Bachelor Thesis

in the study course Urban Renewable Energy Technologies, lecture Networked Energy Technologies - Specialisation Heat Pump

Sound field simulations of air-water heat pumps in a terraced housing estate

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Wien, 15.01.2017

Kurzfassung

Die Luft-Wasser-Wärmepumpe als alternative Heizungsform wird immer beliebter. Jedoch kann der nicht unwesentlich hohe Schall, der aufgrund der Ventilatordrehungen emittiert wird, insbesondere bei einer Außenaufstellung der Wärmepumpe zu Belästigungen führen. Daher beschäftigt sich die vorliegende Arbeit mit Maßnahmen, die zur Einhaltung bestimmter Schallgrenzwerte beitragen.

Eine ausgewählte Reihenhaussiedlung, die aus Einzel- und Doppelhäusern besteht, wird in dieser Arbeit ausschließlich durch Luft-Wasser-Wärmepumpen beheizt, die im Freien platziert werden. Es wird untersucht, wie sich der Schall ausbreitet und wie hoch der Schalldruckpegel entlang der Grundstücksgrenze, die die Reihenhaussiedlung von angrenzenden Flächen trennt, und an den Fenstern bestimmter Räume ist.

Zunächst werden drei verschiedene Szenarien erstellt, die sich in der Anzahl der Wärmepumpen in der Siedlung unterscheiden. Je mehr Haushalte eine Wärmepumpe heizt, desto leistungsstärker muss das verwendete Modell sein und desto weniger Pumpen werden insgesamt benötigt. Der Schallleistungspegel der Wärmepumpen hängt vom verwendeten Modell des jeweiligen Szenarios ab.

Die Simulation der Schallverteilung in der Siedlung wird anhand des Schallprognoseprogramms IMMI durchgeführt. Als Grundlage hierfür dienen die ÖNORM ISO 9613-2 und die ÖNORM S 5021. Bei der Untersuchung, welche Anzahl an Pumpen ideal ist, stellt sich heraus, dass eine Wärmepumpe pro Haus zum schalltechnisch besten Resultat führt. Dieses Ergebnis steht fest, nachdem unterschiedliche Varianten der Aufstellungsorte der Wärmepumpen für jedes Szenario simuliert wurden. Wenn Lärmschutzwände, die den Schalldruckpegel senken, verwendet werden, ist eine Nahwärmeversorgung mit nur zwei Wärmepumpen am besten geeignet.

Da im wirklichen Betrieb nicht immer alle Wärmepumpen laufen, werden realitätsnahe Nutzerprofile erstellt. In der folgenden Simulation, in der manche Wärmepumpen für eine bestimmte Zeit am Tag nicht in Betrieb sind, ergeben sich niedrigere Schalldruckpegel an den kritischen Immissionsorten.

Schlagwörter: Luft-Wasser-Wärmepumpe, Schall, Lärmschutzwände

Abstract

The number of installed air water heat pumps increases but their disadvantage is their sound emission. In this bachelor thesis, 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 and the ÖNORM S 5021. 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.

In the next simulations, the 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.

Keywords: air water heat pump, sound, barriers

Contents

1 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 following diagram (Figure 1) shows a trend towards air-to-water heat pumps. Their share of the market for all heat pump types in Austria is currently over 60% [1].

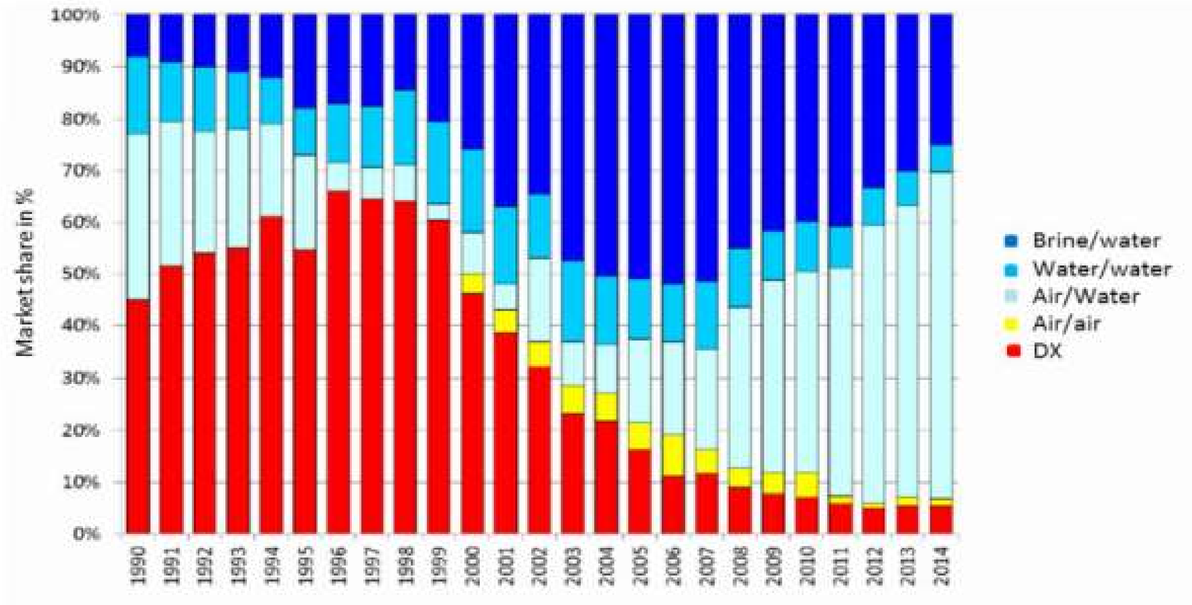

Figure 1 Market shares of different types of heat pumps in Austria [1].

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 bachelor 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.

1.1 Research Question

How can the heating of the described terraced house settlement be carried out using air-to-water heat pumps if the sound pressure levels defined in this paper must not be exceeded?

1.2 Methodology

A housing estate of terraced houses, which is shown on the plans in the appendix, 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 the bachelor thesis „Auslegung einer Luft-Wasser-Wärmepumpenanlage für ein Einfamilienhaus sowie die Simulation und Analyse deren Schallausbreitung“ („Design of an air-to-water heat pump system for a single-family house and the simulation and analysis of its sound propagation”) by Patrick Wimmer [2], a comparison of several programs was carried out. With regard to accuracy, user-friendliness and costs for students, it was found that IMMI [3] is the best suited for a simulation of this kind. Therefore this program is used for the time being.

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 [5]. 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 [4] is also suitable for simulations of this kind.

1.3 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 in the present bachelor thesis. 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.

