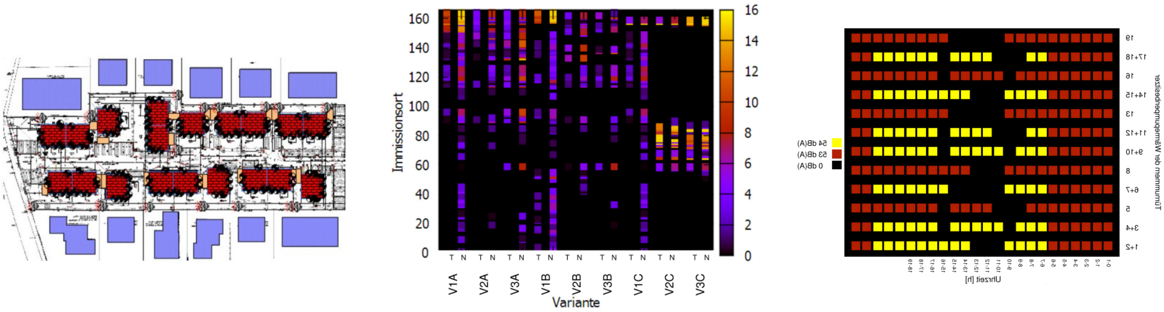


Figure 1-4: Sound field emission studies with multiple heat pump

The report additionally is working on the analysis of unit placement, indoor & outdoor sound propagation. This includes the description of different installation locations and linked sound pressure maps showing the propagation of noise in various scenarios. A table summarizing the sound pressure level, which can be expected depending on the heat pump position is given.

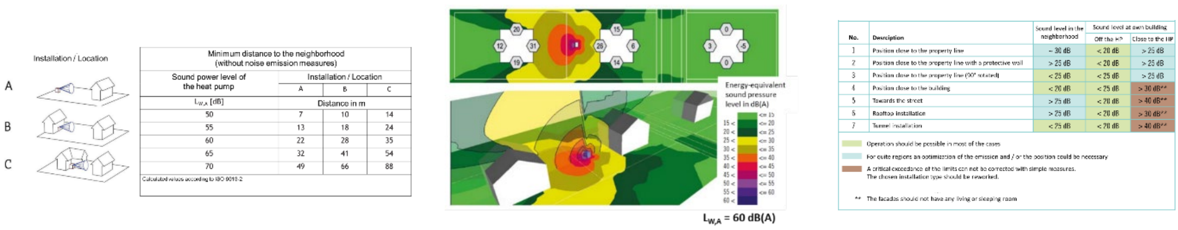


Figure 1-5: Analysis of unit placement, indoor & outdoor sound propagation

We outline the potential of sound absorption at nearby surfaces and tabulates the reduction effects of various measures taken. Finally common unclever decisions in heat pump placement are visited such as wrong locations, roof installation, the (unforeseen) development of the neighbouring properties, the selection of improper sound absorbing measures and finally the installation of further units in the neighbourhood.

2 Introduction

Heat pump heating systems are becoming increasingly popular due to their low operating costs, high security of supply and environmental friendliness. Depending on their design and primary heat source, a distinction is made between several types of heat pumps. Heat sources include deep ground, surface ground, water and air.

The **brine-to-water heat pump** with probe draws heat from the ground by drilling 50 - 100 m deep holes. The deeper the drilling, the higher the temperature. No other heat source provides higher temperatures than the ground used for geothermal probe-based brine-water heat pumps. However, not every plot of land is suitable for such drilling. In addition, a permit is required for construction. The brine-water heat pump with surface collector also draws heat from the ground. However, the collectors are laid at a depth of about 1.4 m and require an area that is about twice as large as the living space of the house to be heated.

Groundwater serves as the energy supplier of the **water-to-water heat pump**. Its advantages are that it does not have to be drilled as deep as required for a probe, that little floor space is required and that the groundwater has a higher temperature than the ambient air. However, the water quality must not deviate from the specified guide values, otherwise this will lead to defects in the heat pump. A permit is required for this type of heat pump.

An **air-to-air heat pump** requires little space, no earthworks and no well drilling and does not require a permit. However, air is less suitable as a heat transfer medium than water, as its heat capacity is comparatively low. The air-to-air heat pump is therefore only recommended for passive houses, as these have a low heating requirement.

Air-to-water heat pumps are also often chosen where space is limited or where there are obstacles in the building regulations. Compared to air-to-air heat pumps, water, which is more suitable for this purpose, is used for heat transfer. A permit is not required.

The disadvantage of the air-to-water heat pump is its comparatively low efficiency and **increased noise emissions**. The latter are mainly caused by the motor of the air intake fan and by the compressor. The aim of this work thesis is therefore **to select and place air-to-water heat pumps in such a way that the sound pressure level in the surrounding houses is kept low.** In the following chapters, light will be shed on several topics surrounding the placement of heat pumps.

Chapter 3 presents a selection of tools, which are used for calculating sound pressure levels. This includes simple formula based tools (section 3.1), which are often available online on websites of heat pump manufacturers or heat pump association. Examples shown include a Swiss, German and Austrian version. Two-dimensional visualization (section 3.2) is based on the same formulas, but allows the user to see the sound pressure levels in a horizontal plane surrounding the freely placeable heat pump. All these tools neglect - apart from the corner- and wall-placement “penalties” - absorption, reflection or frequency dependencies in the calculation. The underlying formula is very ease and can be calculated by hand. To include the effects of directivity and frequency behaviour as well as absorption and reflection a much larger computational effort would have to be made. Some approaches, which try to shed light on these effects are visited next. Advanced sound propagation tools like CadnaA, SoundPlan, NoiseD3D, Mithra-SIG, IMMI, Olive Tree Lab Suite and OpenPSTD are listed in section 3.3. The full three-dimensional calculation of sound propagation is of course possible solving the acoustic wave equation using e.g. FEM and BEM (section 3.4).

In Chapter 4, the virtual placement of heat pumps using augmented reality is presented. This includes a description of acoustic measurements of noise sources (section 4.2.1), the aurealisation approach (section 4.2.2) and the methods for calculation sound propagation (section 4.2.3). The app is realized by a modelling and mapping approach (section 4.3.1) and hardware and software for visualization and acoustics are described (section 4.3.2).

Chapter 5 is analysing the acoustic interaction of multiple heat pumps including reduction measures (section 5.1.3) using primarily the tool IMMI (section 5.1.1). First, the terraced housing estate chosen for a exemplary study is presented (section 5.2) including the description of heating load, hot water provision, heating demand (section 5.2.1) and the analysis of the neighbouring sites (section 5.2.2). The maximum sound propagation is calculated using IMMI (section 5.3) following ÖNORM ISO 9613-2:2018 and ÖNORM S 5021:2010. Several scenarios have been compared: One heat pump per household (section 5.3.3), one heat pump per house (section 5.3.4) and a local heating supply scenario (section 5.3.5). In all cases heat pump selection and placement are outlined. Results are compared (section 5.3.6) using a method introducing penalty points on all defined immission points (doors, windows, borders). For a promising case, calculations have been repeated introducing noise barriers into the calculation (section 5.4). Time of day dependent sound propagation have been visited to introduce user profiles of the different buildings (section 5.5). Alternative tools like OpenPSTD and Olive Tree Lab Suite and the involved options are described (section 5.6).

Chapter 6 is working on the analysis of unit placement, indoor & outdoor sound propagation. This includes the description of different installation locations and linked sound pressure maps showing the propagation of noise in various scenarios. A table summarizing the sound pressure level, which can be expected depending on the heat pump position is given.

Chapter 7 outlines the potential of sound absorption at nearby surfaces and tabulates the reduction effects of various measures taken.

Chapter 8 visits common unclever decisions in heat pump placement as wrong locations (section 8.1), roof installation (section 8.2), the (unforeseen) development of the neighbouring properties (section 8.3), the selection of improper sound absorbing measures (section 8.4) and finally the installation of further units in the neighbourhood (section 8.5).

3 Tools for calculating sound pressure levels

Clever placement of heat pumps is a very important step to exploit the low noise potential of state-of-the-art and next generation heat pumps to its full. This is not the final step, as a clever control strategy also brings possibilities to achieve a good compliance with neighbour expectations. But, placement IS important, and in some cases overlooked.

There are several tools around, which help in visualizing the acoustic impact of the placement of sound sources. Some of them are described here:

3.1 Simple calculation tools

Using simple mathematics, these tools allow for calculating sound pressure levels, if the sound power of the heat pump is known. As examples the Austrian, German and Swiss tools are referenced:

Figure 3-1: Main page of the Austrian "Schallrechner" [1]

In Austria, the current version of "Schallrechner" (see Figure 3-1) can be found using https://www.waermepumpe-austria.at/schallrechner hosted by "Wärmepumpe Austria". It is only available in German, but can be easily translated.

It is based only on the sound power level given by the manufacturer after choosing a heat pump out of a list (the value, however, can also be entered manually). The calculation of the sound pressure level in a user supplied distance is calculated out of this sound power adding increasing and decreasing "factors". In that way, multiple heat pumps, placement alongside walls or in

[1] Wärmepumpe Austria, https://www.waermepumpe-austria.at/schallrechner (October 20, 2020)

corners, manufacturer added measures or directional dependencies can be added. As a result, the sound pressure level at the point of the observer (which is in most cases the boundary of the garden or a window of the neighbour's house). This in brought into context with the allowed maximum sound pressure level at day or night. Apart from the corner- and wall-placement "penalties" no absorption, reflection or frequency dependencies are included in the calculation.

A comparable calculation tool with similar name "Schallrechner" (see Figure 3-2) can be found at https://www.waermepumpe.de/normen-technik/schallrechner/. It is hosted by the Bundesverband Wärmepumpe e.V..

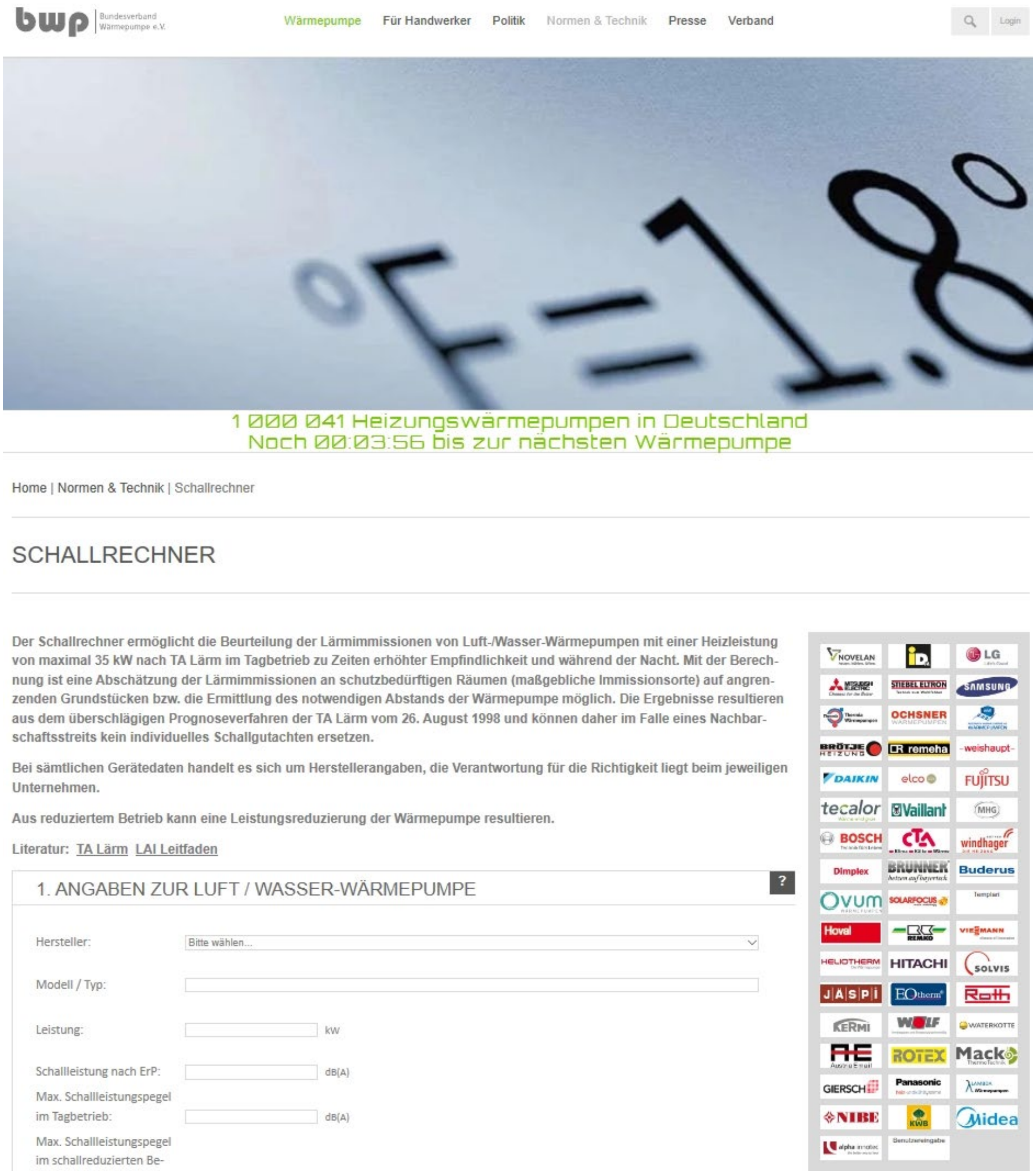


Figure 3-2: Main page of the German "Schallrechner"[2]

The approach of the "Fachvereinigung Wärmepumpen Schweiz" (see Figure 3-3) is a little different, because it provides as a result the list of heat pumps, which are "bewilligungsfähig",

[2] Bundesverband Wärmepumpe e.V., https://www.waermepumpe.de/normen-technik/schallrechner/ (October 20, 2020)

which means "eligible for approval". It can be found here: https://www.fws.ch/unsere-dienstleistungen/bewilligungs-tool-fuer-luft-wasser-waermepumpen/.

There is also a French version available: https://www.fws.ch/fr/nos-services/outil-de-planification-pour-pompes-a-chaleur-air-eau/

Figure 3-3: Main page of Swiss "Schallrechner"[3]

The requested data from the user is much more reduced. The distance, heating power at A-7W35, the noise sensitivity level ("Lärmempfindlichkeitsstufe") and 3 options for the unit placement (outside <5 m from building facade, outside <5m outside in building corner, and >5m outside).

[3] Website Fachvereinigung Wärmepumpen Schweiz
https://www.fws.ch/fr/nos-services/outil-de-planification-pour-pompes-a-chaleur-air-eau/ (October 20, 2020)

3.2 *Two-dimensional visualization*

Although as simple as the already discussed calculation, the tool of the Danish Energy Agency (see Figure 3-4) visualizes the acoustic sound pressure levels originating from a heat pump.

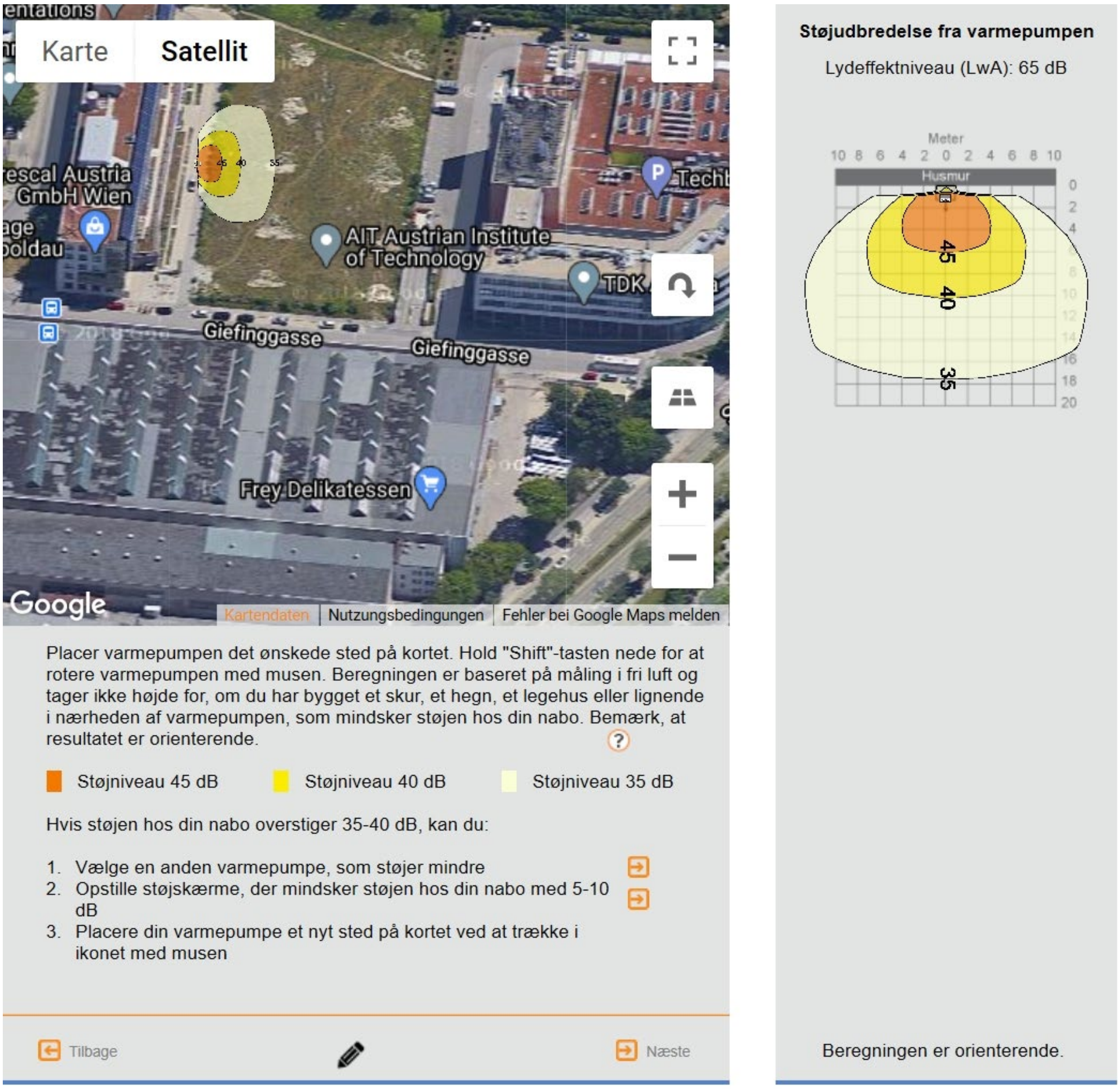


Figure 3-4: Visualization of the sound power level of a heat pump using the "Heat Pump Sound Emission Calculator" of the Danish Energy Agency[4]

Although seeming to be restricted to the Danish country, an arbitrary address can be enters (and found, see Figure 3-5).

[4] Danish Energy Agency, http://stoejberegner.ens.dk (October 20, 2020)

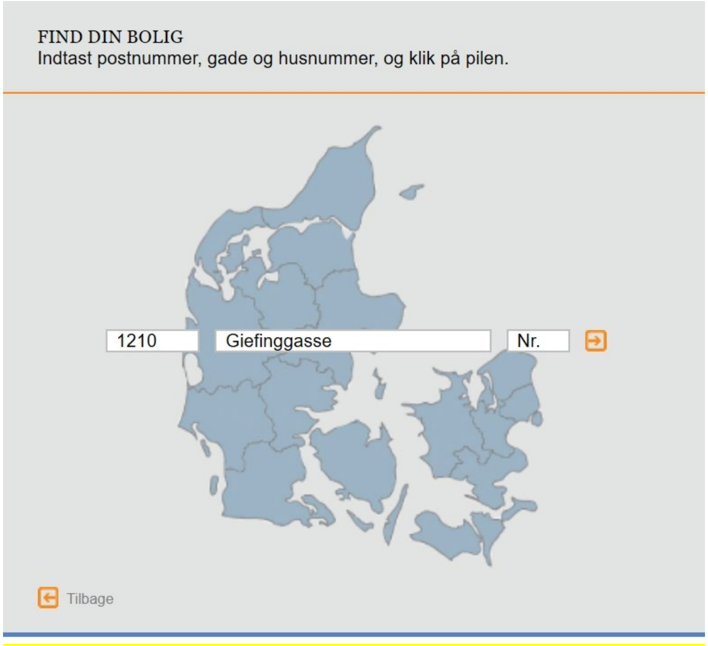


Figure 3-5: Selection of heat pump location [Source: Danish Energy Agency, Denmark - http://stoejberegner.ens.dk]

The placement of the heat pump in the vicinity of walls is also accounted for (see Figure 3-6).