2 Theoretical Background

The following section discusses the types of air-to-water heat pumps and their respective characteristics. In addition, basics about sound are discussed, important terms are defined and some facts are discussed.

2.1 Construction Methods of Air-to-Water Heat Pumps

A distinction is made between air-to-water heat pumps in compact and split design. Compact units suck in air and generate heat directly in the heat pump. In the case of indoor installation, the air is fed via air ducts into the interior of the house where the heat pump is located. This requires large wall breakthroughs, which can cause thermal bridges. In an outdoor installation, the air is drawn in directly by the heat pump using a fan. This eliminates the need for a large wall opening and the risk of a thermal bridge, as the required supply to the house is very small compared to an air duct. The split installation is characterised by the fact that the evaporator is located outside, while the compressor is located inside the house. The heat is transferred to the refrigerant in the outdoor unit and transported via a refrigerant line to the hydraulic unit installed inside. [6] Only split units and compact units installed outside are used to heat the terraced house estate presented below, in order to avoid large wall openings and thus thermal bridges. The sound of the heat pumps of the selected designs is distributed outside.

2.2 Sound

This chapter explains how noise is generated during the operation of air-to-water heat pumps. In addition, it is discussed how loud people perceive different sound sources. The measures that lead to a reduction of the sound pressure level caused by the heat pump are also described.

2.2.1 Difference between Sound Power Level and Sound Pressure Level

The sound power level is determined by the properties of the heat pump. It describes the source volume of a sound generator and is independent of the receiving location. In contrast, the receiving location and the radiation characteristics influence the sound pressure level. The sound pressure level is an orienting measure of the perceived loudness.

2.2.2 Difference between dB and dB(A)

Sound pressure levels are measured without weighting filters, i.e. in dB. They represent a physical measured variable. However, the human ear perceives low frequencies as quieter than high frequencies. For this reason, the A-weighting filters the sound signals in such a way that the characteristics of the human ears are reproduced. The designation "dB(A)" indicates that such an evaluation is present. [7]

2.2.3 Origin

On the one hand, sound is caused by mechanical vibrations, such as those generated in the engine of the fan of an air-to-water heat pump. In addition, further acoustic sources are generated by flow effects. In addition, the compressor contributes to the total sound power level of the heat pump acting outdoors. With split units, however, this is only the case if the compressor is located in the outdoor unit. A high fan speed and an unfavourable choice of location for the heat pump also contribute to acoustic pollution.

2.2.4 Perception

Sound pressure levels cannot simply be added arithmetically. Rather, an increase in sound pressure level occurs with an increasing number of sound sources with the following relationship.

Formula (1) shows how the simultaneous occurrence of several sound sources affects the sum level [8].

$$L_{gesamt} = 10\lg(10^{L1/10} + 10^{L2/10} + \cdots + 10^{Ln/10}) \quad (1)$$

Doubling sound sources with the same sound power level thus causes an increase of 3 dB. (“gesamt” means “total” in English).

The human ear perceives sound level differences of noises of the same type as follows. If the difference between the different sound levels is less than 1 dB, it is hardly audible. A difference of 3 dB is clearly perceived, and a sound source that is 10 dB louder is perceived as approximately twice as loud. [8]

Table 1 shows some examples of sound sources known from everyday life. The sound levels of these are listed.

Table 1 Examples of sound pressure levels [8]

Sound level	Sound source
0	inaudible (hearing threshold)
10	snowfall
20	light wind, ticking of a pocket watch
30	whispering
40	fridge
50	quiet stream or river, quiet conversation
60	normal conversation
70	loud talk, lawn mower at 7m distance
80	loud radio music, heavy traffic
90	pneumatic hammer at 1 m, heavy truck at 5 m distance
100	disco (inside)
110	propeller-driven airplane at 7 m distance
120	commercial aircraft at 7 m distance

2.2.5 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. [9]

3 Limits

Since there is no uniform legally permitted sound pressure level, the following limits are set for this bachelor thesis. 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.

4 Introduction of 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 Lorenz Ramsmaier [10] and „Wärmeversorgung einer Reihenhaussiedlung durch ein zentrales Wärmepumpennetz“ („Heating supply of a housing estate of terraced houses by a central heat pump network”) by Lukas Kager [11] 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.

4.1 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 [12]. The heating requirement was determined using PHPP [10 and 11].

The power required to heat water for one person is 250 W [13]. 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 2 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 2 Heating load, output for water heating and heating demand per household [10 and 11]

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**

4.2 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 [14]. The following figure 2 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.

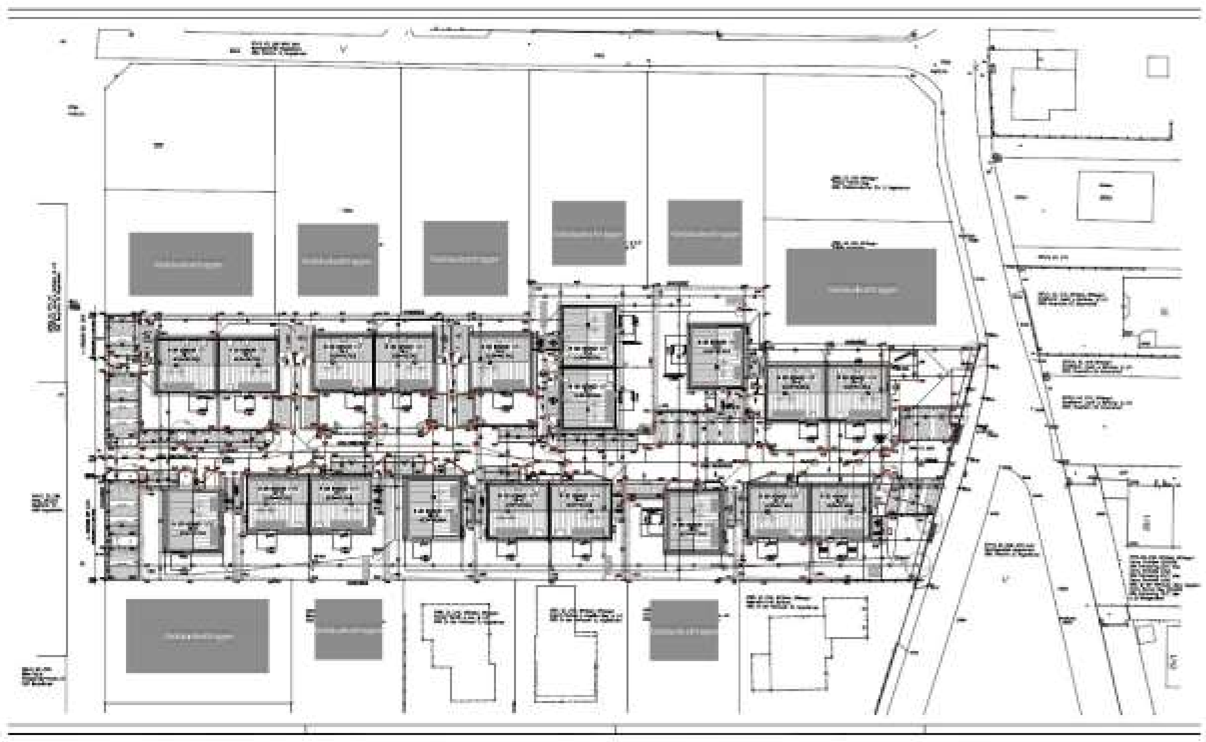

Figure 2 Site plan with dummy buildings

5 Simulation of maximum Sound Propagation using IMMI

Simulations with the IMMI program are performed and evaluated on the basis of ÖNORM ISO 9613-2 [15] and ÖNORM S 5021 [16]. 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 3 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.

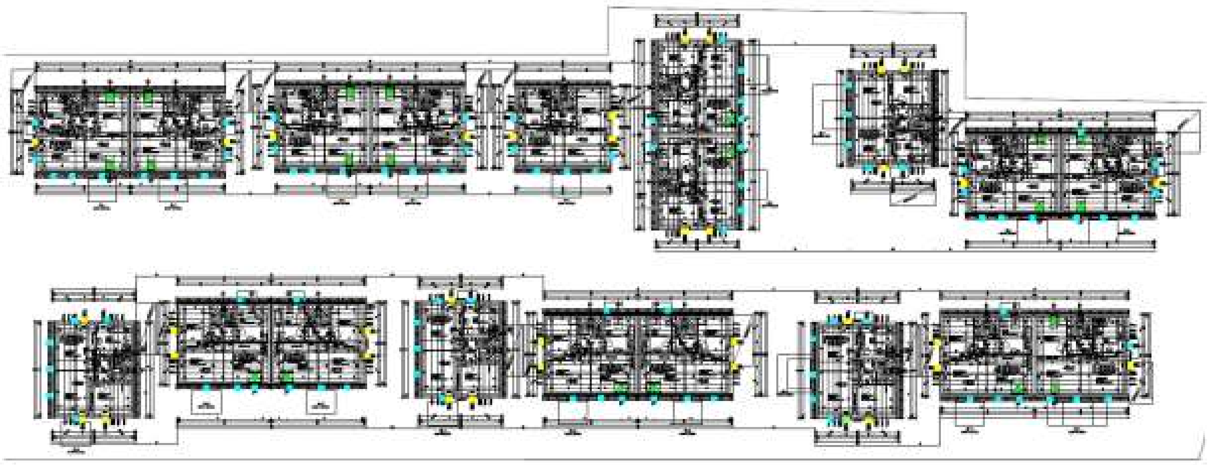

Figure 3 Plan of the terraced house settlement with marking of the sound measuring points

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 3. 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 3 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.

5.1 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 thesis.

5.2 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 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.

5.3.1 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 [17] 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.

5.3.2 Placement

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 4.

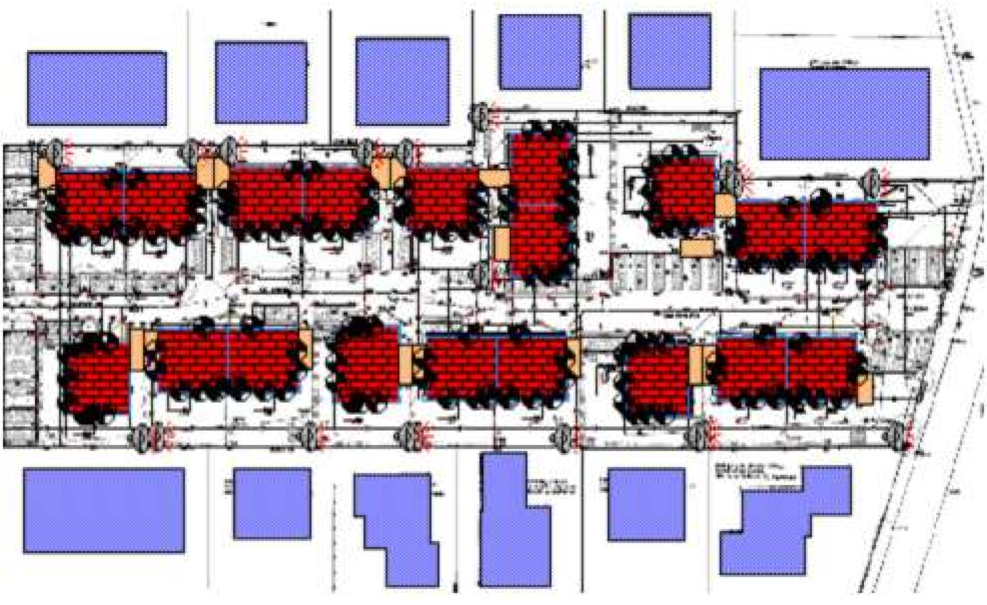

Figure 4 Placement of heat pumps in scenario A, variant 1A

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 shows the installation locations.

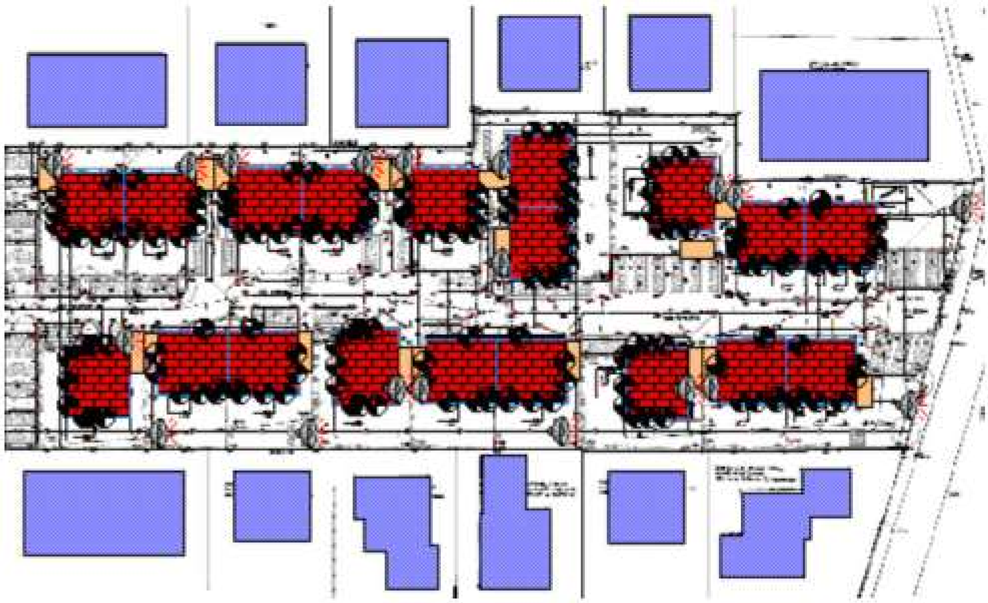

Figure 5 Placement of heat pumps in scenario A, variant 2A

In variant 3A most heat pumps are placed near the walls of terraced houses. This is shown in figure 6.