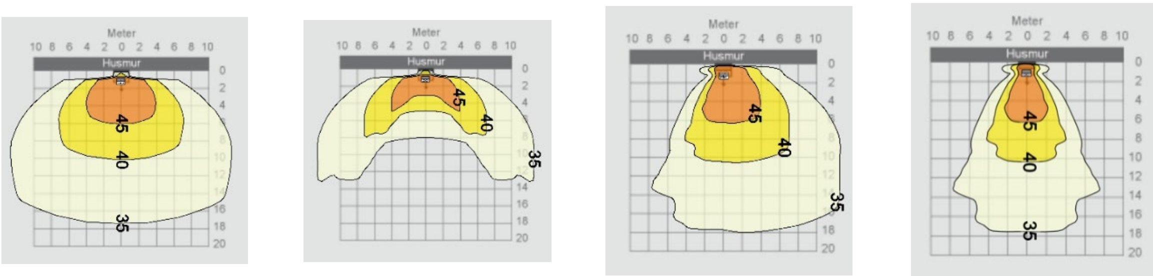


Figure 3-6: Sound propagation visualization depending on the nearby walls [Source: Danish Energy Agency, Denmark - http://stoejberegner.ens.dk]

All these tools neglect - apart from the corner- and wall-placement "penalties" - absorption, reflection or frequency dependencies in the calculation. The underlying formula is very ease and can be calculated by hand. To include the effects of directivity and frequency behaviour as well as absorption and reflection a much larger computational effort would have to be made. Some approaches, which try to shed light on these effects are described below.

3.3 Advanced sound propagation calculation tools

There are several tools available both commercial and opensource, which provide sound immission calculation capabilities. In Table 3-1 a list is providing a reference:

Table 3-1: List of tools for sound immission calculation

CadnaA	https://www.datakustik.com/de/produkte/cadnaa/cadnaa/
SoundPlan	https://www.soundplan.eu/en/
Noise 3D	http://noise3d.com/wp/start/
MITHRA-SIG	http://www.ingeniasrl.it/english/software.html
IMMI	https://www.immi.eu/en/noise-mapping-with-immi.html?no_cache=1
Olive Tree Lab Suite	https://www.mediterraneanacoustics.com/olive-tree-lab-suite.html
OpenPSTD	http://cordis.europa.eu/project/rcn/104345_en.html

For deeper insight into CadnaA and Soundplan, Tables 3-2 and 3-3 give some references and software comparisons.

Table 3-2: List of publications with respect to CadnaA

CadnaA literature	Nicholas Sylvestre-Williams, Ramani Ramakrishnan, *Error bounds, uncertainties and confidence limits of outdoor sound propagation*, Canadian Acoustics, Vol 43 No. 3 (2006)
	Fabian Probst, *Prediction of Sound Pressure Levels at Workplaces*, Euronoise Prague 2012
	Xinhao Yang, Yuan Zhang, Siyang Guo, *Investigation and Study on the Influence of High-Density Urban Traffic Noise on the Acoustic Environment of Urban Parks*, Proceedings of the 23rd International Congress on Acoustics, 9-13 September 2019, Aachen, Germany
	Dipeshkumar Sonaviya, Bhaven Tandel, *A Quick review on Noise propagation models and software*, Conference Paper
	Golder Associates, *Midtown Oakville Class Environmental Assessment*, report number 1401739

Table 3-3: List of publications with respect to CadnaA

SoundPLAN literature	Jimmy Diamandopoulos, Jonas Larsson, *An empirical investigation of the directivity of external industrial noise sources*, Master's Thesis in the Master programme in Sound and Vibration, Chalmers University of Technology
	Esteban Zanardi, Jorge Carrasco Henríquez, Jorge Torres, *Noise propagation software comparison: A case of study between SoundPLAN and Code_TYMPAN*, proceddings of the 22nd International Congress on Acoustics, Buenos Aires, 5-9 September, 2016
	MMRA Technical Note, *SoundPLAN Noise Modelling for Airborne Construction Noise*, Melbourne Metro Rail Project Environment Effects Statement Inquiry and Advisory Committee, Technical Note Number 058, 19 September 2016
	Hayden Puckeridge, Timothy Braunstein, Conrad Weber, *Comparison of rail noise modelling with CadnaA and SoundPLAN*, Acoustics 2009, Sound Decisions: Moving forward with Acoustics, 10-13 November 2019, Cape Schanck, Victoria, Australia

3.4 Full three-dimensional calculation of sound propagation

Of course, the possibility exists, to calculate the propagation of sound by solving the acoustic wave equation. Most prominent techniques include the finite element approach (FEM; Bathe, 2014; Reiter et al., 2017) and boundary element approach (BEM; Duhamel, 1996; Kasess et al., 2016a). Besides open source and in-house codes, also commercial software is available for this purpose.

4 Virtual placement of heat pumps

Here, on the one hand, methods of sound measurement are briefly recapped, on the other hand **advances in augmented reality**, which allow for a **virtual representation** of the sound emitting device and the resulting sound dispersion in a real environment, are discussed. Directional and frequency-dependent sound emission behaviour of a device can be transiently determined in addition to the sound power level under different operating conditions with the employed sound measurement methods discussed here. The focus, however, is set on the development of an **application for mobile devices** utilizing direction-dependent sound propagation virtually in a real environment. The virtual noise emitting HVAC system can be freely positioned using augmented reality. In a second step the source can be simply moved to find the acoustically optimal location and orientation in the real environment. At any position selected by the observer, the sound emissions and the sound pressure level can be determined and visualized taking eventually into account absorption and reflection behaviour by recognizing the environment. The technology should assist the planning and installation procedure of heating and air conditioning units with focus on noise pollution.

4.1 Introduction

To find the best position of heat pumps, the direction-dependent sound pressure level has to be taken into account, along with operating state, frequency dependence as well as the influence of the environment. However, sound emissions are mostly determined from a single number representing a location- and direction-independent sound power level and a direction-dependent value is calculated by mathematical methods without regard for the mentioned additional factors.

To assist with the placement of heat pumps and other HVAC equipment, an app is developed using AR (augmented reality) and manual input to identify the surrounding environment as well as add additional virtual elements such as walls and noise barriers which are taken in account in the calculation of the emitted noise. With this app different locations for the heat pump as well as settings to adapt the surroundings are tried out and optimized before building or installing anything on the selected area.

Using acoustic augmented reality has already been examined in other projects, where other approaches were used than in the present work. Green and Murphy (2020) published a study of an intuitive environmental sound monitoring system that can be used on-site and return meaningful measurements beyond the standard LA_{eq} using an iOS app. Additional virtual sound sources can be placed and their effect on the readings are observed. The Japanese technology group NEC is pursuing a concept of as-signing sound sources to real objects in the environment (Kölling, 2020). A similar approach has also been followed at the Finnish University of Aalto together with Nokia (Albrecht et al., 2011).

4.2 Methods and Measurements

4.2.1 Acoustic measurements of noise sources

To be able to characterize the directional dependence of sound propagation, measurements with many microphones are necessary. For the measurements used in this project the acoustic sound pressure levels of 64 microphones are recorded using an acoustic dome setup (see Figure 4-1) with a sampling rate of 48.000 Hz and a bit depth of 24 bit. The results are stored as raw data in the wave-file format. As recoding software, the scriptable program REAPER is used. The data from the 64 microphones can be used to generate a transient sound power level presented in dB. Various weighting functions can be applied to account for the human sound perception (dB(A), dB(C), …). In addition, a comprehensive analysis of the sound emission directivity can be performed. After processing, all sound pressures are available in a third octave band evaluation as a function of time.

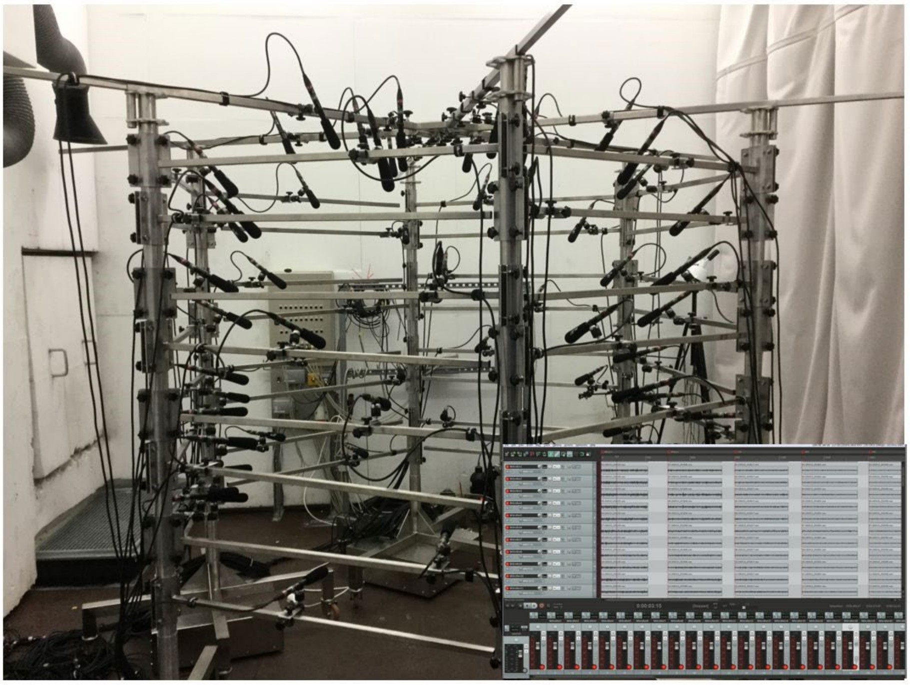


Figure 4-1: Up op 64 microphones are placed around a sound emitting object forming an acoustic "dome". In this case a six-fold symmetrical setup has been constructed. The right lower part of the image shows the some of the wave-signals recorded during a typical test.

To have a simplified understanding of the directivity of the sound emitters, a 5-channel acoustic pressure measurement is performed (see Figure 4-2). Again, data is recorded using REAPER and stored in the wave-format. On the one hand, the transient sound pressure levels and their frequency content in third octave band representation is calculated out of this data, on the other hand, the wave files are used for direction-dependent aurealisation of the sound emitter.

The effort to measure every possible sound source with 64 microphones is relatively high. Additionally, the mobile device must provide a large data volume (16,48 MB/min per microphone) to store all sound files, which can quickly lead to problems when recording 64 microphones. However, for estimating the error that is made when using 5 microphones, the measurement with 64 microphones is a suitable method and will be performed for every noise source.

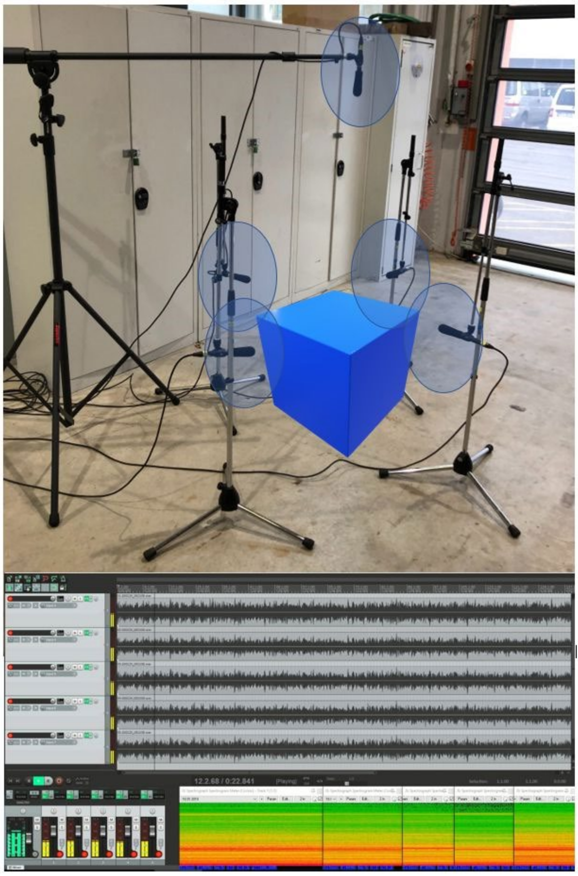


Figure 4-2: 5 microphones are placed around a sound emitting object, one at each side and one from the top. The lower part of the image shows the 5 five signals and their corresponding frequency content represented in waterfall images.

4.2.2 Aurealisation

In the far field of the sound emitter, the best way is to work with half-spheres. Therefore, a method-ology has been developed to geometrically calculate 5 sections of a half-sphere, where each sector is attributed to one of the microphones (see Figure 4-3). The sound emitter is presented as a red box (see Figure 4-3a). Five microphones are placed in a specified distance to this box forming a measurement box (see Figure 4-3b). Connecting 8 corners of the sound emitter with 8 corners of the measurement box, 8 rays are formed (see orange and green rays in Figure 4-3c) – four on a horizontal place (orange) and four reaching to the sky (green). One green and one orange rays are stretching a plane and these four planes are intersected with a sphere (see Figure 3d). Finally, the correlation between the 5 parts of the sphere and the corresponding microphone position can be calculated. For this calculation, the following values have to be known: (a) dimensions of the sound emitter, (b) distance between sound emitter and micro-phone, (c) radius of the sphere.

The aurealisation of the sound emitter is made by a real-time mixing of the 5 wave files (which have been simultaneously recorded) using the position on the sphere. Therefore, one to three signals are used: In the centre point of the spheres only one signal is used, on the connection lines between two centre points two signals are used, at all other positions three signals have to be mixed. Mixing is performed to ensure that the noise pressure level around the heat pump remains smooth.

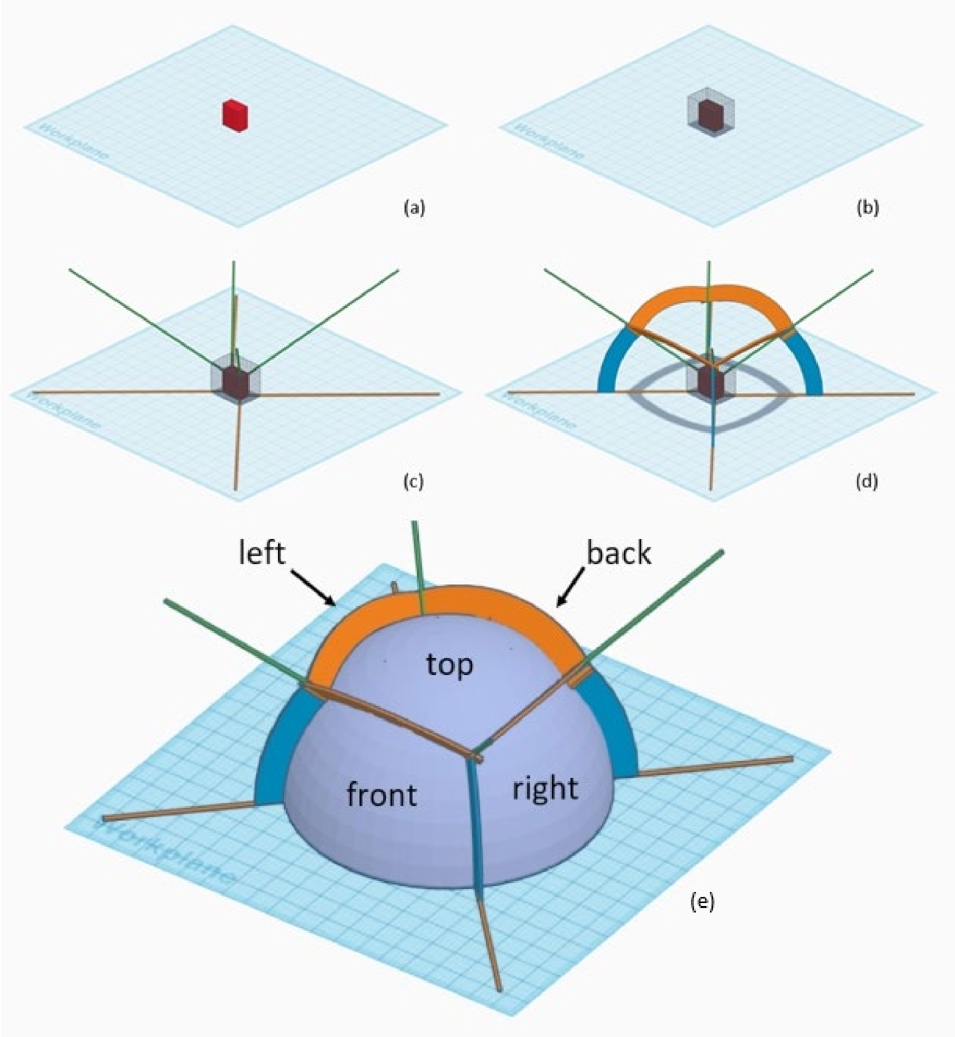


Figure 4-3: Visualization of the directivity aurealisation technique: (a) the red box represents the sound emitting HVAC component (e.g. heat pump); (b) the acoustic pressure is recorded in a specific distance to the emitting surfaces at 5 locations – a measurement surface is formed; (c) rays are generated connecting the emitter's corners with the corners of the measurement surface; (d) parts of the planes stretched by these rays intersected with a sphere; (e) final visualization of the 5 parts of the half-sphere attributed to the 5 microphone measurement positions.

4.2.3 Methods for calculating sound propagation

Various methods are commonly used for calculating sound propagation: Ray tracing, noise mapping, finite element, boundary element, and hybrid methods, among others.

Ray tracing is mostly used for interior problems. This approach is very efficient compared to exact methods such as finite and boundary element method (FEM and BEM, respectively). Sound propagation in large spaces with many borders can be calculated. Ray tracing is only suitable for outdoor applications if some model for diffraction is included.

Methods of noise mapping can be used when calculating direct sound and first and second reflex-ions. Diffractions are usually only considered approximately based on experiments as well as analytic solutions. The computational effort is relatively low such that these methods can be used on a large scale. However, the efficiency of the analytical approaches is also limited here (Wei et al., 2015). For more complex noise barrier designs, frequency-dependent correction factors can be used to adjust noise mapping calculations (Kasess et al., 2016a). It is however necessary to adjust these values for low heights, short distances and shorter lengths, which are common for the situations considered in this project.

Calculations of the sound distribution using **Finite Element Method** (Bathe, 2014; Reiter, 2017), are limited to small rooms. Radiation can be considered using semi-infinite elements or Perfectly Matched Layers (PMLs). This method can only be used to determine diffraction correction factors behind noise barriers, which is essentially limited to the 2D case.

For noise barriers, the use of the **Boundary Element Method** is usually restricted to mainly 2D or 2.5D calculations, i.e. the cross-section geometry is assumed to be constant in the third dimension, where the latter approach also allows point sources (Duhamel, 1996). Although the efficiency of 2.5D was increased recently (Kasess et al., 2016b), the computational effort required for this does not allow an ad-hoc calculation. Thus, this method is also only suitable for the determination of correction factors. Small geometries allow 3D-BEM calculations, however the frequency range is usually restricted to relatively low frequencies due to the much higher effort.