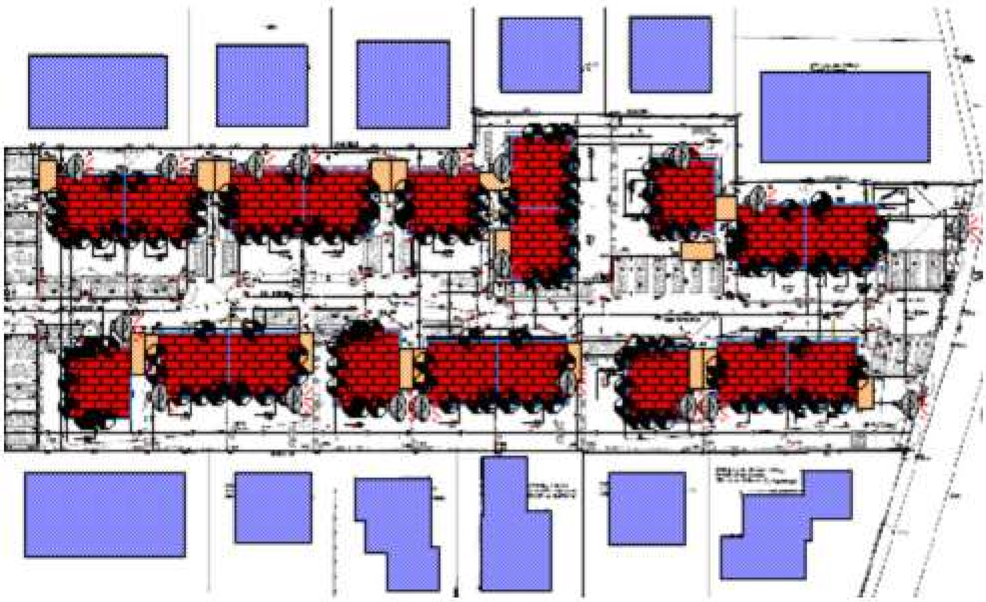

Figure 6 Placement of heat pumps in scenario A, variant 3A

5.4 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.

5.4.1 Heat Pump Selection

The following table 4 shows the heating loads of each building.

Table 4 Heating load and output for hot water preparation per building

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

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 [18] 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.

5.4.2 Placement

Figure 7 shows the locations of the heat pumps in variant 1B. They are mostly located south of the houses to be heated.

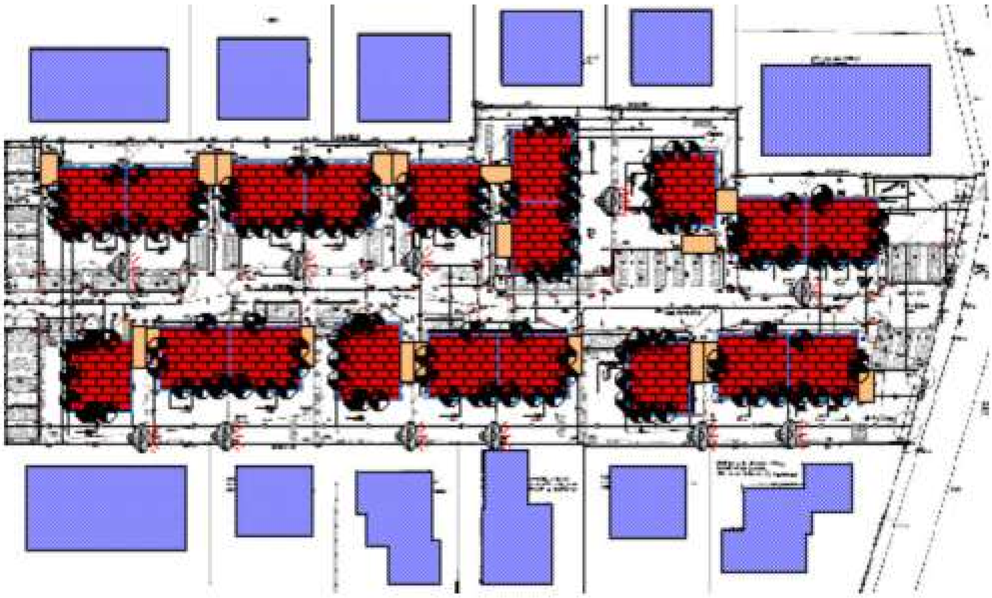

Figure 7 Placement of heat pumps in scenario B, variant 1B

The locations of the heat pumps in variant 2B are shown in Figure 8.

Figure 8 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 9.