Following methods were considered additionally in terms of their usefulness in the current project: The use of the **Finite-Difference Time-Domain Method** for outdoor sound propagation modelling is discussed in (van Renterghem, 2014). The **Wave Based Method** (Deckers et al., 2014) is usually used for indoor spaces. **Transformation methods** may be useful in some special cases in this project when only single bordered areas are considered.

4.3 Realization

4.3.1 Modelling and mapping

The sound propagation of outdoor HVAC units still requires a lot of testing and experimental methods, especially when placed in urban areas. Simulating noise propagation of such units was also re-searched in (Poysat et al. 2019) and noise propagation with a focus on urban areas is discussed in (Ismail and Oldham, 2003).

Here, the following approach was chosen to calculate the values at different positions and distances around the HVAC unit: The recorded sound pressure levels are used as a basis for the simulation of the sound propagation. The directivity of the source is modelled using one monopole and three dipoles, because this assumption simplifies the mapping from source to receiver. The mapping is done mainly as described in ÖNORM ISO 9613-2:2008.This standard includes diffraction, where the diffraction from di-poles is assumed to be identical to the diffraction from monopoles.

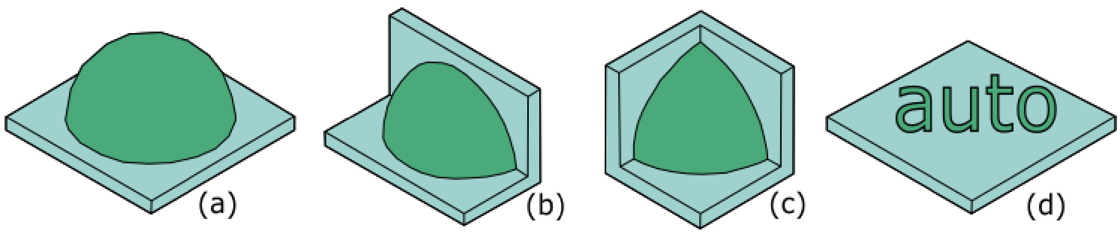


Figure 4-4: Calculation of sound propagation with different options regarding the surrounding environment: (a) free field with floor plane; (b) along a wall; (c) in a corner; (d) automatically detect the surrounding geometry for the simulation

The reflection from the wall and the ground are simulated using mirror sources. If both are included four sources are needed. If a noise barrier is used also, five sources are needed, since the mirror source behind this barrier is the same for all sources on the source side. Special edges can be calculated with the boundary element method before the real-time session starts, which are performed in 2.5D. The result of this method is attenuation factor depending on the diffraction angle. For deriving a curve, which can be interpolated in real-time, the calculation is repeated. In the developed application the user can select one of four options for the calculation, according to the surrounding environment, as seen in Figure 4-4.

The results of these calculations are visualized for the specific user for clarifying their meaning in an augmented reality environment. There, different visualization options are considered: The measurement values can be projected on the floor or rendered as three-dimensional tags at given distances and directions. The sound pressure level, the user would hear at their current position, can also be visualized using a gradient of traffic light colours according to the effect of the sound pressure level on the human health, which means: green for unproblematic and red for severely damaging sound pressure levels. A textual representation of the current distance to the sound source along with the simulated sound pressure level is another possible approach. A transparent wall or coloured plane that signifies the exceeding of a certain threshold in a given area is another option.

In the developed application, the sound pressure levels are visualized using several of these options, as seen in Figure 4-5.

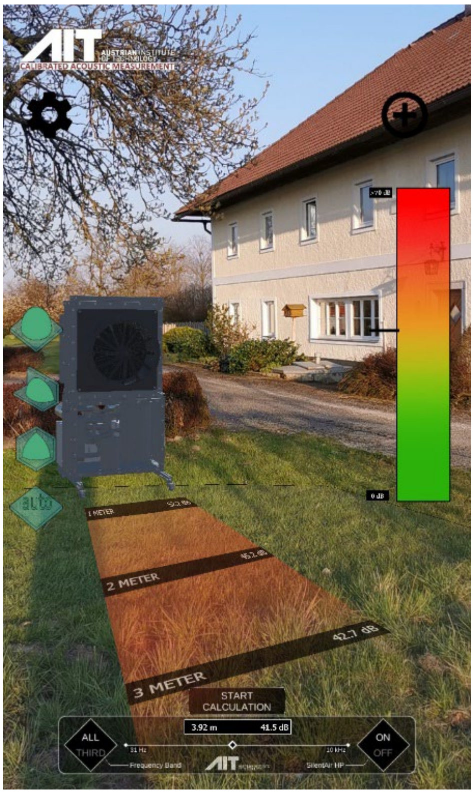


Figure 4-5: A laboratory heat pump (SilentAirHP) placed in a real environment using AR, with frequency-dependent sound propagation.

4.3.2 Hardware and software for visualization and acoustics

Various SDKs (Software Development Kits) and development environments are available for developing augmented reality applications. These include vendor-specific solutions, which are only working on their native platforms, like SDKs from BOSE (2020) or Apple Inc. (2020a), as well as solutions working on multiple platforms like Vuforia (PTC, 2020), DeepAR (2020) or Kudan (2020). While some of the toolkits are re-leased as open-source or free projects, others are only available as commercial software or still exist only as beta versions. In Amin and Govilkar (2015) a further categorization according to their overlaying capabilities is discussed. For iOS applications Apple released a native framework, ARKit, in 2017. Google's ARCore (Google, 2020) primarily targets Android devices and became popular after Google's Tango was discontinued in 2017 (Jansen, 2020). Most SDKs rely on third party 3D engines such as Unity Technologies (2020), Unreal Engine (2020) or Apple Inc. (2020b) as development environment (Romilly, 2020).

For this project the Unity environment and Unity's AR Foundation, which acts as a common inter-face for both ARKit and ARCore, are used to develop an app for iOS as well as Android devices.

4.4 *Summary*

Calculation and visualization methods of outdoor noise sources, i.e. of HVAC units, were examined and an augmented reality application was developed. These works can help users to evaluate the environmental noise, which is emitted by different noise sources virtually, as well as to find a suitable position before the units are physically placed. The next steps in this project are the automated detection of the environment and including these results into the sound pressure level calculation. Thus, sound-specific properties of the environment are meant to be configurable and considered in the calculation by adding reflexion and absorption.

The current state of the app can be downloaded in

- Google Playstore: HVAC Positioner[5]
- iOS store: iOS HVAC Positioner[6]

[5] https://play.google.com/store/apps/details?id=at.ac.ait.hvacpositioner&gl=AT
[6] https://apps.apple.com/at/app/hvac-positioner/id1462057877

5 Analysis of acoustic interaction of multiple heat pumps

This part is based on a bachelor thesis performed by Elisabeth Wasinger in Vienna, Austria. The full work translated in English is available from the IEA HPT Annex 51 website for free download.

The number of installed air water heat pumps increases but their disadvantage is their sound emission. In this part, it is considered how the sound spreads in a housing estate which is only heated by air water heat pumps. The sound must not exceed a defined level at critical rooms and along the property line.

Three scenarios with different numbers of installed pumps are created. A small number means that the performance of the used model must be high because one pump heats many households. The sound power level depends on the models chosen.

Then, simulations are done with the sound prediction software IMMI. It calculates on the bases of the ÖNORM ISO 9613-2:2008 and the ÖNORM S 5021:2010. It comes out that one pump per house is optimal for low sound pressure levels. If noise barriers are used a local heating is the ideal scenario.

Additional simulations have been performed, where the heat pumps are not in operation all day long but there are time depending switching profiles because of the individual user behaviour of the families. The sound immission is identified for every hour of one day. It is shown that the sound pressure levels are lower when considering realistic user behaviour.

5.1 Introduction

5.1.1 Methodology

A housing estate of terraced houses forms the basis for this work. It comprises seven semi-detached houses and five detached houses. Thus there is room for a total of 19 households, each of which has a garden. The use of space in the individual buildings is defined. The heating loads are known and the hot water demand is assumed based on empirical values.

Suitable air-to-water heat pumps are now selected depending on the required output. Three different scenarios are created. In the first scenario each household is heated with its own heat pump, in the second there is one heat pump per house and in the third a local heating supply is used for the whole settlement.

In the next step, the scenarios are examined using a sound simulation program. In previous investigations a comparison of several programs was carried out. With regard to accuracy, user-friendliness and costs for students, it was found that IMMI (Wölfel, 2016) is the best suited for a simulation of this kind.

Each heat pump has a sound power level which is needed to simulate sound fields in the residential area. First of all, the maximum sound power level is used without considering any partial load behaviour or simultaneity factor. Only when designing the heat pump for local heating supply is a simultaneity factor taken into account at this point, as a permanent heat supply of all consumers is unlikely and would require a more powerful heat pump. The sound power level of this would then possibly be unrealistically high.

The periodically occurring defrosting noise is not considered. A point-like sound propagation is assumed and a distinction is made between day and night operations. Even on undeveloped areas adjacent to the settlement, buildings are placed virtually in order to take into account possible reflections and diffractions of the sound in advance.

For each scenario three variants of heat pump placements are simulated. The aim is to ensure that the defined maximum sound pressure levels in the rooms requiring protection are not exceeded. The rooms requiring protection include bedrooms, children's rooms, cloakrooms and cooking, dining and living areas (Baugutachter, 2016). In addition, a certain sound pressure level along the property boundaries that separate the terraced house settlement from adjacent areas must not be exceeded. This results in an optimal placement of the heat pumps for each scenario.

In the next step, it is no longer assumed that each heat pump runs all day, but time-dependent switching profiles are created, which are based on the individual user behaviour of the inhabitants. The sound pressure level is now measured at every hour of the day at the windows of the rooms requiring protection in each house. This simulation is performed for the best configuration of all placement variants and scenarios.

Subsequently, it will be investigated whether the open source program OpenPSTD (2016) is also suitable for simulations of this kind.

5.1.2 Expected Results

Neglecting reflection and diffraction effects, the sound pressure level in the houses is lower when the heat pumps are placed further away than when they are placed in the immediate vicinity of the houses. However, the mentioned effects have an influence on the sound propagation and are considered here. Furthermore, heat pumps with a higher fan speed have a higher sound power level compared to heat pumps of the same design with lower fan speed. Thus, it is assumed that the sound is more evenly distributed in the settlement when a large number of heat pumps with low speed are placed in a distributed manner than when a few heat pumps with high speed are used. What is acoustically more advantageous cannot yet be answered at this point. The evaluation of the installation site variants in this thesis depends on the number of decibels exceeding the defined maximum permissible sound pressure level.

5.1.3 Reduction Measures

As a matter of principle, it must be determined by suitably trained persons to what extent the sound pressure level is changed when measures are taken to reduce the level. However, guideline values are known which evaluate the effect of the respective steps. By selecting a suitable installation site, a level reduction of up to 25 dB can be achieved. Carefully selecting a heat pump has a reduction potential of up to 10 dB. Technical measures such as a sound insulation hood or a noise barrier can reduce the sound pressure level by up to 8 dB. A reduction of 2 to 6 dB is achieved by scooping or reducing the speed (Interkantlab, 2016).

5.1.4 Assumed Limits

Since there is no uniform legally permitted sound pressure level, the following limits are set for in this section. In front of the rooms in need of protection, which include the bedroom, the two children's rooms, the cloakroom and the cooking, dining and living areas of each household, a maximum of 30 dB may be reached during the day and a maximum of 25 dB at night. The level is measured directly in front of the outside surface of the windows of the rooms described. At the boundary of the property, the sound pressure level may not exceed 35 dB during the day and 30 dB at night. The highest sound pressure level occurring along the property boundary is measured.

5.2 The Terraced Housing Estate

The estate is a terraced house settlement for 19 parties, with floor plans and site plans attached to the appendix. The settlement is located in the market town of Hagenbrunn in the district of Korneuburg in Lower Austria. The houses with the door numbers 5, 8, 13, 16 and 19 are detached, while all others are designed as semi-detached houses. A garden belongs to each household. The numbering of the households is ascending from the most north-western household to the east and then continues to the south and then to the west.

In the bachelor theses „Planung einer dezentralen Wärmepumpenanlage“ („Planning of a decentralised heat pump system”) by Ramsmaier (2016) and „Wärmeversorgung einer Reihenhaussiedlung durch ein zentrales Wärmepumpennetz“ („Heating supply of a housing estate of terraced houses by a central heat pump network”) by Kager (2016) the U-values of the building components were determined. In each household there are three people whose hot water demand is 50 litres per day. The hot water temperature is 55 °C, which is high enough to prevent the proliferation of legionella. The heat output system, which serves to maintain the target room temperature at 20 °C, is an underfloor heating system with a temperature of 35 °C in the flow pipe and 28 °C in the return pipe. The standard outside temperature is -12.8 °C and the minimum temperature on the surface of the earth is 2 °C.

5.2.1 Heating Load, Hot Water Provision and Heating Demand

The heating load calculation was performed using the Solar Computer program in accordance with ÖNORM EN 12831:2018. The heating requirement was determined using PHPP (Ramsmaier, 2016) and Kager (2016).

The power required to heat water for one person is 250 W (Sobotta, 2008). Since three people live in one household, the heat pumps must be dimensioned in such a way that, in addition to the heating load, they provide the power required for hot water preparation of 750 W per household.

Table 5-1 shows the heating load together with the capacity for domestic hot water preparation. In addition, the list also contains the specific and absolute heating requirement for each household.

Table 5-1: Heating load, output for water heating and heating demand per household (Ramsmaier, 2016; Kager, 2016)

Door number	Heating load and output for hot water preparation [W]	Dedicated heating demand [kWh/(m²*a)]	Absolute heating demand [kWh/a]
1	4 688	35	5 145
2	4 688	33	4 851
3	4 688	35	5 145
4	4 688	33	4 851
5	4 976	31	4 873
6	4 717	33	4 914
7	4 717	32	4 678
8	5 134	32	4 704
9	4 688	35	5 145
10	4 688	33	4 851
11	4 688	33	4 851
12	4 688	35	5 145
13	5 134	32	4 704
14	4 688	33	4 851
15	4 688	35	5 145
16	5 134	32	4 704
17	4 688	33	4 851
18	4 688	35	5 145
19	5 134	32	4 704
mean value	**4 800**	**33**	**4 908**
sum	**91 202**		**93 257**

5.2.2 Neighbouring Sites

Around the settlement there are mostly empty green spaces. However, since it is assumed that buildings will be constructed on them in the foreseeable future, virtual building dummies are placed on them for this bachelor thesis. Thus, possible sound reflections, which are caused by the impact of the sound on additional building surfaces and which increase the sound pressure level, are already considered in advance. The building dummies are placed 3 m away from the lateral and rear property boundary, as this corresponds to § 50 of the currently valid Lower Austrian Building Regulations 2014 (RIS, 2016). The following Figure 5-1 shows the existing housing estate including the dummy buildings. This list is used for the simulations. For this work, the numbering of the dummies and the neighbouring buildings is carried out in ascending order from the most north-western building to the east and then continued to the south and then to the west.

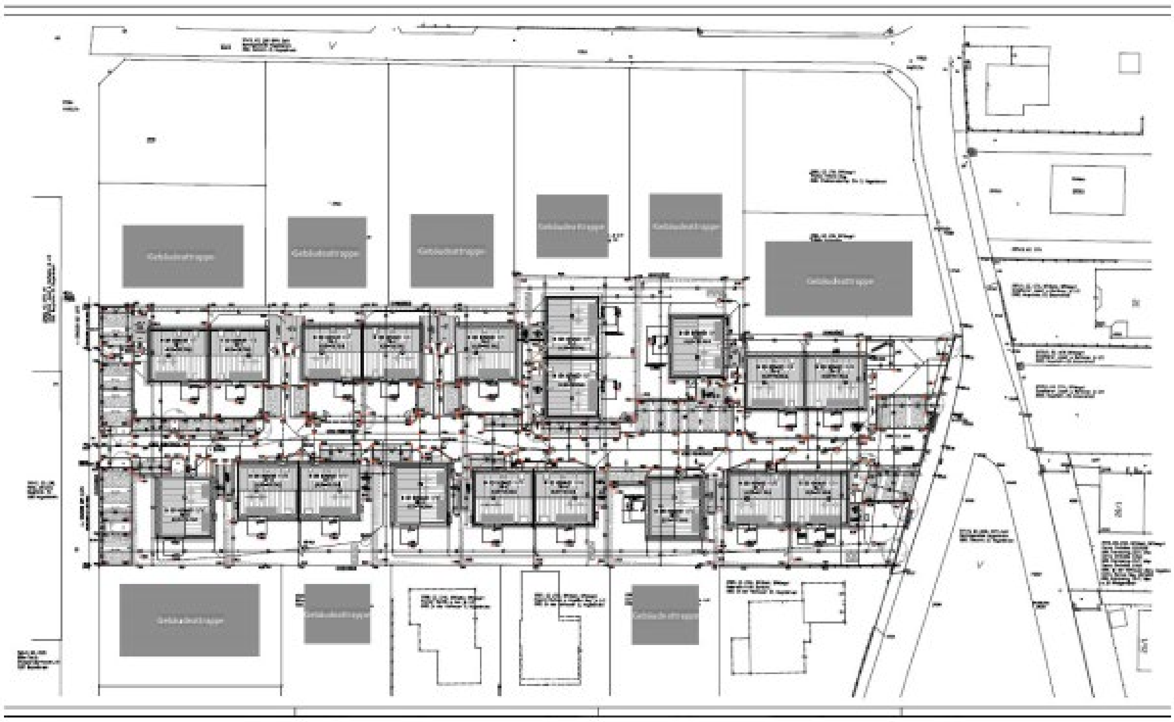


Figure 5-1: Site plan with dummy buildings

5.3 Simulation of maximum Sound Propagation using IMMI

Simulations with the IMMI program are performed and evaluated on the basis of ÖNORM ISO 9613-2:2008 and ÖNORM S 5021:2010. The effects of diffraction, reflection and absorption of sound are considered.

The dimensions of the buildings are taken from the plans in the appendix. In IMMI the row houses, the associated equipment rooms, the existing neighbouring buildings and the dummy buildings are constructed. As there are no plans of the latter two, they are designed as flat-roofed houses with a height of 7,75 m. This height is chosen because it corresponds to the height of the ridge of the gable roofs of the row houses. The flat-roofed houses are chosen because they have a large wall surface and therefore the most unfavourable case possible in terms of reflection is examined. Heat pumps are placed as point sources at a height of 1 m. We refrain from considering the planting, which can be seen in the plans in the appendix, as it changes seasonally and over the years.

The following figure 5-2 shows the plan of the row house settlement with marking of the points on the building envelopes where the defined sound pressure level must not be exceeded. The measuring points are located in the middle of the outer surfaces of the windows and glass doors of the rooms requiring protection. In order to be able to clearly see the height of the measuring points despite the representation in the top view, colours with different meanings are assigned to the markings. Light blue squares mean that the measuring point is at ground floor level. Yellow squares are placed in front of vertical windows on the top floor and green squares in front of sloping skylights.

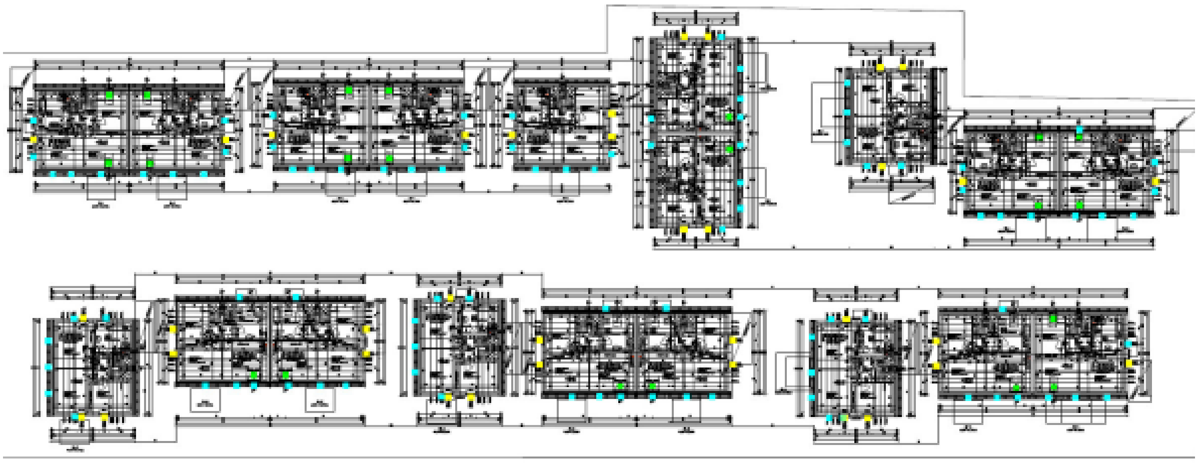


Figure 5-2: Plan of the terraced house settlement with marking of the sound measuring points

The adjacent property boundaries of the neighbouring areas are also considered. The sound pressure level is recorded along the property boundaries at a height of 0 to 7.75 m. At these vertical grids a value is recorded vertically per meter and horizontally per decimeter. The highest sound pressure level occurring on the vertical grid of a site boundary must not exceed the defined limit value.

This results in a total of 164 locations where sound immission is measured. These are listed and numbered in Table 5-2. The same numbering will be used later in the work. The abbreviations used in the names of the places of immission indicate where they are located. T1 to T19 indicate the door number. EG is used to designate points on the ground floor, DG points on the attic floor. DF means that the window at which the sound pressure level is measured is a roof window. KEW stands for „Koch-, Ess- und Wohnbereich“ („cooking, dining and living area”).

Table 5-2: Name and numbering of critical points of immission

Nr.	Immissionsort	Nr.	Immissionsort	Nr.	Immissionsort	Nr.	Immissionsort
1	T1 Kinderzimmer 1 DF Nord	42	T6 Schlafzimmer DF Ost	83	T11 Kinderzimmer 1 DF Nord	124	T16 KEW EG Nord
2	T1 Kinderzimmer 2 DF Süd	43	T6 Kinderzimmer 1 DG Nord	84	T11 Kinderzimmer 2 DF Süd	125	T16 Garderobe EG Nord
3	T1 Schlafzimmer DG West	44	T6 Kinderzimmer 2 DG Nord	85	T11 Schlafzimmer DG Ost	126	T16 KEW EG Süd
4	T1 KEW EG Süd 1	45	T6 KEW EG Nord	86	T11 Garderobe EG Ost	127	T16 KEW EG West 1
5	T1 KEW EG Süd 2	46	T6 KEW EG Ost 1	87	T11 KEW EG Süd 1	128	T16 KEW EG West 2
6	T1 KEW EG Süd 3	47	T6 KEW EG Ost 2	88	T11 KEW EG Süd 2	129	T16 KEW EG West 3
7	T1 KEW EG West	48	T6 KEW EG Ost 3	89	T11 KEW EG Süd 3	130	T17 Schlafzimmer DF Süd
8	T1 Garderobe EG West	49	T6 Garderobe EG West	90	T12 Schlafzimmer DF Süd	131	T17 Kinderzimmer 1 DG Ost
9	T2 Kinderzimmer 1 DF Nord	50	T7 Schlafzimmer DF Ost	91	T12 Kinderzimmer 2 DG West	132	T17 Kinderzimmer 2 DG Ost
10	T2 Kinderzimmer 2 DF Süd	51	T7 Kinderzimmer 2 DG Süd	92	T12 Kinderzimmer 1 DG West	133	T17 Garderobe EG Nord
11	T2 Schlafzimmer DG Ost	52	T7 Kinderzimmer 1 DG Süd	93	T12 Garderobe EG Nord	134	T17 KEW EG Süd 1
12	T2 Garderobe EG Ost	53	T7 KEW EG Ost 1	94	T12 KEW EG Süd 1	135	T17 KEW EG Süd 2
13	T2 KEW EG Ost	54	T7 KEW EG Ost 2	95	T12 KEW EG Süd 2	136	T17 KEW EG Süd 3
14	T2 KEW EG Süd 1	55	T7 KEW EG Ost 3	96	T12 KEW EG Süd 3	137	T18 Schlafzimmer DF Süd
15	T2 KEW EG Süd 2	56	T7 KEW EG Süd	97	T13 Schlafzimmer DG Nord	138	T18 Kinderzimmer 2 DG West
16	T2 KEW EG Süd 3	57	T7 Garderobe EG West	98	T13 Kinderzimmer 1 DG Süd	139	T18 Kinderzimmer 2 DG West
17	T3 Kinderzimmer 1 DF Nord	58	T8 Kinderzimmer 2 DG Nord	99	T13 Kinderzimmer 2 DG Süd	140	T18 Garderobe EG Nord
18	T3 Kinderzimmer 2 DF Süd	59	T8 Kinderzimmer 1 DG Nord	100	T13 KEW EG Nord	141	T18 KEW EG Süd 1
19	T3 Garderobe EG West	60	T8 Schlafzimmer DG Süd	101	T13 Garderobe EG Nord	142	T18 KEW EG Süd 2
20	T3 Schlafzimmer DG West	61	T8 Garderobe EG Süd	102	T13 KEW EG Süd 1	143	T18 KEW EG Süd 3
21	T3 KEW EG West	62	T8 KEW EG Süd	103	T13 KEW EG Süd 2	144	T19 Schlafzimmer DG Nord
22	T3 KEW EG Süd 1	63	T8 KEW EG West 1	104	T13 KEW EG West 1	145	T19 Kinderzimmer 1 DG Süd
23	T3 KEW EG Süd 2	64	T8 KEW EG West 2	105	T13 KEW EG West 2	146	T19 Kinderzimmer 2 DG Süd
24	T3 KEW EG Süd 3	65	T8 KEW EG West 3	106	T13 KEW EG West 3	147	T19 KEW EG Nord
25	T4 Kinderzimmer 1 DF Nord	66	T9 Kinderzimmer 1 DF Nord	107	T14 Schlafzimmer DF Süd	148	T19 Garderobe EG Nord
26	T4 Kinderzimmer 2 DF Süd	67	T9 Kinderzimmer 2 DF Süd	108	T14 Kinderzimmer 1 DG Ost	149	T19 KEW EG Süd
27	T4 Schlafzimmer DG Ost	68	T9 Schlafzimmer DG West	109	T14 Kinderzimmer 2 DG Ost	150	T19 KEW EG West 1
28	T4 Garderobe EG Ost	69	T9 KEW EG Süd 1	110	T14 Garderobe EG Nord	151	T19 KEW EG West 2
29	T4 KEW EG Ost	70	T9 KEW EG Süd 2	111	T14 KEW EG Süd 1	152	T19 KEW EG West 3
30	T4 KEW EG Süd 1	71	T9 KEW EG Süd 3	112	T14 KEW EG Süd 2	153	max. Wert Grundgr. Attrappe 1
31	T4 KEW EG Süd 2	72	T9 KEW EG West	113	T14 KEW EG Süd 3	154	max. Wert Grundgr. Attrappe 2
32	T4 KEW EG Süd 3	73	T9 Garderobe EG West	114	T15 Schlafzimmer DF Süd	155	max. Wert Grundgr. Attrappe 3
33	T5 Kinderzimmer 1 DG Ost	74	T10 Kinderzimmer 1 DF Nord	115	T15 Kinderzimmer 2 DG West	156	max. Wert Grundgr. Attrappe 4
34	T5 Kinderzimmer 2 DG Ost	75	T10 Kinderzimmer 2 DF Süd	116	T15 Kinderzimmer 1 DG West	157	max. Wert Grundgr. Attrappe 5
35	T5 Schlafzimmer DG West	76	T10 Schlafzimmer DG Ost	117	T15 Garderobe EG Nord	158	max. Wert Grundgr. Attrappe 6
36	T5 KEW EG Ost	77	T10 KEW EG Nord	118	T15 KEW EG Süd 1	159	max. Wert Grundgr. Nachbar 1
37	T5 KEW EG Süd 1	78	T10 Garderobe EG Ost	119	T15 KEW EG Süd 2	160	max. Wert Grundgr. Attrappe 7
38	T5 KEW EG Süd 2	79	T10 KEW EG Ost	120	T15 KEW EG Süd 3	161	max. Wert Grundgr. Nachbar 2
39	T5 KEW EG Süd 3	80	T10 KEW EG Süd 1	121	T16 Schlafzimmer DG Nord	162	max. Wert Grundgr. Nachbar 3
40	T5 KEW EG West	81	T10 KEW EG Süd 2	122	T16 Kinderzimmer 1 DG Süd	163	max. Wert Grundgr. Attrappe 8
41	T5 Garderobe EG West	82	T10 KEW EG Süd 3	123	T16 Kinderzimmer 2 DG Süd	164	max. Wert Grundgr. Attrappe 9

Three scenarios are created. The heat pumps are placed in each scenario in three different ways, which are shown in illustrations in the further course of this work.

5.3.1 Evaluation System

The sound pressure level is recorded for each measuring point. One penalty point is given for each decibel above the specified value. Then all penalty points that a placement variant has in total are summed up. The variant with the lowest number of penalty points is considered the optimum based on the criteria defined in this work.

5.3.2 Graphical representation in IMMI

In the following course of this bachelor thesis image sections from the IMMI program are inserted. The views are from the top view, unless another view is explicitly indicated. Red brick pattern shows the houses of the described terraced house settlement. Neighbouring buildings and dummy buildings are represented through blue areas, equipment rooms through light brown ones. The speakers in the illustrations symbolise the heat pumps, while black-transparent patterned circles stand for sound immission points.

5.3.3 Scenario A: One Heat Pump per Household

In scenario A, a heat pump is available for each household in the corresponding garden. This results in such short pipe lengths so that the heat loss via these pipes is so low that it is neglected.

Heat Pump Selection

Since the heating loads of the individual households differ by 446 W at most, a uniform heat pump model is chosen. The sum of the heating load and the output required for DHW heating for a household is a maximum of 5134 W. The air-to-water heat pump LA 9S-TU (Dimplex, 2016a) from Dimplex, for example, which is selected as the heating system in this scenario, is suitable for covering the required output. With an air temperature of 2 °C and a water outlet temperature of 35 °C, which is suitable for the underfloor heating of terraced houses, the output of this heat pump is 7.2 kW at the optimum operating point A2/W35. If 55 °C domestic hot water is required, the unit to be installed outside is operated at point A2/W55. An output of 6.6 kW and a COP of 2.6 are achieved here. The sound power level is 53 dB(A) per heat pump both during the day and in reduced night operation.

Placement

Since the heating loads of the individual households differ by 446 W at most, a uniform heat

In variant 1A, the heat pumps are placed within the gardens of the respective owners next to the property boundaries separating the terraced house settlement from the neighbouring properties. Only the heat pump of door number 7 is not placed next to one of the described plot boundaries, as the garden of this party is surrounded exclusively by plots of land of the terraced house settlement. A graphic overview is given in Figure 5-3.

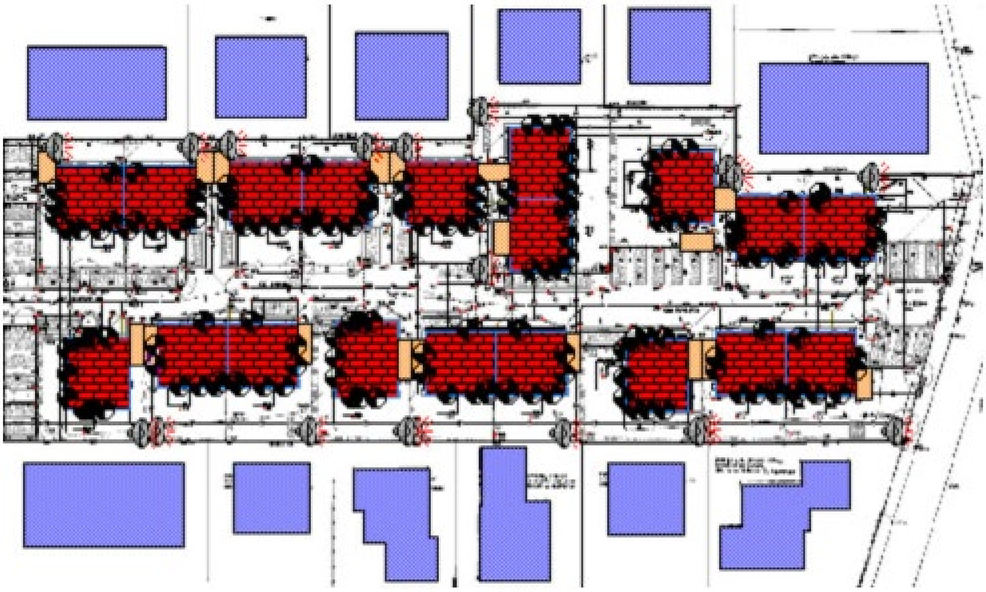


Figure 5-3: Placement of heat pumps in scenario A, variant 1A

In contrast to variant 1A, variant 2A places the majority of the heat pumps closer to the houses in order to avoid a strong noise pollution of the neighbouring properties. Figure 5-4 shows the installation locations.

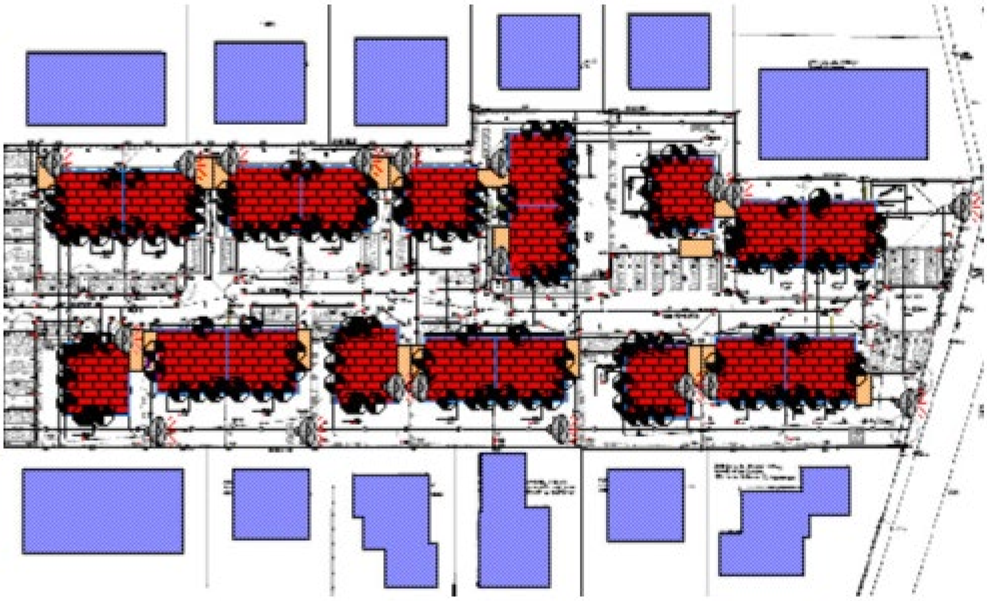


Figure 5-4: Placement of heat pumps in scenario A, variant 2A

In variant 3A most heat pumps are placed near the walls of terraced houses. This is shown in figure 5-5.

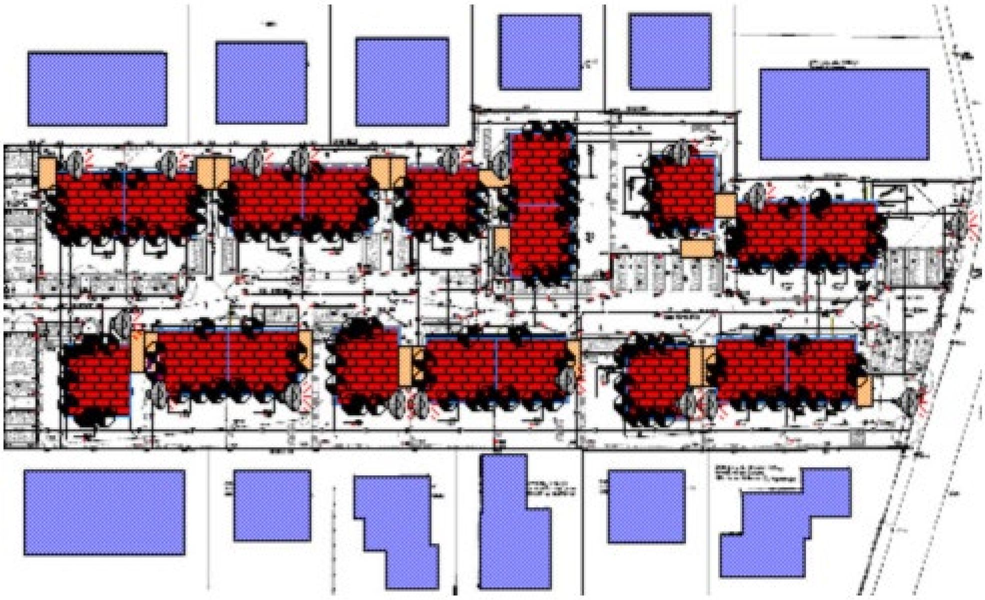


Figure 5-5: Placement of heat pumps in scenario A, variant 3A

5.3.4 Scenario B: One Heat Pump per House

In scenario B, a separate heat pump is not installed for each household, but for each house. This means that a semi-detached house is not heated with two heat pumps, but with only one. This results in pipes that are so short that the heat loss via these pipes is low enough to be neglected. Heat pumps that supply a semi-detached house are installed in the garden of the two households, where a location with low sound propagation is more easily achieved.

Heat Pump Selection

The following table 5-3 shows the heating loads of each building.

Table 5-3: Heating load and output for hot water preparation per building

<table>
<tr><th>Door number</th><th>Heating load and output for hot water preparation per household [W]</th><th>Heating load and output for hot water preparation per building [W].</th></tr>
<tr><td>1</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>2</td><td>4 688</td></tr>
<tr><td>3</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>4</td><td>4 688</td></tr>
<tr><td>5</td><td>4 976</td><td>4 976</td></tr>
<tr><td>6</td><td>4 717</td><td rowspan="2">9 434</td></tr>
<tr><td>7</td><td>4 717</td></tr>
<tr><td>8</td><td>5 134</td><td>5 134</td></tr>
<tr><td>9</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>10</td><td>4 688</td></tr>
<tr><td>11</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>12</td><td>4 688</td></tr>
<tr><td>13</td><td>5 134</td><td>5 134</td></tr>
<tr><td>14</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>15</td><td>4 688</td></tr>
<tr><td>16</td><td>5 134</td><td>5 134</td></tr>
<tr><td>17</td><td>4 688</td><td rowspan="2">9 376</td></tr>
<tr><td>18</td><td>4 688</td></tr>
<tr><td>19</td><td>5 134</td><td>5 134</td></tr>
</table>

Since the highest required heat output of a semi-detached house is 9434 W and only has a difference of 58 W to the heating loads of the other semi-detached houses, the air-to-water heat pump LA 18S-TU (Dimplex, 2016b) from Dimplex is used for each semi-detached house. This unit, designed for outdoor installation, has an output of 14.2 kW at operating point A2/W55 and achieves a COP of 2.90. The sound power level is 54 dB(A). In lowered operation this value is reduced to 53 dB(A).

The detached houses are heated with the LA 9S-TU air-to-water heat pump from Dimplex. This model has already been described in scenario A.

Placement

Figure 5-6 shows the locations of the heat pumps in variant 1B. They are mostly located south of the houses to be heated.