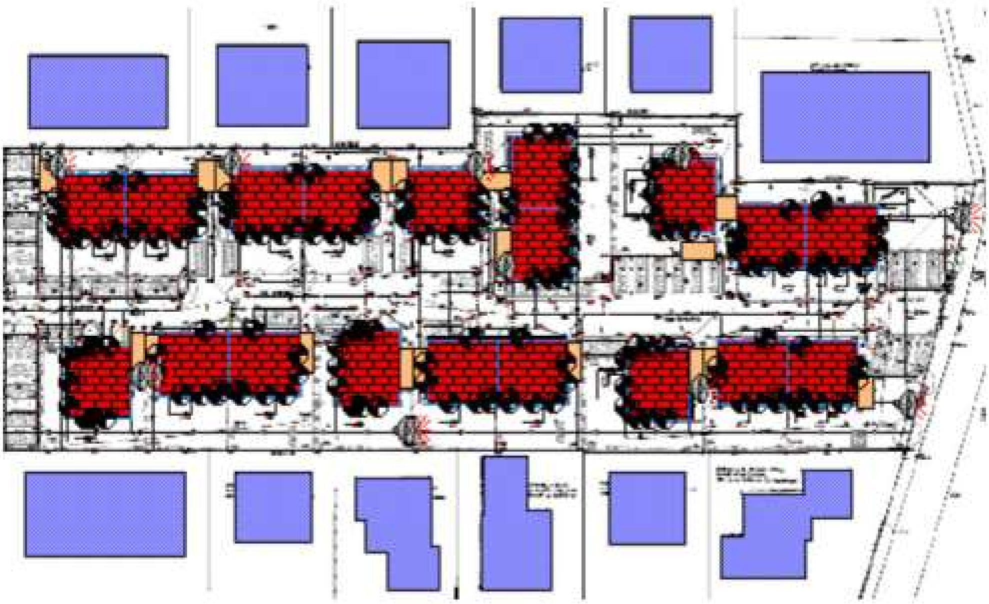

Figure 9 Placement of heat pumps in scenario B, variant 3B

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

5.5 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 [11].

5.5.1 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, formula (2) applies [19, p. 3]. The variable n stands for the number of consumers and the variables a, b, c and d are empirically determined factors.

$$F_{Gl} = a + \frac{b}{1+\left(\frac{n}{c}\right)^{d}} \tag{2}$$

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

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

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. Formula (3) shows the calculation procedure ("nenn" means "nomimal" in English).

$$\dot{Q}_{nenn} * F_{Gl} = \dot{Q}_{max} \tag{3}$$

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

The maximum connected load is 84372 W.

5.5.2 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. [11] 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. [11]

5.5.3 Heat Pump Selection

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

$$required\ output = maximum\ connected\ load + \ heat\ losses\ from\ pipes \tag{4}$$

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

The heat pump must cover an output of 86418 W. Two pieces of the air-to-water heat pump LA 60-TU [20] 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.

5.5.4 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 10 shows that the two heat pumps are located directly next to each other.

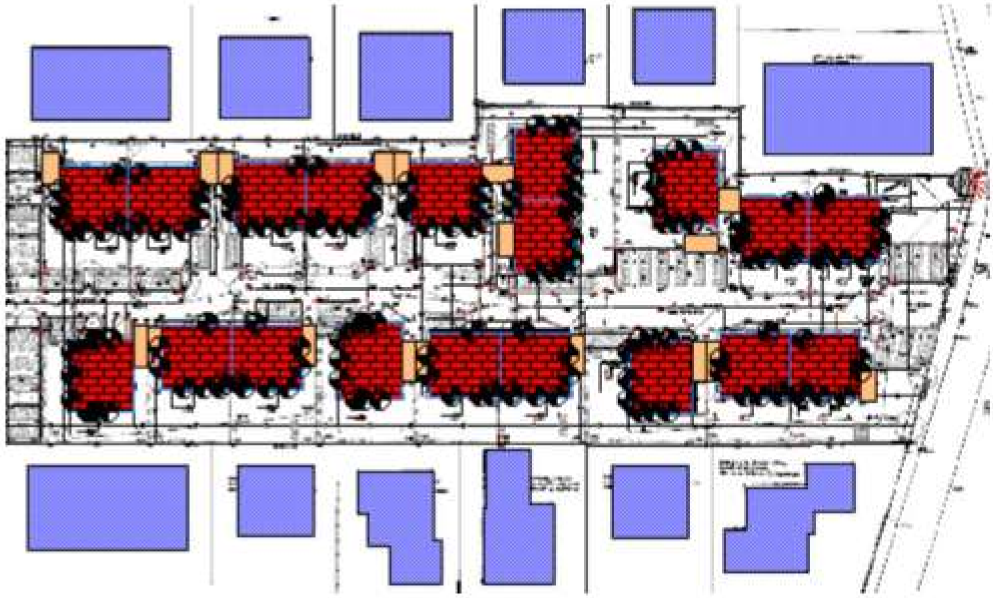

Figure 10 Placement of heat pumps Scenario C, variant 1C

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 11 shows the installation location.

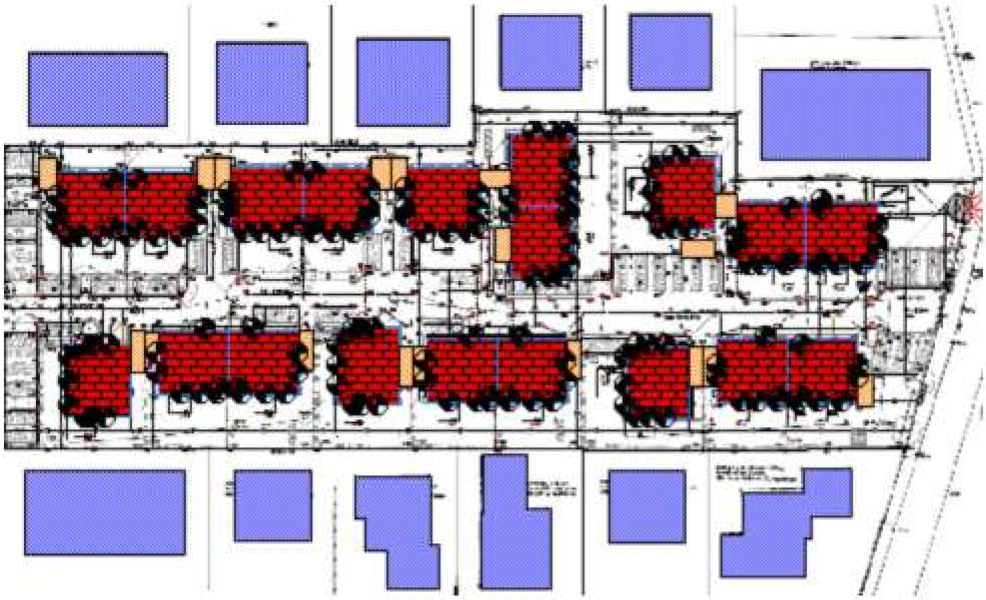

Figure 11 Placement of heat pumps in scenario C, variant 2C

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 12. 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.