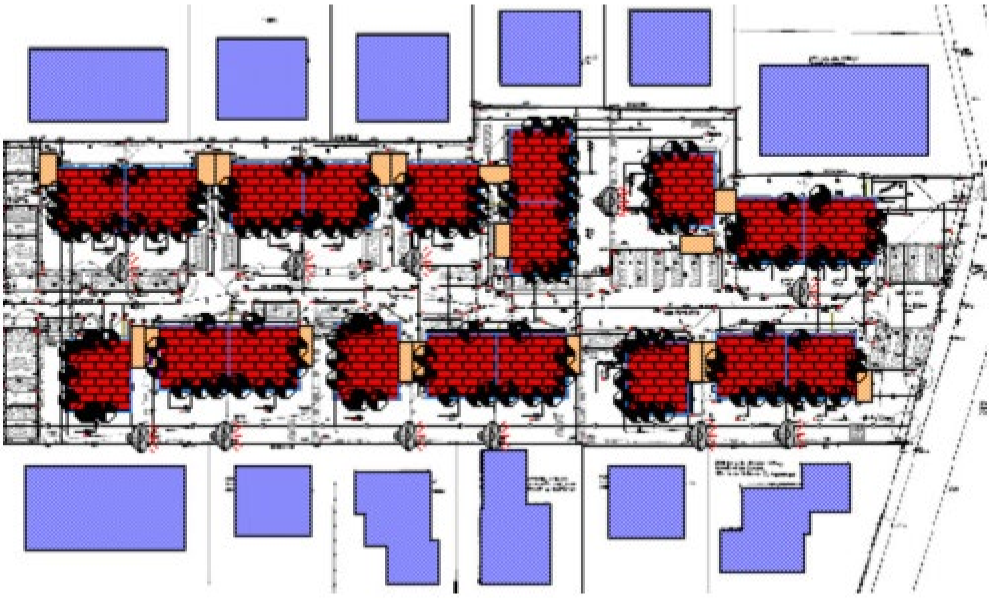


Figure 5-6: Placement of heat pumps in scenario B, variant 1B

The locations of the heat pumps in variant 2B are shown in Figure 5-7.

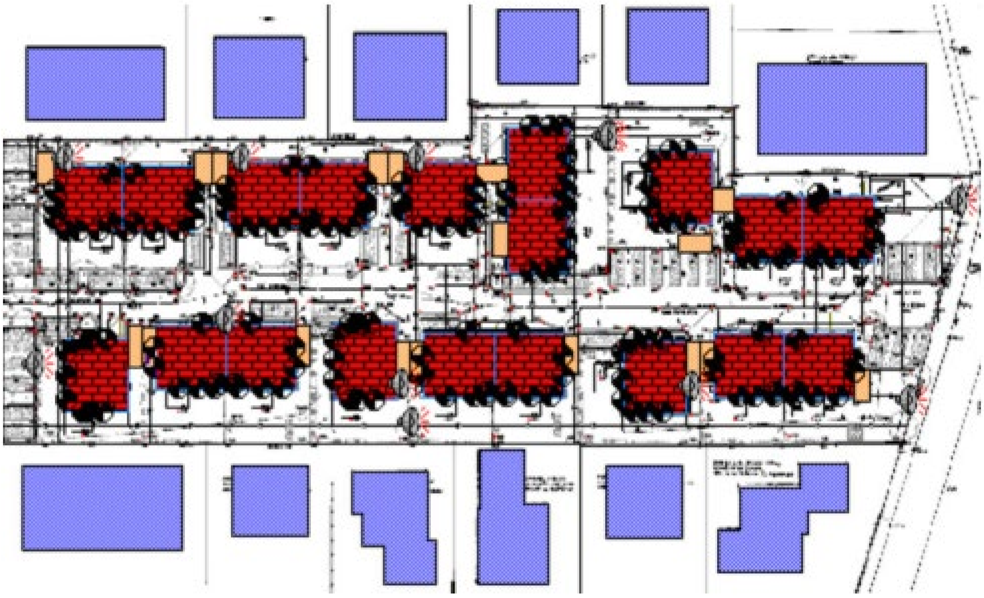


Figure 5-7: Placement of heat pumps in scenario B, variant 2B

In variant 3B, some of the heat pumps are placed in the corner of the owner's property that is enclosed by the equipment room and a house wall. The placement locations are shown in Figure 5-8.

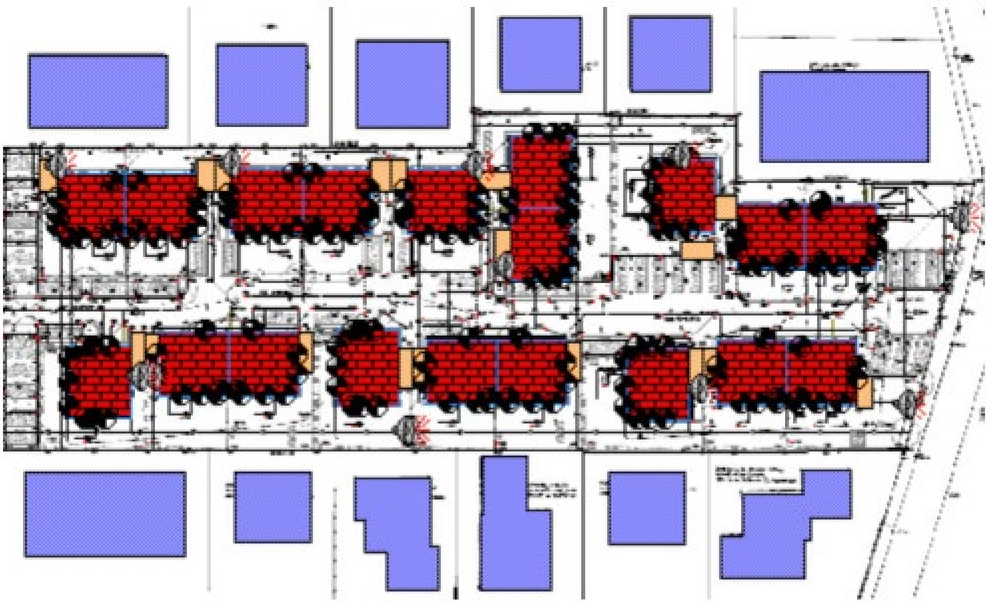


Figure 5-8: Placement of heat pumps in scenario B, variant 3B

Variant 3B has the fewest penalty points and is therefore the best tested variant of scenario B.

5.3.5 Scenario C: Local Heating Supply

In scenario C, a local heating supply is simulated. The whole settlement is supplied with heat by a central heat pump system. This is placed in the garden that is best suited for this purpose in terms of sound insulation.

The required heat pump capacity is calculated by adding the maximum connected load, the heat losses in the main pipe and the heat losses in the supply pipes (Kager, 2016).

Maximum Delivery Rate

Since not all households use heat output at the same time, the total output required is reduced. For this reason, the central heat pump system is dimensioned taking a simultaneity factor into account ("Gl stands for Gleichzeitigkeit, which means "simultaneity" in English).

If the consumers are similar to those in the terraced housing estate, eq. (1) applies (BKW, 2012). The variable n stands for the number of consumers and the variables a, b, c and d are empirically determined factors.

$$F_{Gl} = a + \frac{b}{1+\left(\frac{n}{c}\right)^{d}} \tag{1}$$

$$a = 0{,}4497 \qquad b = 0{,}5512$$
$$c = 53{,}8438 \qquad d = 1{,}7627$$

$$F_{Gl} = 0{,}4497 + \frac{0{,}5512}{1+\left(\frac{19}{53{,}8438}\right)^{1{,}7627}} = 0{,}925$$

The calculation results in a diversity factor of 0.925. In order to determine the maximum connected load, the nominal connected load, which is the sum of the total heating load and the total capacity for domestic hot water preparation of all buildings together, is multiplied by the diversity factor. Eq. (2) shows the calculation procedure ("nenn" means "nomimal" in English).

$$\dot{Q}_{nenn} * F_{Gl} = \dot{Q}_{max} \tag{2}$$

$$91\ 202\ W * 0{,}925 = 84\ 372\ W$$

The maximum connected load is 84372 W.

Heat Loss in the Pipes

Assuming that the main pipe extends from the westernmost to the easternmost row house and the heat pump system is placed in the eastern part of the housing estate, the pipe has a single length of about 126 m. It is designed as a steel pipe with a diameter of DN40 and insulated with a 4 cm thick layer of rigid polyurethane foam. The supply and return pipes have a pipe distance of 0.2 m from each other and are located in 0.5 m deep soil. A heat flow of 1380 W is lost via the main pipe, which is 252 m long in total (Kager, 2016). Since the heat pumps in the following installation site variants are not always placed in such a way that the main pipe is 252 m long in total, but this length is roughly maintained, the heat loss hardly changes and can always be assumed to be 1380 W.

Every residential building has a heat transfer station in the form of a heat exchanger. Approximately 6 m long supply lines connect the latter with the distribution nodes of the main line. In total, the supply lines, which are designed as steel pipes with a diameter of DN8, are approximately 60 m long. They are insulated in the same way as the main pipes. Nevertheless, there is an absolute heat loss of 667 W via the supply lines of the pipeline network (Kager, 2016).

Heat Pump Selection

Eq. (4) is used to determine the required heat pump output.

$$required\ output = maximum\ connected\ load + heat\ losses\ from\ pipes \quad (4)$$

$$required\ output = 84\,372\ W + 1\,380\ W + 667\ W = 86\,418\ W$$

The heat pump must cover an output of 86418 W. Two pieces of the air-to-water heat pump LA 60-TU (Dimplex, 2016c) are selected, which is designed for outdoor installation. The maximum heat output of this model is 50 kW with an air temperature of 2 °C at operating point A2/W35. However, since a flow temperature of 55 °C is essential for DHW heating, the operating point A2/W55 is selected, which guarantees an output of 46.07 kW. The compact unit from Dimplex has a COP of 2.56 and a sound power level of 74 dB(A). In reduced operation mode, 71 dB(A) are emitted.

Placement

In variant 1C, the two units that supply the entire terraced house settlement are placed in the corner of the settlement that is most north-east. Figure 5-9 shows that the two heat pumps are located directly next to each other.

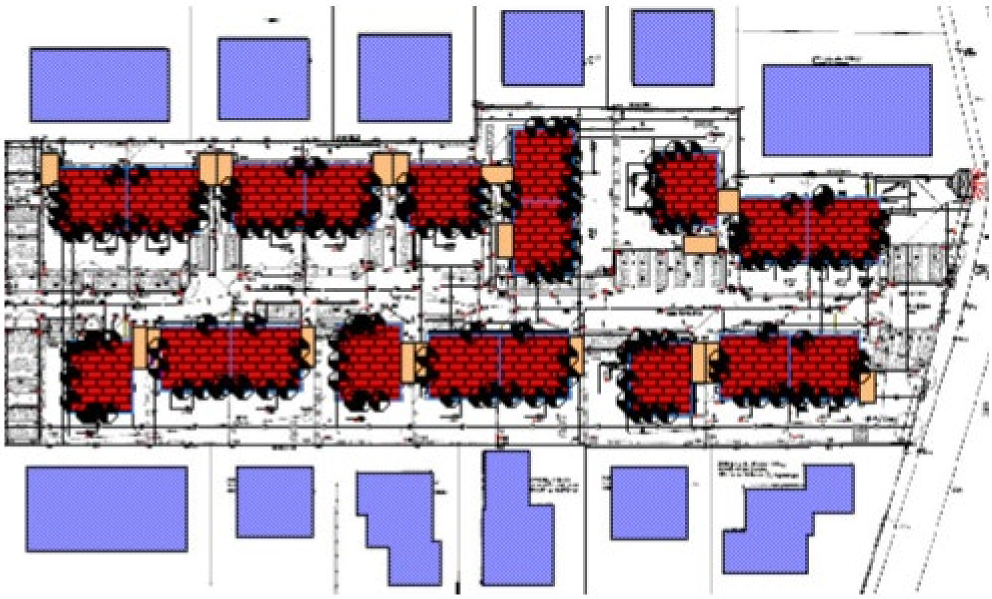


Figure 5-9: Placement of heat pumps Scenario C, variant 1C

The placement of the two heat pumps in variant 2C is similar to that in variant 1C. The difference is that the units are located at a greater distance from the northern boundary of the site. Figure 5-10 shows the installation location.

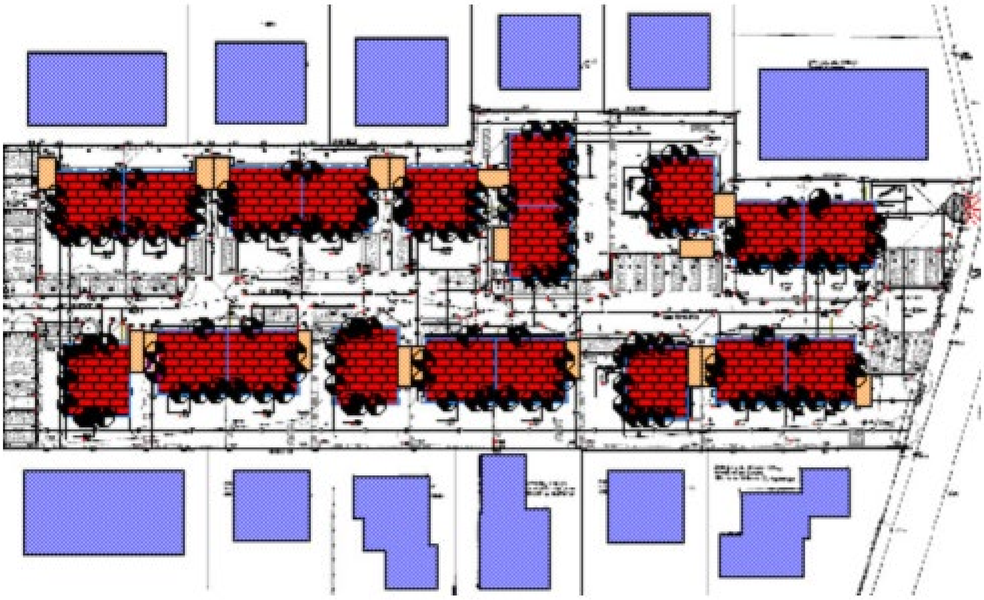


Figure 5-10: Placement of heat pumps in scenario C, variant 2C 3B

In variant 3C, the heat pumps are not installed next to each other, but at a greater distance from each other than in the two previous variants. This can be seen in Figure 5-11. One of the two pumps is located in the corner enclosed by the equipment room and the wall of the 8th house. The second heat pump is located on the wall of the equipment room of the 11th household.

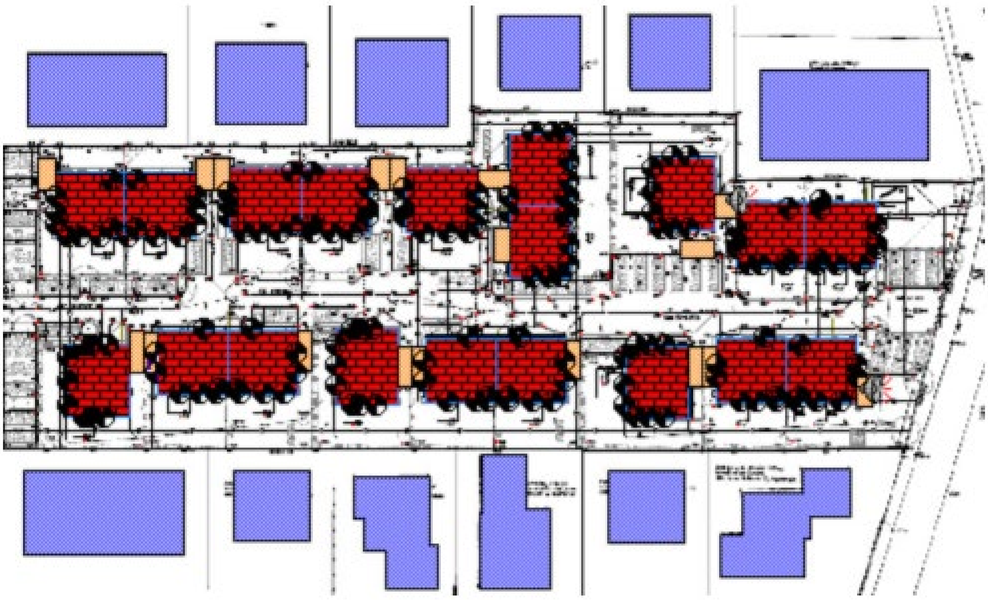


Figure 5-11: Placement of heat pumps in scenario C, variant 3C

5.3.6 Comparison of the Options

Each of the simulated variants receives penalty points and is therefore not permitted if the defined noise limits are enforced. The following Figure 5-12 shows by how many decibels the maximum permissible sound pressure levels are exceeded at the places of immission. One penalty point is awarded for each decibel that exceeds the permitted value. The variants are marked in the diagram with their abbreviations. The letters T and N indicate whether the values are daytime or nighttime values. For each point of immission, a short horizontal line in a specific colour is drawn for each variant. The colouring makes it clear how many penalty points are assigned to each variant at each point of immission. Values greater than or equal to 15 are assigned to the colour yellow.

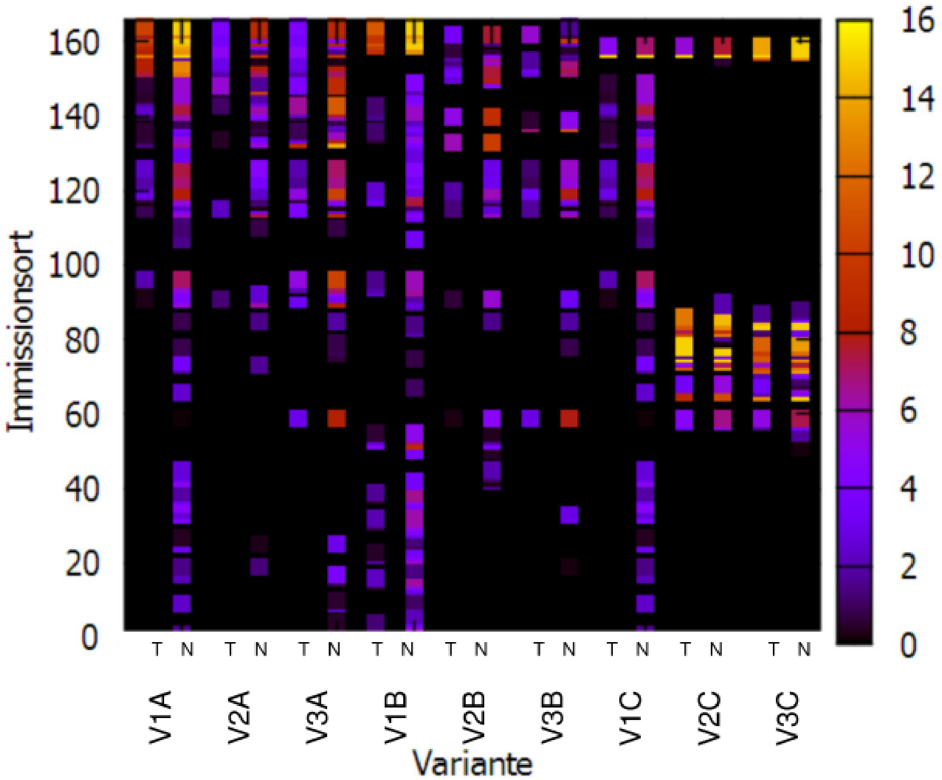


Figure 5-12: Penalty points at the points of immission ("Immissionsort") for different variants and scenarios

Table 5-4 shows how many penalty points each of the variants, which differ in number and location of the heat pumps, receives. First of all, the penalty points are added up, which are awarded on the basis of the exceedances at the critical immission locations. A distinction is made between day and night, as some of the heat pump models used are operated at night in lowered mode, which results in a lower sound power level. The figures in bold in the table indicate the sum of the penalty points for the periods day and night. The list also contains the maximum and minimum number of penalty points that are awarded for exceeding the limit values at a single critical point of immission. The evaluation of the minimum value is such that only penalty point values that are greater than zero are taken into account. When determining the average number of penalty points, only those penalty point values that are greater than zero are also taken into account. The minimum value of each parameter is highlighted in green, while maximum values are highlighted in red.