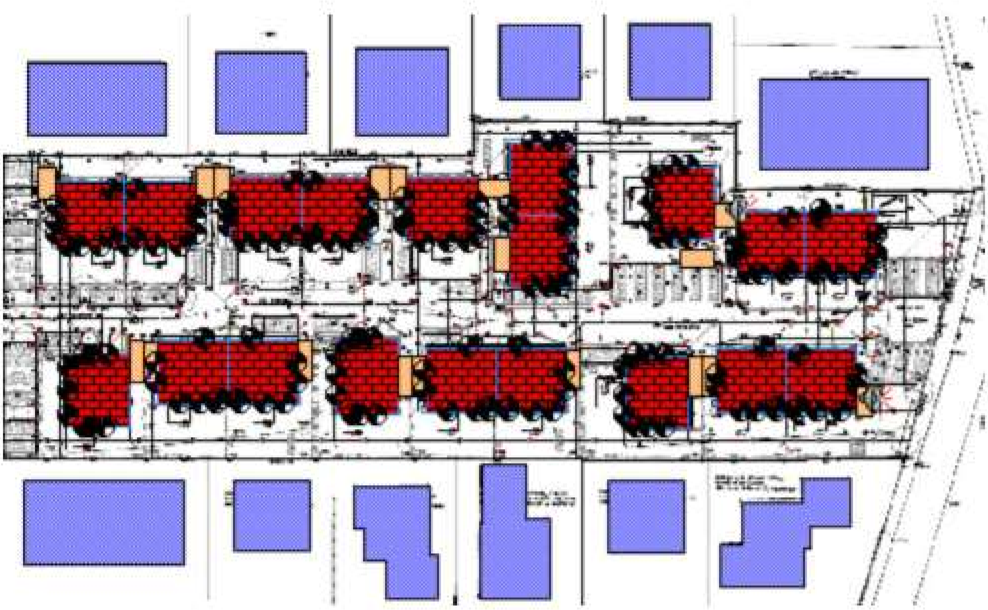

Figure 12 Placement of heat pumps in scenario C, variant 3C

Variant 1C has the fewest penalty points and is therefore the best tested variant of scenario C.

5.6 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 13 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 color yellow.

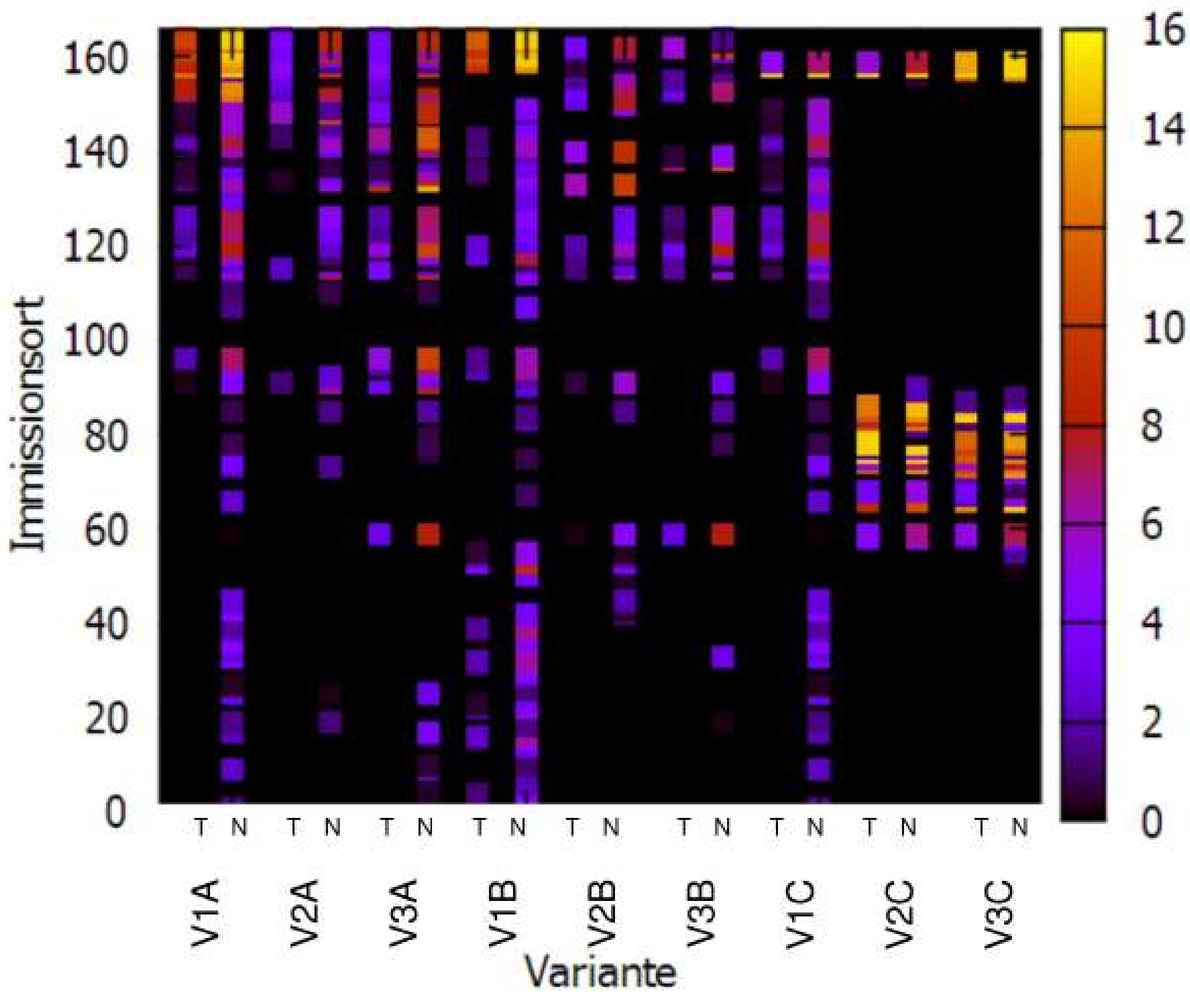

Figure 13 Penalty points at the points of immission ("Immissionsort") for different variants and scenarios

Table 5 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 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.

6 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 14 shows such a cladding in a three-dimensional view.

Figure 14 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 16. 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 15. 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.