Table 5-4: Distribution of penalty points to the nine variants (green shows the best value in a row, red the worst number in a row)

Scenario A	Variant 1A	Variant 2A	Variant 3A

	Day	Night	Day	Night	Day	Night
Sum penalty points	119,71	346,64	33,41	153,08	76,46	239,72
Sum penalty points	**466,35**		**186,49**		**316,18**	
Max. penalty points	12,56	17,56	5,52	10,52	8,93	13,93
Min. penalty points	0,13	0,06	0,37	0,18	0,01	0,15
Mean penalty points	4,13	5,59	2,78	3,93	3,19	4,99
Scenario B	Variant 1B		Variant 2B		Variant 3B	
	Day	Night	Day	Night	Day	Night
Sum penalty points	98,73	341,81	36,89	133,71	30,59	108,86
Sum penalty points	**440,54**		**170,60**		**139,44**	
Max. penalty points	11,32	16,30	5,95	9,95	6,78	11,23
Min. penalty points	0,29	0,40	0,17	0,11	0,53	0,15
Mean penalty points	3,40	4,81	2,46	4,05	2,78	4,19
Scenario C	Variant 1C		Variant 2C		Variant 3C	
	Day	Night	Day	Night	Day	Night
Sum penalty points	57,28	230,82	160,62	198,64	167,65	215,25
Sum penalty points	**288,10**		**359,26**		**382,90**	
Max. penalty points	31,87	33,87	22,44	24,44	22,13	24,13
Min. penalty points	0,13	0,06	1,82	0,04	1,07	0,12
Mean penalty points	2,86	4,44	10,04	9,03	8,38	7,97

Due to its low number of penalty points, variant 3B of scenario B scores best when the presented rating system is used as a basis. The reason for the good performance of scenario B is the optimal ratio between the number and sound power level of the heat pumps. Fewer heat pumps are used than in scenario A, which means fewer noise sources in the settlement. In addition, the sound power level of the individual devices is lower than that of the model used when a local heating supply with only two heat pumps is set up for the entire settlement.

5.4 Simulation of maximum Sound Propagation when using Noise Barriers

Since the 3rd variant of scenario B has achieved the fewest penalty points, it is further optimized by building noise barriers around the heat pumps. Figure 5-13 shows such a cladding in a three-dimensional view.

Figure 5-13: Noise protection cladding of a heat pump in variant 3B

This protective device can be found above every heat pump. It is 1.70 m high, 1 m long and 1 m wide. As the dimensions of the heat pumps are only slightly smaller, the attached walls are space-saving. Two opposite sides must remain free to allow air to be sucked in and blown out. In this simulation, the openings are oriented either north and south or east and west. Depending on the position of the pump, the direction of the opening that is better suited in terms of sound insulation is chosen. A minimum distance of 3 m is maintained between the discharge area and the house walls to prevent premature ice formation. This would occur because the air blown out is colder than the ambient air.

The results of the simulation of variant 3B with noise barriers are shown in Figure 5-15. It is shown how high the overshoots or undershoots are when the defined maximum sound pressure levels are used as a guide value. In order to illustrate the comparison with the variant without noise barriers, it is also shown in the diagram. The designations "with" ("mit") and "without" ("ohne"), which are attached to the abbreviation of the variants in the diagram, indicate whether the test results show the case with or without the use of noise barriers. In case of 16 penalty points and more, the marking is in yellow.

The local heating supply scenario has the advantage that the sound is emitted by only two heat pumps instead of 13. Moreover, in the best variant of scenario C both heat pumps are placed next to each other. This means that there is practically one central sound source. The sound power level of this is higher than that of the model of the 13 heat pumps of variant 3B. However, since the sound emanates from a central point, it is obvious to surround this with noise barriers in order to achieve the lowest sound pressure levels at the critical immission points. Three barrier layers are built around the heat pumps from variant 1C, which can be seen in Figure 5-14. The outermost layer is the highest at 7.75 m. When erecting the walls, care is taken to ensure that the air blown out on one side of the heat pumps is not drawn in on the other side.

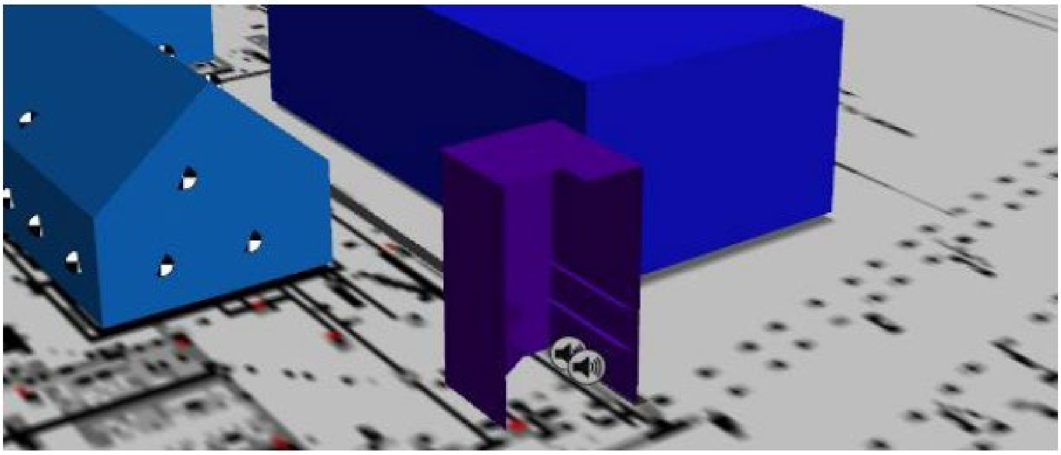


Figure 5-14: Noise protection cladding of heat pumps in variant 1C

The following diagram (Figure 5-15) shows that after the construction of noise barriers in variant 1C, penalty points are only awarded at a critical immission point.

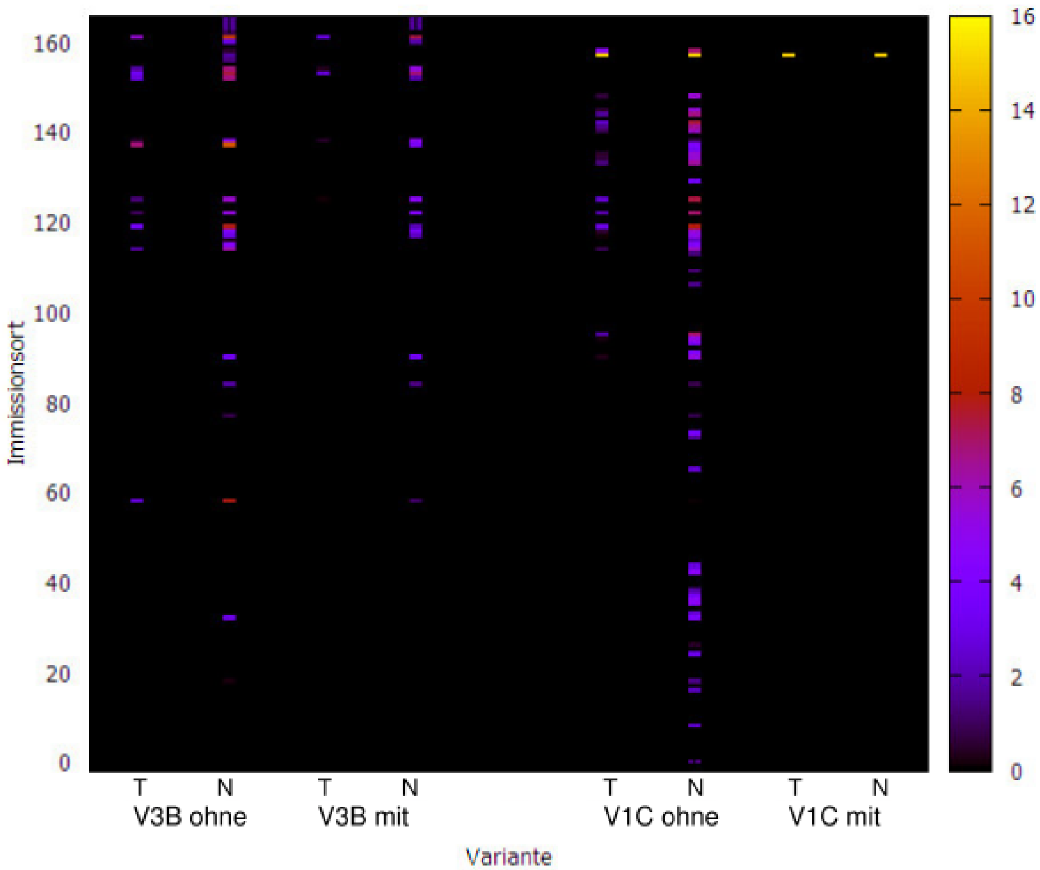


Figure 5-15: Penalty points at the places of immission for two variants with ("mit") and without ("ohne") noise barriers

Table 5-5 shows the sum, maximum, minimum and average value of the penalty points awarded for the variants with noise barriers. For comparison, the values of the previous chapter are given again.

Table 5-5: Distribution of penalty points on two variants with noise barriers

Variant 3B	with noise barriers		without noise barriers	
	Day	Night	Day	Night
Sum penalty points	30.59	108.86	6.66	55.37
Sum penalty points	**139.44**		**62.03**	
Max. penalty points	6.78	11.23	3.10	7.30
Min. penalty points	0.53	0.15	0.08	1.10
Mean penalty points	2.78	4.19	1.33	3.46
Variant 1C	**with noise barriers**		**without noise barriers**	
	Day	Night	Day	Night
Sum penalty points	57.28	230.82	23.03	25.03
Sum penalty points	**288.10**		**48.06**	
Max. penalty points	31.87	33.87	23.03	25.03
Min. penalty points	0.13	0.06	23.03	25.03
Mean penalty points	2.86	4.44	23.03	25.03

The use of barriers also leads to impermissible exceeding of the sound pressure level. To ensure that the defined limits are complied with, the heat pump model in variant 1C may emit a maximum of 50.97 dB(A) during the day and 45.97 dB(A) at night. For the model used to heat the individual houses in variant 2B, these maximum values are 49.9 dB(A) during the day and 45.7 dB(A) at night. For the model which, in the same variant, is used to heat the semi-detached houses, these maximum values are 50.9 dB(A) during the day and 45.7 dB(A) at night. This is the result of a simulation in IMMI, in which the sound power levels of the heat pump models are changed so that the defined maximum permissible sound pressure levels are maintained at all critical immission points.

5.5 Time dependent Sound Propagation

So far, this work assumes the highest possible sound propagation. This means that all heat pumps are in continuous operation both during the day and at night. Here it turns out that the devices in the 3rd variant of scenario B are placed in the best acoustic position, if the use of noise barriers is omitted. For the simulation of the time-dependent sound propagation over one day, this installation location variant is therefore used. The variant without noise barriers is chosen as an example.

In order to show that in reality lower sound pressure levels can occur, exemplary realistic switching profiles are created for the heat pumps. In the following simulation the latter are always in operation when the users need heat. If no energy converted by the heat pump is required at certain times of day, the device is switched off during these times. When a device is switched off, its sound power level is 0 dB(A). Partial load behaviour is not simulated, as no data is available on the sound power level.

Since a winter day is considered when heating is required to achieve a comfortable room temperature, the heat pumps are only switched off when the users are away from home. Since not every user behaves in the same way, four exemplary user profiles are created.

5.5.1 User profiles

In this example, the residents of a semi-detached house show the same user behaviour. During the night, which lasts from 10 pm to 6 am until the following day, all heat pumps are switched on in each user profile, as all users are at home.

In the 1st profile, the heat pump is switched off for three hours at midday, as the users are only in the house at night, in the morning and in the evening. The pump is not switched off for the entire duration of the occupants' absence. This prevents the house from cooling down, which in turn prevents the temperature in the building from rising to the desired level in time due to the limited capacity of the heat pump.

People who behave according to user profile 2 are out of the house in the morning and afternoon. At noon, however, they are at home. Their heat pump is therefore not in operation for one hour in the morning and one hour in the afternoon.

User profile 3 is similar to user profile 2. The residents are also not in the house in the mornings and afternoons. However, they leave earlier in the morning and are present for a shorter time at noon. The heat pump is not in operation for 3 hours in the morning and one hour in the afternoon.

The 4th profile is similar to the 1st profile, but people who exhibit this user behaviour do not come home until later at the end of the day. The heat pump is therefore switched off for 5 hours during the day.

The four described user profiles are distributed evenly among the residents of the terraced housing estate. Figure 5-16 shows a diagram on which the sound power level of each heat pump is plotted for each hour of the day for an exemplary winter day. Since semi-detached houses have a common heat pump, there are a total of 13 such units in the estate. The LA 9S-TU model, which is used to heat the individual houses, emits 53 dB(A) both during the day and at night. The semi-detached houses are heated by the LA 18S-TU model, which emits 54 dB(A) during the day and 53 dB(A) at night.

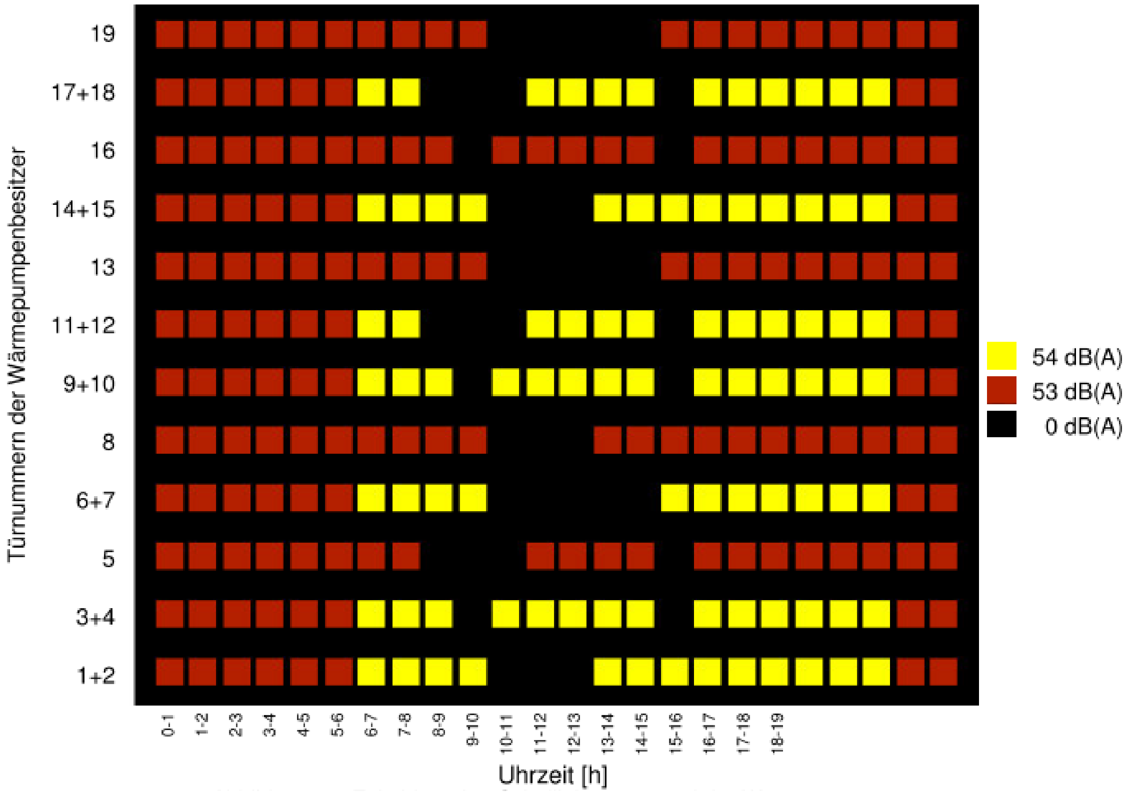


Figure 5-16: Time dependent sound power level of heat pumps (the x-axis shows time of day, y-axis the different door numbers of the considered houses)

5.5.2 Simulations

The following Figure 5-17 shows by how many decibels the value occurring at the places of immission is higher than the maximum acceptable sound pressure level for each hour of the day. In comparison with the time-independent sound propagation of variant 3B, lower sound pressure levels are achieved in the present simulation during the day at certain hours. Hereby it is shown that in real working conditions it is likely that lower sound pressure levels are achieved than the previous simulations in this thesis have shown so far.

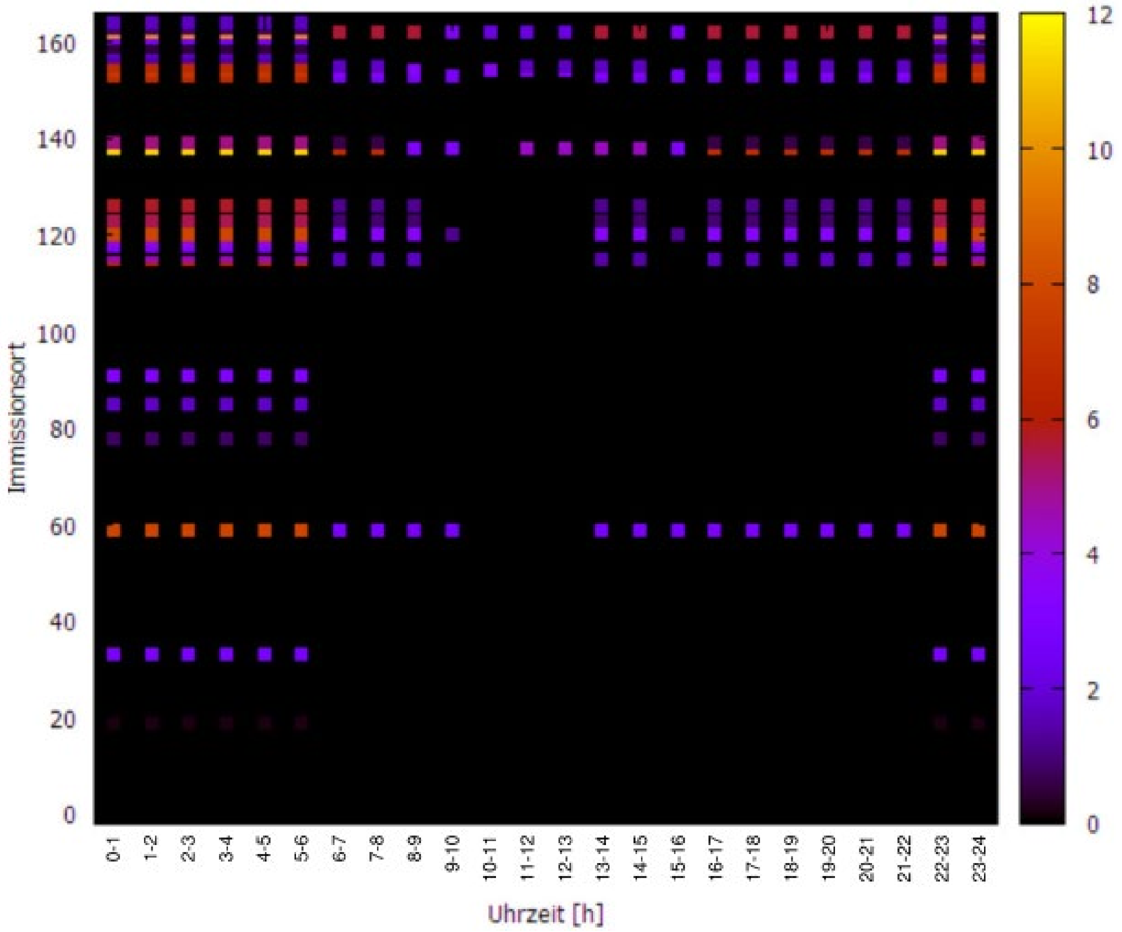


Figure 5-17: Penalty points at the points of immission during the day for variant 3B

5.6 Alternative Simulation Software

Since the software IMMI for companies and private users can only be obtained for a fee and the price of the entry level version "Standard" is about 4900 € once (in the year 2016), a free alternative program is being searched for, with which sound field simulations of the same kind as those carried out in this bachelor thesis are possible. For this reason, the open source program OpenPSTD will be evaluated.

5.6.1 OpenPSTD

It turns out that OpenPSTD, which was developed within the framework of an EU project, is designed exclusively for the prediction of two-dimensional sound propagation. Since IMMI calculates on a three-dimensional basis, no meaningful comparison of the two programs is possible with regard to the sound pressure levels to be determined in the terraced housing estate. After consultation, the developers of the software recommend the sound prediction program Olive Tree Lab (2016). For this reason, we refrain from simulating with OpenPSTD.

5.6.2 Olive Tree Lab

Olive Tree Lab is a Cypriot sound prediction program in English language, available for 195 € per user and month (in the year 2016). For 6000 € the program can be used for an unlimited period of time.

The simulations performed with IMMI in this bachelor thesis are also possible with Olive Tree Lab. As in the IMMI software, ÖNORM ISO 9613-2:2018 is applied. Figure 5-18 gives an insight into the program and shows the terraced houses, the neighbouring buildings and the building dummies in a simplified three-dimensional view. The heat pumps with their installation locations from variant 3B can also be seen. The project deals with sound propagation outdoors. However, the Olive Tree Lab program can also be used to test concepts that include sound distribution in an interior space.

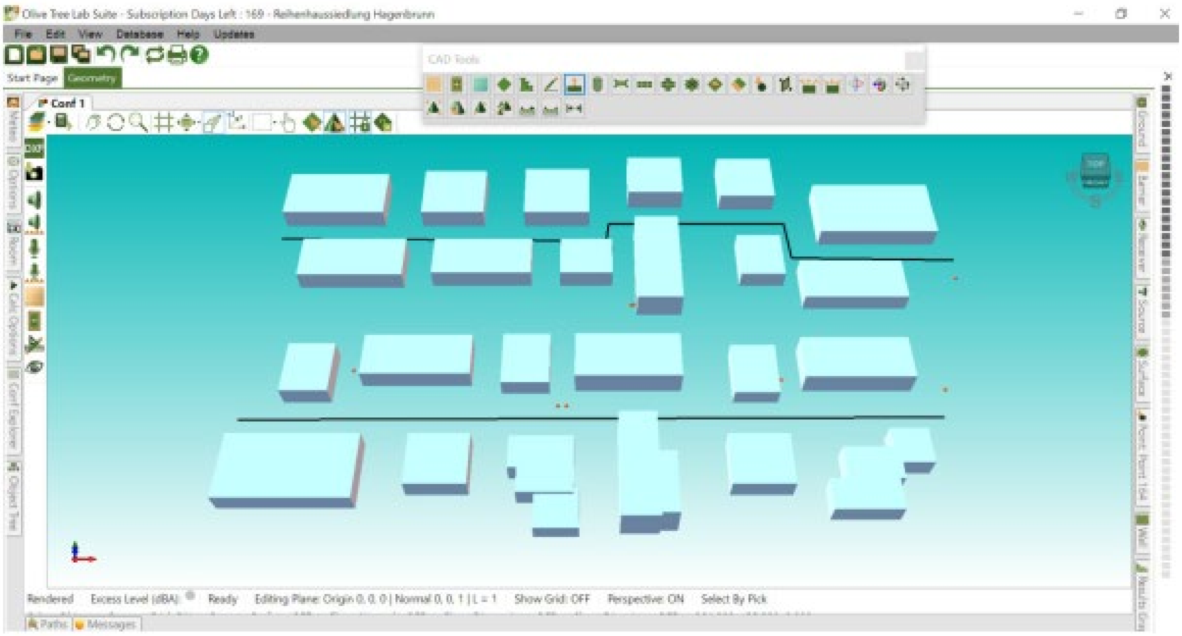


Figure 5-18: User interface of the program Olive Tree Lab with a simplified terraced house settlement

It is possible to create both sound sources and sound receivers, which are executed as a point or line, as well as buildings and noise barriers. The sound pressure level is determined at the immission points.

In Olive Tree Lab you can choose between predefined types of sound sources when creating a sound source. As shown in Figure 5-19 on the left, the sound pressure levels associated with the selected sound source are displayed as a function of frequency. The information is given in both dB and dB(A). The simulations in IMMI have been performed with sound sources with equally distributed frequency. A section of the details of such a sound source is shown in Figure 5-19 on the right.

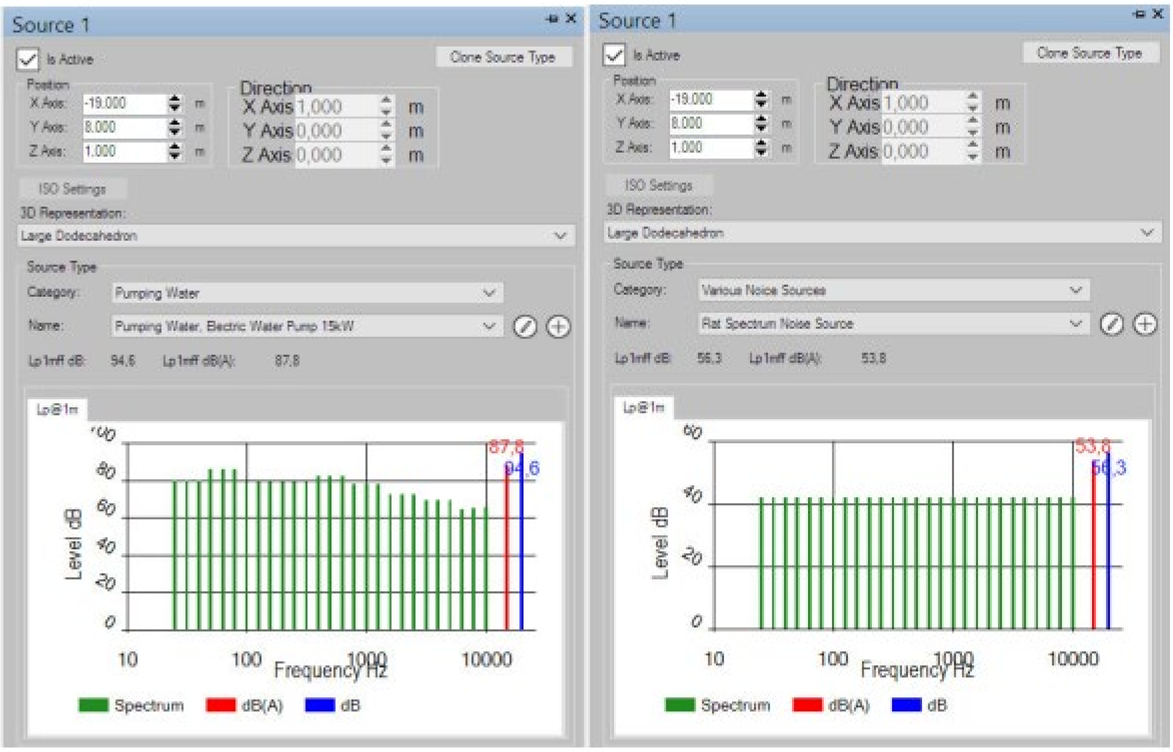


Figure 5-19: Input mask of an exemplary sound source (left: frequency-dependent sound source, right: frequency-independent sound source) (Olive Tree Lab, 2016)

When selecting the material, the sound characteristic impedance and the absorption coefficient at different frequencies are shown in a diagram. In addition, the temperature, humidity and pressure can be adjusted.

When entering noise barriers, the material properties are taken into account. As when creating a sound source, the sound characteristic impedance and the absorption coefficient depending on the height of the frequency are demonstrated. By defining layers of the barrier, further frequency curves are generated, again showing the sound characteristic impedance and the absorption coefficient. Figure 5-20 shows the input mask of a noise barrier. In this view the height of the absorption coefficient can be viewed.

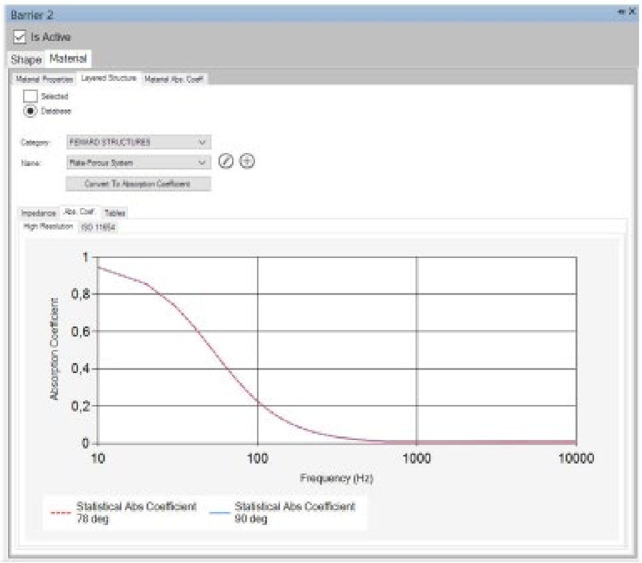


Figure 5-20: Input mask for a noise barrier (Olive Tree Lab, 2016)

The same options for the construction of walls are available as those for the construction of noise barriers. There are similar options when defining surfaces. Also the input mask of a floor is approximately the same. The soil type, material properties and soil structure are selected.

For the calculations in Olive Tree Lab several parameters can be set, some of which are visible in Figure 5-21.

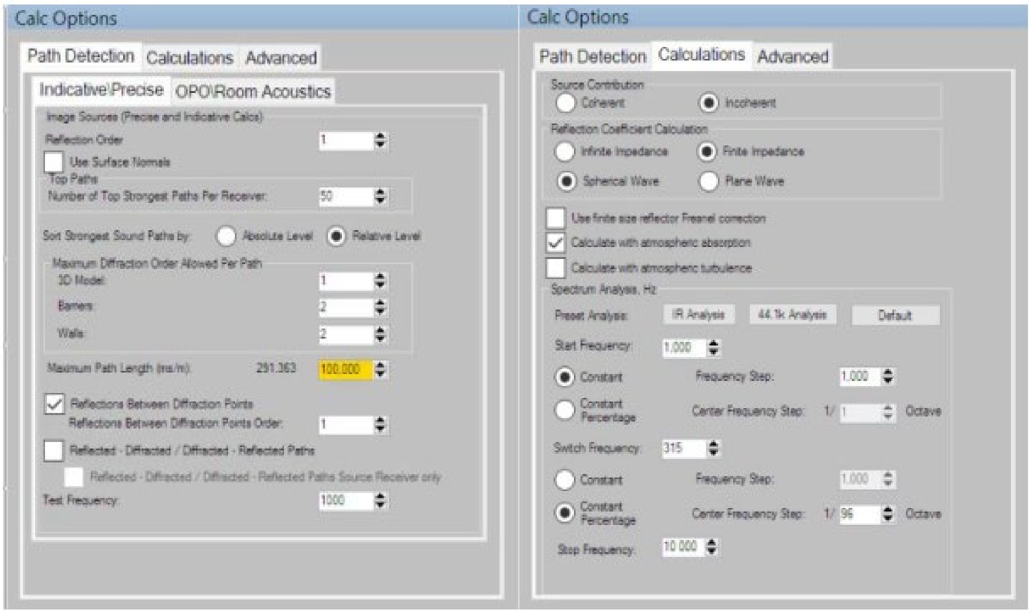


Figure 5-21: Calculation options (Olive Tree Lab, 2016)

5.7 Interpretation

Figure 5-22 shows how sound rays propagate. This example shows which sound sources influence the immission point at the window of the children's room 1 of the first household. The immission point is shown as a light green filled circle. Grey rays indicate direct sound, while turquoise rays stand for reflections. It is clear that reflection plays a major role in sound propagation.

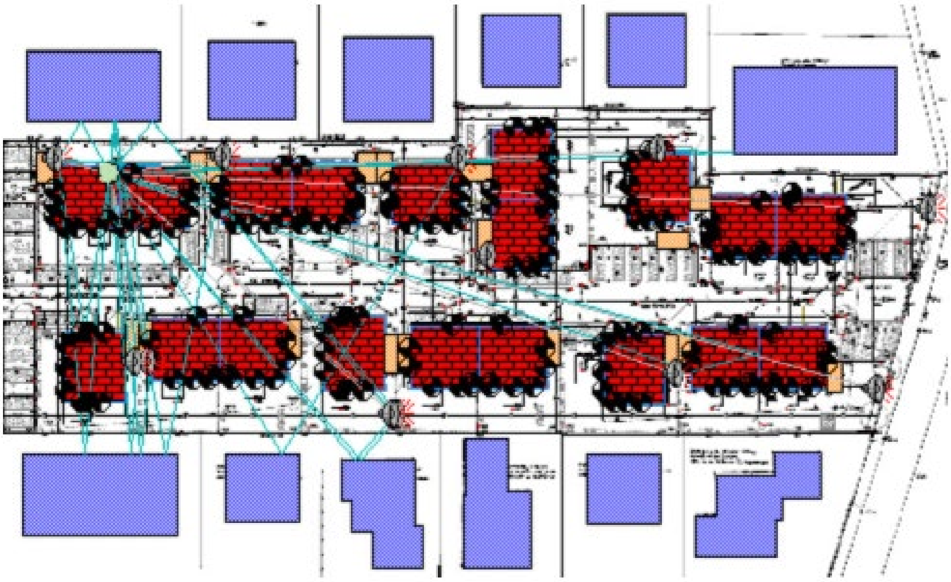


Figure 5-22: Influence of sound radiation on an immission point

In all simulations carried out, the most unfavourable case is assumed with regard to sound propagation. The largest possible number of neighbouring buildings with the largest possible dimensions is used. These reflect the sound and contribute to an increase of the sound pressure level at the critical immission points. It is possible, however, that there will be no, fewer or smaller buildings on neighbouring plots of land in the future. This would improve the sound situation.

The sound field is also optimized by using noise barriers. The use of these makes sense, since the sound pressure level is thereby greatly reduced. Although in the simulations of maximum sound propagation a variant of the scenario with one heat pump per house achieved the best results, it is more advantageous to favour a local heating supply using only two heat pumps if noise barriers are installed. This is because in the latter variant of the heating supply considerably fewer noise barriers have to be installed and fewer penalty points are distributed.

Since, despite this sound-reducing measure, the defined sound pressure levels are exceeded, consideration is being given to reducing the sound power levels of heat pumps. One way to achieve the maximum sound power levels mentioned in chapter 6 is an innovative technical improvement of the models. Care must be taken to ensure that the heat output of the heat pumps is not affected.

When considering the time course of sound propagation, it becomes clear that the sound pressure level is reduced at some hours of the day, which is an improvement.

5.8 Summary

In order to determine how the heating of the described terraced house settlement can be carried out exclusively by air-to-water heat pumps if the defined sound pressure levels are to be maintained, the following procedure is followed. Different scenarios are created, which differ in the number of households that are heated per heat pump. Depending on the power required, different models are used in the scenarios, whose sound power level in this case increases with their heat output. Since all pumps are installed outside, the sound is distributed outside. Defined sound pressure levels must not be exceeded at the windows of rooms in the houses that require protection and along the boundary of the property that separates the terraced house settlement from neighbouring properties. The sound field simulations are carried out with the sound prognosis program IMMI.

Despite variations in the installation locations of the heat pumps, the maximum permissible sound pressure levels are not guaranteed everywhere in any scenario. Therefore, the situation is optimised by means of noise barriers which are erected around the pumps. Although this measure leads to improvements, it also does not lead to an approved variant. The latter can be achieved by making technical modifications to the heat pumps that reduce the sound power level.

As it is not realistic to expect that all heat pumps will be in continuous operation, switching profiles are created for a single day. These profiles record at which times of the day which heat pumps are running and which are switched off. Taking these assumptions into account, sound pressure levels for certain hours of the day are lower than in the previous simulations.

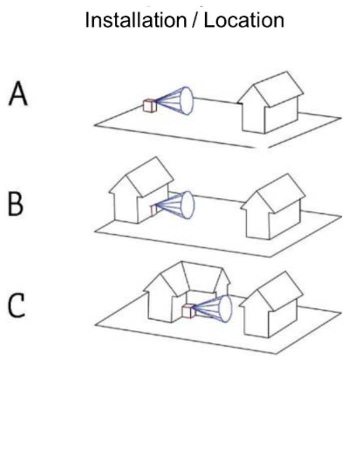
The proposed alternative program OpenPSTD, which is available free of charge, is designed exclusively for two-dimensional simulations. Therefore, no meaningful comparison with IMMI is possible. When investigating the sound prediction program Olive Tree Lab, it turns out that it is suitable for work of this kind and can be used as an alternative if required.

6 Analysis of unit placement, indoor & outdoor sound propagation

Based on experience, available air-water heat pumps on the market have a sound pressure level $L_{W,A}$ of around 56 dB(A) (Kopatsch and Doppler, 2014). The value of the appropriate air-water heat pump has to be indicated by the supplier.

According to Forum Schall (2013) - a group of experts (appraisers, …) which is supported by the Austrian Federal Environment Agency - the basis level of the local noise immission should be used for the limits of continuous noise sources. Based on experience it can be assumed that the base level in a silent residential area is between 20 to 25 dB(A) during the night (10 p.m. to 6 a.m.). In order to avoid any disturbances due to noise immissions and especially low-frequency noise immissions from air-water heat pumps continuous noises should be below the base level, from a medical point of view (Österreichischer Arbeitsring für Lärmbekämpfung, 2008). For this reason a target value of 25 dB(A) during the night should be achieved. Higher values are only justified if measurements show that the base level is actually significantly higher. Without additional noise protection measures a minimum distance between to air-water heat pump (sound source) and the property line or the closest bedroom window (depending on the legal regulations) is necessary.

Figure 6-1 shows an overview of approximate distances from the heat pump to the neighbourhood to fulfil the target value of 25 dB(A) - at the property line or the closest window of e. g. a sleeping room - depending on the sound power level of the heat pump and the installation / location. Especially in quiet areas, in combination with a perceptible, low-frequency component of the noise of the air-water heat pump, larger distances may be necessary. In case of doubt, the next higher distance value from the table should be used. For areas with a target value of 30 dB(A), the distance value of the previous row in Figure 5-1 may be used (e.g. with $L_{W,A}$ = 60 dB(A) and Location B a distance of 18 m instead of 28 m is necessary). The values shown are only for an estimation and for planning purposes and don't have any legal relevance. The final approval of the installation location has to be done by e.g. the building authority.



Minimum distance to the neighborhood (without noise emission measures)			
Sound power level of the heat pump	Installation / Location		
	A	B	C
$L_{W,A}$ [dB]	Distance in m		
50	7	10	14
55	13	18	24
60	22	28	35
65	32	41	54
70	49	66	88
Calculated values according to ISO 9613-2			

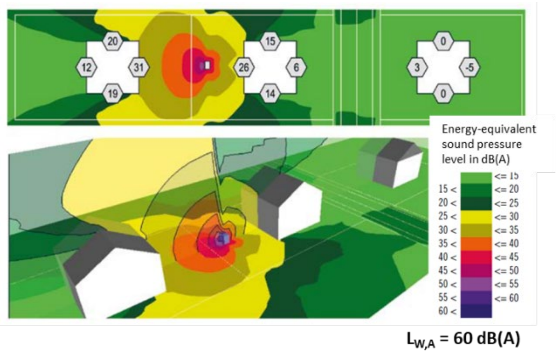
Figure 6-1: Minimum distance to fulfil the 25 dB(A) target value (german version: Forum Schall (2013))

The Austrian Heat Pump Association has carried out a simulation study to show the sound propagation of different installation variants. The study should show the distribution of the sound pressure level by increasing the distance and the effects in the neighbourhood.