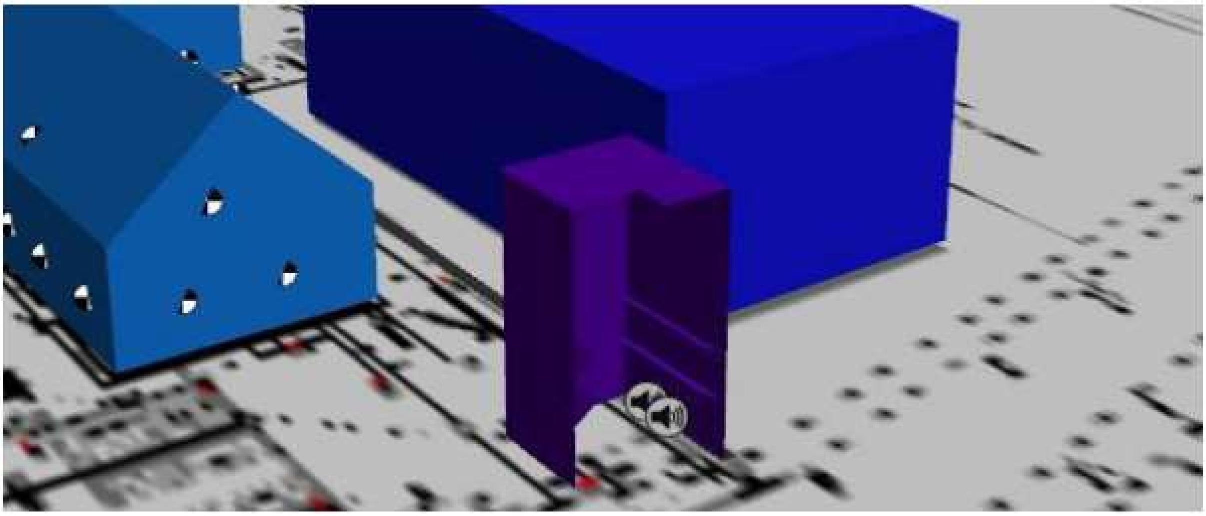

Figure 15 Noise protection cladding of heat pumps in variant 1C

The following diagram (Figure 16) shows that after the construction of noise barriers in variant 1C, penalty points are only awarded at a critical immission point.

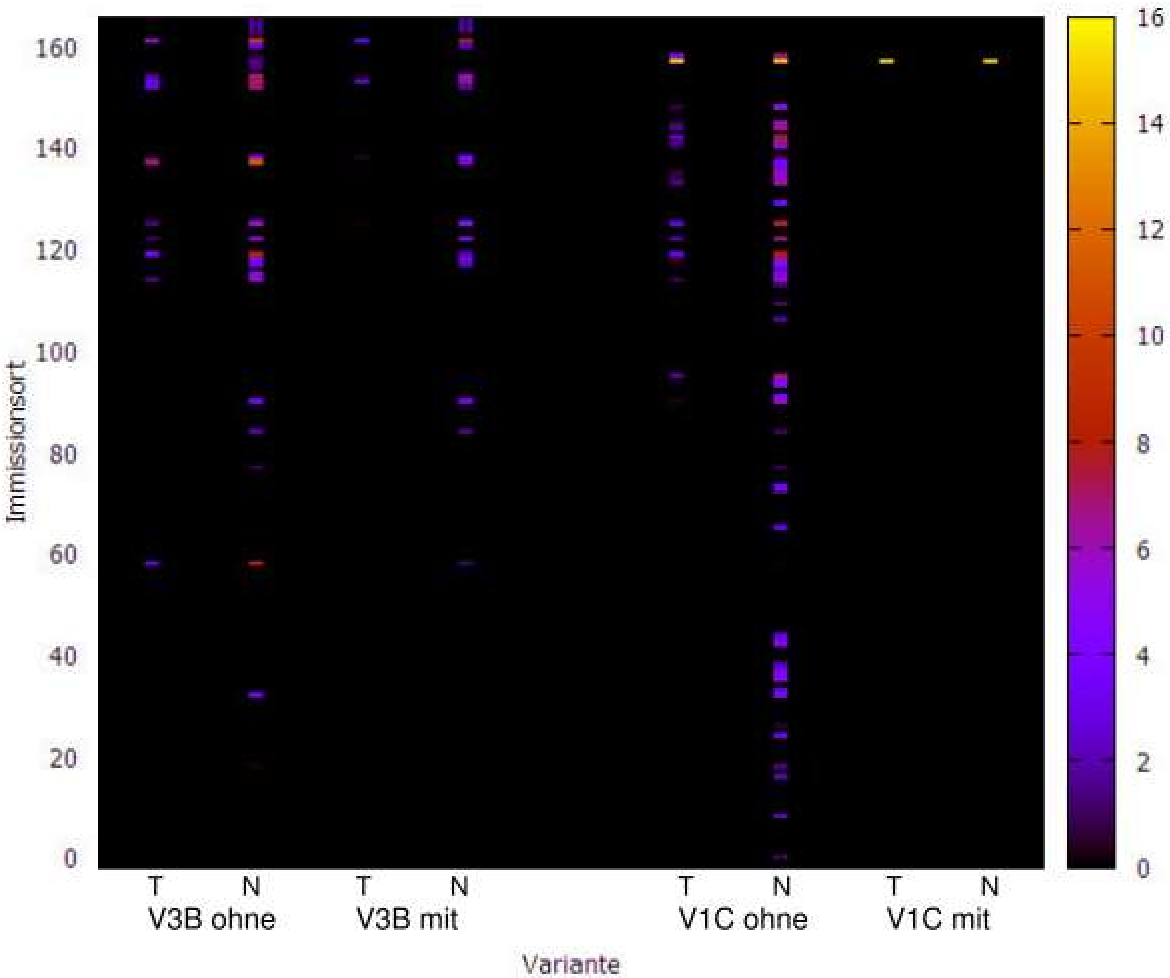

Figure 16 Penalty points at the places of immission for two variants with ("mit") and without ("ohne") noise barriers

Table 6 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 6 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.

7 Time dependent Sound Propagation

So far, this bachelor thesis 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.

7.1 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 17 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.