Figures 6-2 to 6-8 are showing the sound propagation for typical installation variants of air-water heat pumps. For the simulation a air-water heat pump with a A-rated sound power level ($L_{W,A}$) of 60 dB(A) was used. The examples describe the sound propagation at the owner's property and the nearest neighbour. The distance between the buildings is 20 m and the property line was assumed to be in the middle between the buildings. In principle the sound propagation is dependent on:

- Preferred sound emission directions of the heat pump unit/system
- Shielding by massive obstacles, e. g. buildings, walls, …
- Single or multiple reflections on solid surfaces, e. g. ground, buildings, roofs, …
- Sound absorbing surfaces

Figure 6-2 shows the sound propagation by placing the heat pump with its preferred sound propagation direction towards the neighbour with a distance of 12 m. The sound pressure level at the nearest building is above 30 dB(A). Typically near a city or in high traffic areas the basis level is above 30 dB(A) where an operation of this unit would be conceivable. With a protective wall (e. g. opaque garden wall, noise protection wall with a height of 2 m) at the property line the sound propagation shown in Figure 6-3 arises. With this measure the sound pressure level at the neighbour can be reduced by around 4 dB(A) and could reach the target values. Due to the reflections on the wall the sound pressure level at the owners property is increased by around 3 dB(A).



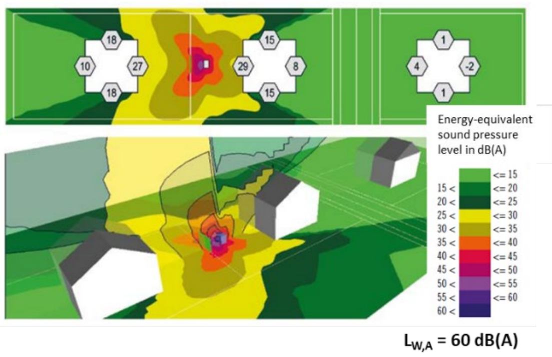
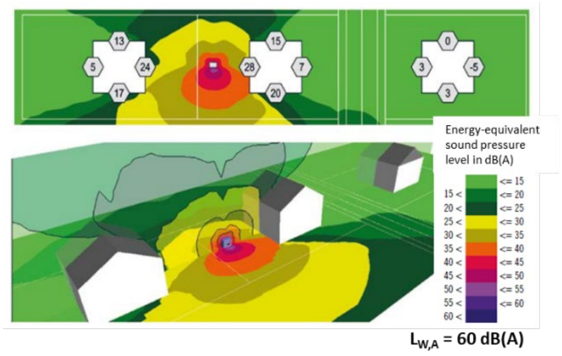


Figure 6-2 (left): Position close to the property line (Kopatsch and Doppler, 2014)

Figure 6-3 (right): Position close to the property line with a protective wall (Kopatsch and Doppler, 2014)

Figure 6-4 shows the sound propagation by turning the heat pump by 90 ° to change the preferred sound emission direction away from the buildings. With this orientation the sound pressure level at the neighbour can be reduced by around 7 dB(A) compared to the position close to the property line (see Figure 6-2) and is less than the usual base level of roughly 25 dB(A). Of course, it has to be ensured, that no other neighbour is affected by the changed sound propagation of the heat pump. It has also be noted, that not every heat pump has a definite sound emission direction. If the directivity of the sound emission of the system is similar to all sides, turning the heat pump has only little or no success. Due to a change of the location close to the owners building the distance to the neighbour can be increased and shielding by the building itself can be achieved. The corresponding sound propagation is shown in Figure 6-5. The immission situation at the neighbour is now uncritically. However, it should be noted, that at the owners building there should not be any worth protecting room (e. g. sleeping room) at the side of the building where the unit is placed.



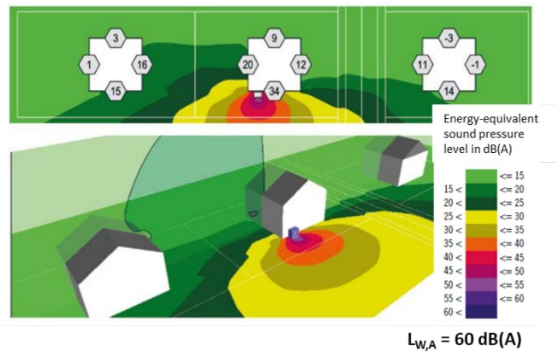
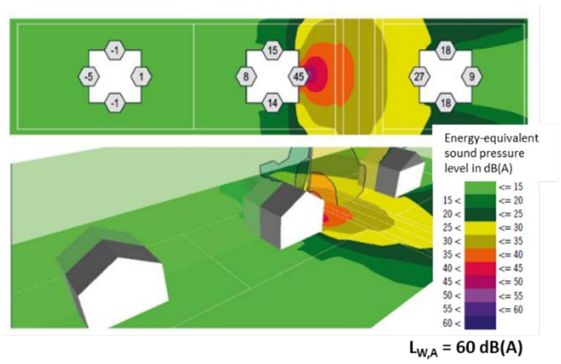


Figure 6-4 (left): Position close to the property line (90° rotated) (Kopatsch and Doppler, 2014)

Figure 6-5 (right): Position close to the building (Kopatsch and Doppler, 2014)

Figure 6-6 shows the sound propagation if the preferred sound emission direction is changed towards the street. With this orientation the sound immission on the property of the right neighbour is increased. If there are no worth protecting rooms (e. g. sleeping rooms) - usually these rooms are away from the street - at the owners and neighbours buildings, this arrangement can be a solution for many cases.

If the distance to the neighbour has to be increased to reduce the sound immission on the neighbours property, an installation on the roof is a possibility. Figure 6-7 shows the corresponding sound propagation. The main advantages are the larger distances to the neighbours and that the sound propagates upwards. But the sound pressure level at the neighbour is still above 25 dB(A) and it is also too high at the owners building façade (neglecting the structure born sound immissions). A protective / sound absorbing wall or a rotation of the heat pump can help to reach the target value.



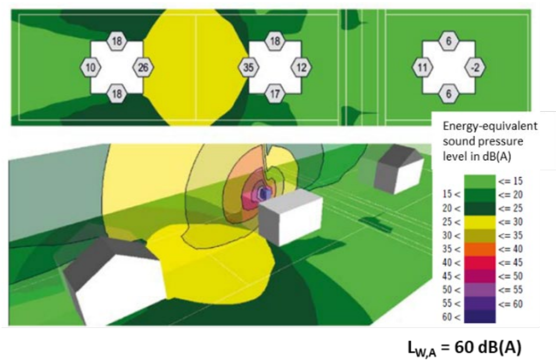


Figure 6-6 (left): Orientation towards the street (Kopatsch and Doppler, 2014)

Figure 6-7 (right): Installation on the roof (Kopatsch and Doppler, 2014)

Figure 6-8 shows the sound propagation for the installation in a duct. This arrangement is basically suitable to limit the immission on the neighbours properties because the sound is directed upwards instead of sideways. By using silencers or sound absorbing materials in the ventilation tunnel, the sound emission can be further limited. It has to be noted that the sound immission at the owners property and building is quite high. There should be no worth protecting room (e. g. sleeping rooms) on the side of the ventilation tunnel or close to the duct.

In practical applications the size of the area with a sound pressure level below 25 dB(A) in the neighbourhood is sufficient.

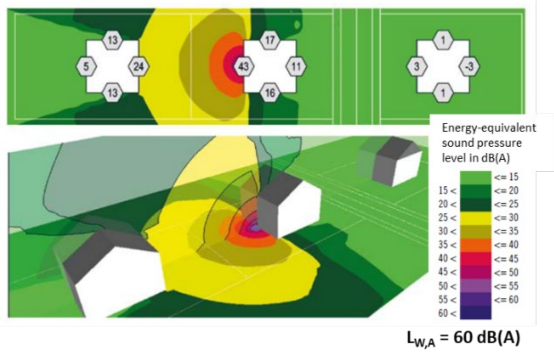


Figure 6-8: Installation in a duct (Kopatsch and Doppler, 2014)

Table 6-1 gives an overview of the expected sound pressure levels at the own property and the neighbourhood dependent on the position of the heat pump. The values shown in Table 6-1 are A-rated values, even though it is not stated.

Table 6-1: Sound pressure level dependent on the heat pump position (LW,A = 60 dB) (german version: Kopatsch and Doppler, 2014)

No.	Desrcription	Sound level in the neighborhood	Sound level at own building	
			Off the HP	Close to the HP
1	Position close to the property line	~ 30 dB	< 20 dB	> 25 dB
2	Position close to the property line with a protective wall	> 25 dB	< 20 dB	> 25 dB
3	Position close to the property line (90° rotated)	< 25 dB	< 25 dB	> 25 dB
4	Position close to the building	< 20 dB	< 25 dB	> 30 dB**
5	Towards the street	> 25 dB	< 20 dB	> 40 dB**
6	Rooftop installation	> 25 dB	< 20 dB	> 30 dB**
7	Tunnel installation	< 25 dB	< 20 dB	> 40 dB**

(light green) Operation should be possible in most of the cases

(light blue) For quite regions an optimization of the emission and / or the position could be necessary

(brown) A critical exceedance of the limits can not be corrected with simple measures. The chosen installation type should be reworked.

** The facades should not have any living or sleeping room

7 Potential of sound absorption at nearby surfaces

If the noise immission limits at the neighbours property or building can not be observed under the given circumstances noise protection measures can be realised to meet the target values. There are different possible measures. The most effective measure is to use a heat pump that is as quite as possible and an appropriate location. The optimum location of the heat pump for systems installed outside and the location of the ventilation tunnels for systems installed inside must be considered as early as possible. Table 7-1 gives an overview of different noise protection measures and an estimation of possible effects.

Table 7-1: Noise protection measures (german version: Kopatsch and Doppler (2014), Cercle Bruit (2012))

Measures		Effects
Precautionary Measures	Location	till -25 dB
	Low-noise heat pump	till -10 dB
Technical Measures (indoor installation)	Light tunnel	-3 to -6 dB
	Sound absorbing materials in tunnel	-3 to -6 dB
	Silencer in ventilation tunnel	-3 to -15 dB
	Silencer in weather protection grille	0 to -3 dB
	Splitter attenuator in the light tunnel	-3 to -15 dB
	Anti-noise wall in front of light tunnel	till -8 dB
Technical Measures (outdoor installation)	Sound jacket	till -8 dB
	Ducts	-2 to -6 dB
	Anti-noise wall	till -8 dB
Operational Measures	Reduction of the rotation speed	-2 to -6 dB
	Quiet mode (during night-time)	-2 to -6 dB
Measures for structure-borne sound	Structure-borne sound insulation of **the compressor**	no value available
	Structure-borne sound insulation of **the fan**	no value available
	Structure-borne sound insulation of **the pipes**	no value available

8 Common “unclever” decisions in heat pump placement

In this section some notable “unclever” situations during heat pump placement are listed and discussed.

8.1 Wrong location chosen

A common mistake is to place the air water heat pump in the "last corner". This means that the unit is installed in a place where there is hardly any air movement or sunshine, e.g. in the shadow (north), in grooves or under balconies. This means that the air source heat pump cannot work under optimal operating conditions, the evaporator freezes more often, which increases the number of defrosting operations. This leads to a significant increase in noise emissions and a reduction in efficiency, which in turn leads to high operating costs. Figure 8-1 shows the sound pressure level in a distance of 2 m for one icing – de-icing cycle. During icing there is a slight increase of the sound pressure level. As soon as the defrosting process starts a sudden increase of the sound pressure level of about 22 dB occurs. After the defrosting process is finished the sound pressure level is at its initial value. It is obvious that it is more annoying for the neighbours if this process takes place more often.

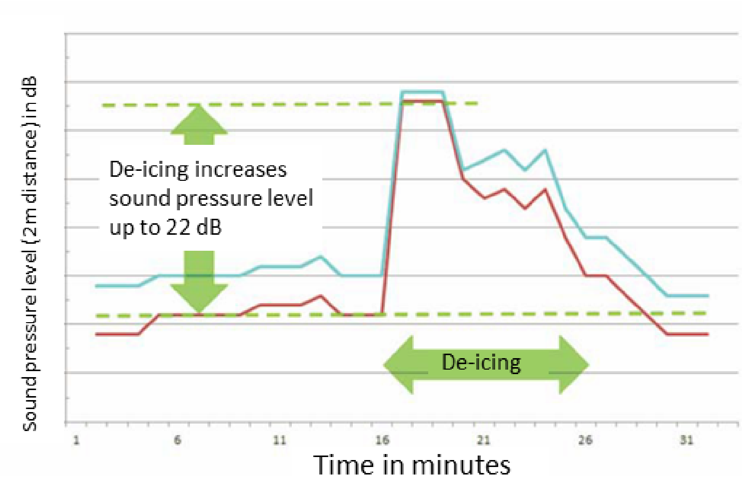


Figure 8-1: Example of the sound pressure level during icing and de icing (german version: Kopatsch, and Doppler, 2014)

8.2 Installation on the roof

In order to increase the distance to the neighbouring property and thus to decrease sound immission over the distance, air water heat pumps are also mounted on the roofs. However, this can lead to unexpected reflections of the sound emission in combination with a photovoltaic system. If the air water heat pump is installed in front of the elements of the photovoltaic system (see “Heat Pump Installation Variant 1” in figure 8-2). The surface of the photovoltaic systems elements, which are usually tilted, reflects the sound into the surroundings and sometimes causes undesired sound immissions in the neighbourhood. It would be better to place the heat pump below the elements of the photovoltaic system (see “Heat Pump Installation Variant 2” in figure 8-2), which has a damping effect due to the reflections towards the roof of the house.

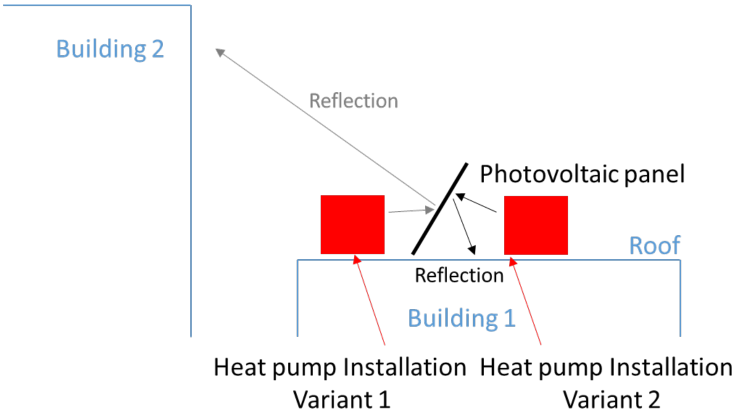


Figure 8-2: Problem case: Installation on the roof

8.3 Development of the neighbouring property

If an air water heat pump is installed on a property (see “Property B” in figure 8-3), which is separated from the highway by another property (see “Property B” in figure 8-3) which is undeveloped (without a building) at the time the unit is installed the corresponding target values can be met. Due to the noise emission of the highway (and therefore the noise immission on the property A) the heat pump is not disturbing. However, if a house is built on the originally undeveloped property (see “House B” in figure 8-3), there was a noticeable reduction in the noise immission of the highway on the property A, so that the heat pump suddenly became disturbing. Appropriate measures are necessary to reduce the disturbing noise emission of the heat pump.

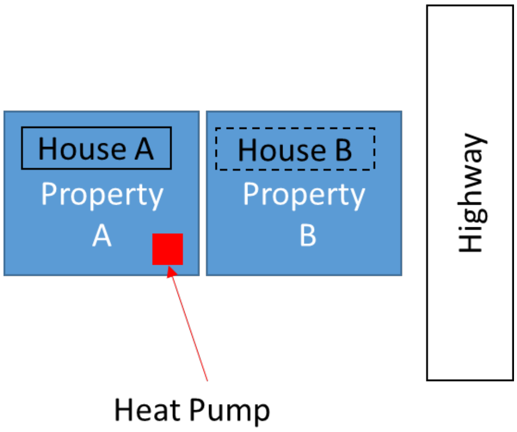


Figure 8-3: Problem case: Development of the neighbouring property

8.4 Improper sound absorbing measures

To reduce noise immission on the neighbouring property, it can intended to place a hedge between the air water heat pump and the neighbours fence (see figure 8-4). In principle the less disturbing high-frequency noises are immediately damped, the problematic and disturbing low-frequency noises can pass through the hedge almost undamped. In addition, the hedge causes a shadow and snow accumulates in front of the heat pump in winter. This leads to a lower air (heat source) temperature a higher pressure drop the fan has to overcome and an increased number of icing – de-icing cycles. Therefore the noise emissions are increased. It has to be stated that the installation of the hedge or similar is unsuitable to reduce noise immissions in the neighbourhood.

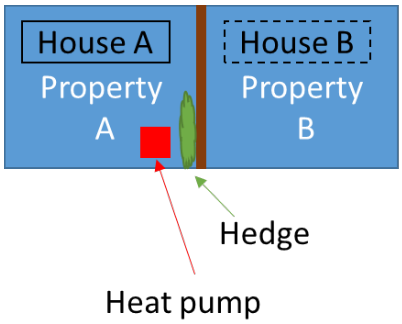


Figure 8-4: Problem case: Improper sound absorbing measures

8.5 Installation of further units in the neighbourhood

The increased amount of installed heat pumps e.g. by renewing the heating system in terraced houses can lead to a problem of sound emissions and therefore sound immissions on the neighbouring properties. On the one hand, the number of installed systems influences the sound emission and on the other hand the architecture (see figure 8-5) leads to a reflection of the sound emission between the terraced houses. In order to comply with the target values, it can come to the fact, that no additional heat pump can be installed/approved by the building authority.

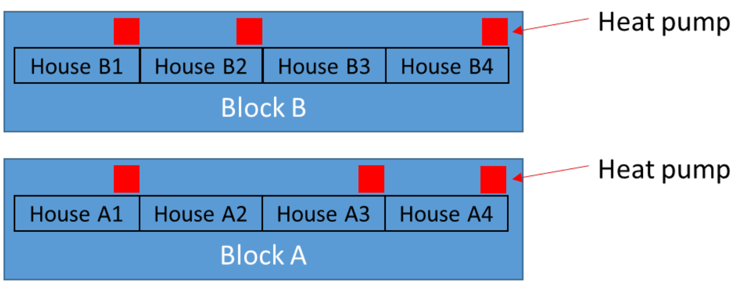


Figure 8-5: Problem case: Installation of further units in the neighbourhood

9 Further Reading

In this section we point to interesting sites in the world wide web, which we came across or were brought to our attention during our Annex 51 journey.

White paper on Sound Measurement

We have been pointed towards a white paper called "Multi-Wing Sound Measurement White Paper" sponsored by the company "multi-wing". It is freely downloadable from www.hpac.com and deals with the challenges in field test sound measuring. It's abstract is inserted here:

Sound test data helps manufacturers meet noise level requirements. Multi-Wing's white paper and video offer equipment manufacturers an understanding of the challenges associated with sound measurements in field tests. The white paper explains sound propagation in simplified, ideal and real-world conditions. The video demonstrates sound measurement of fan noise with a sound meter at given distances.

Currently the link reads: https://www.hpac.com/whitepapers/whitepaper/21137323/multiwing-sound-measurement-white-paper?code=MultiWingWP3-11052020&utm_rid=CPG04000020617547&utm_campaign=32334&utm_medium=email&elq2=6f99905c501d43bd8bfadcf725504c76&oly_enc_id=4922C8429278I1Y

But it is hoped, to be reachable in the future searching in https://www.hpac.com/whitepapers will keep the accessibility. At time of writing it can be found by searching "white papers" at www.hpac.com

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