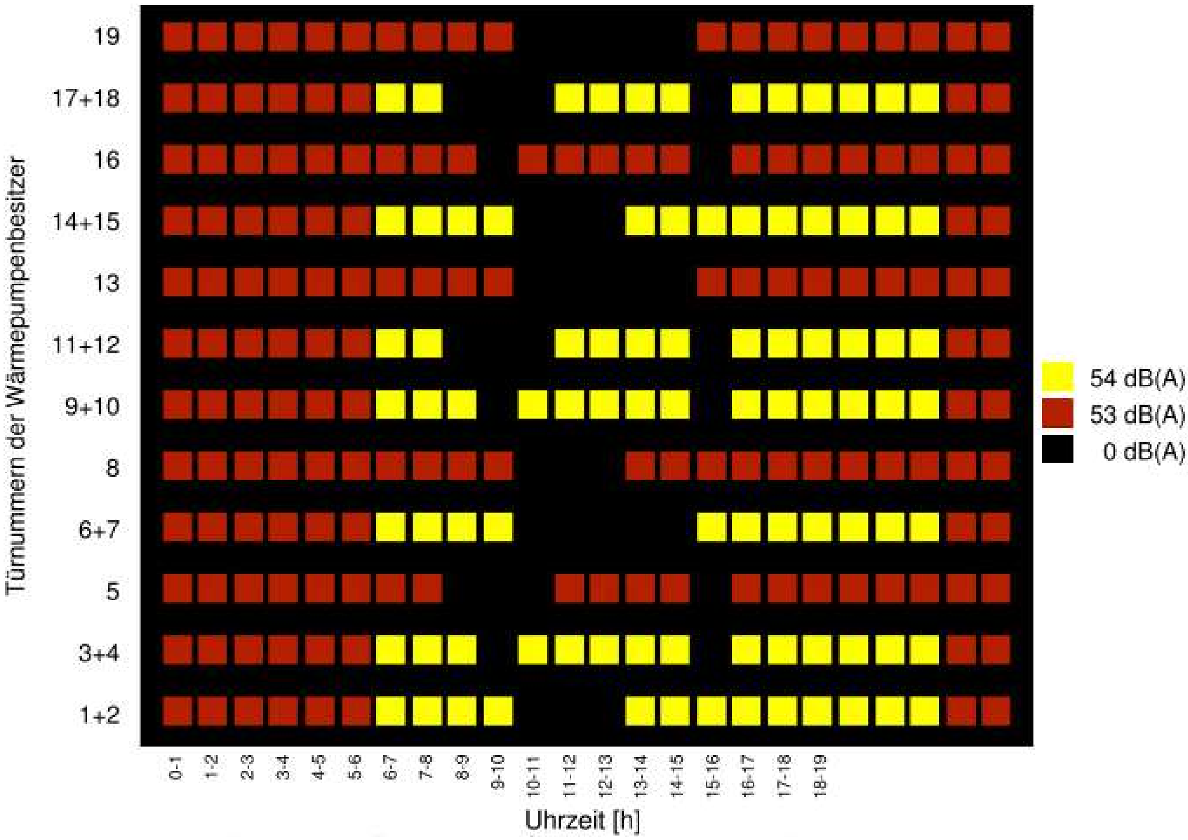

Figure 17 Time dependent sound power level of heat pumps (the x-axis shows time of day, y-axis the different door numbers of the considered houses)

7.2 Simulation

The following Figure 18 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.

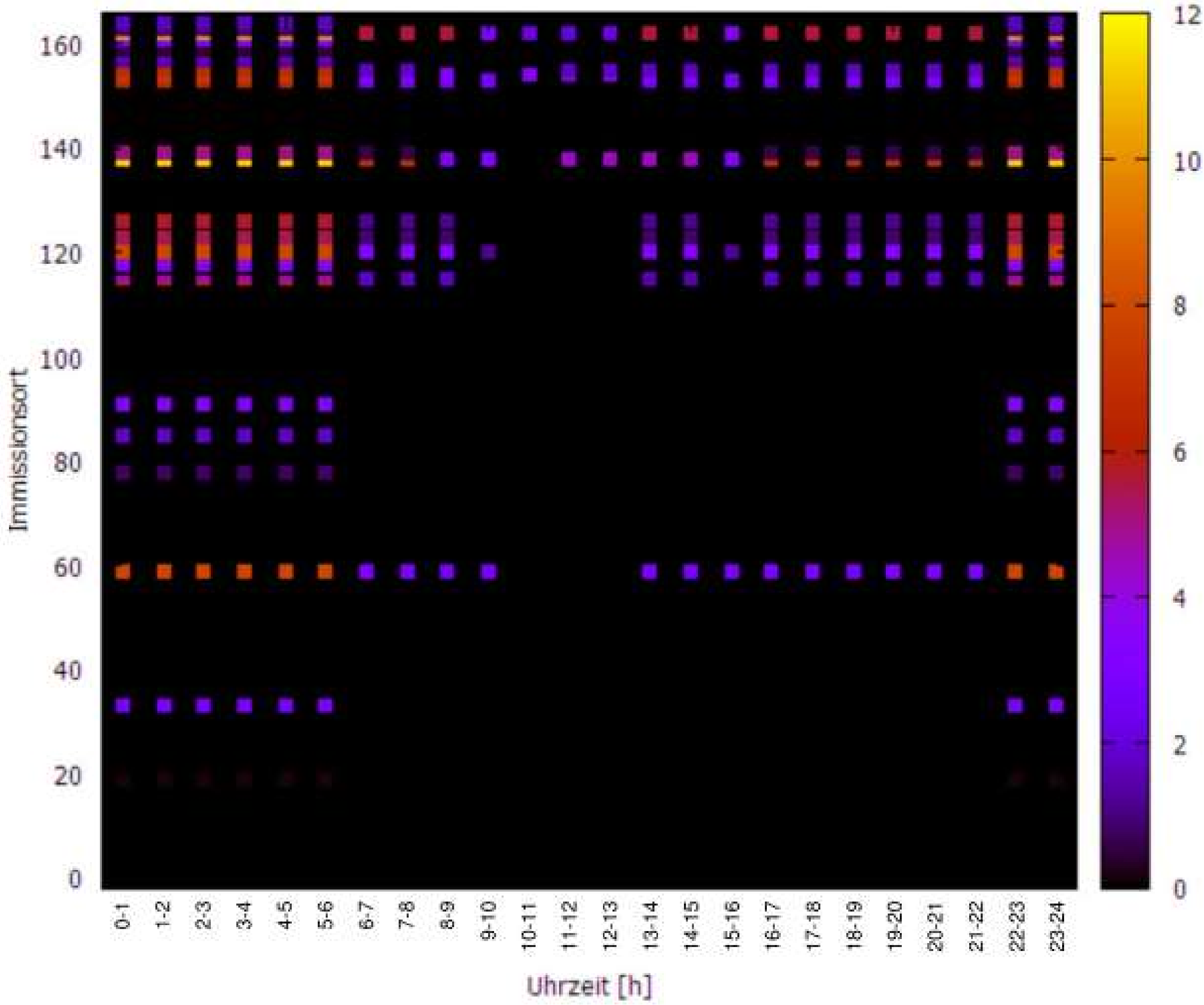

Figure 18 Penalty points at the points of immission during the day for variant 3B

8 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, 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.

8.1 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 [21]. For this reason, we refrain from simulating with OpenPSTD.

8.2 Olive Tree Lab

Olive Tree Lab is a cypriot sound prediction program in English language, available for 195 € per user and month. 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 96132 is applied. Figure 19 gives an insight into the program and shows the terraced houses, the neighboring 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.

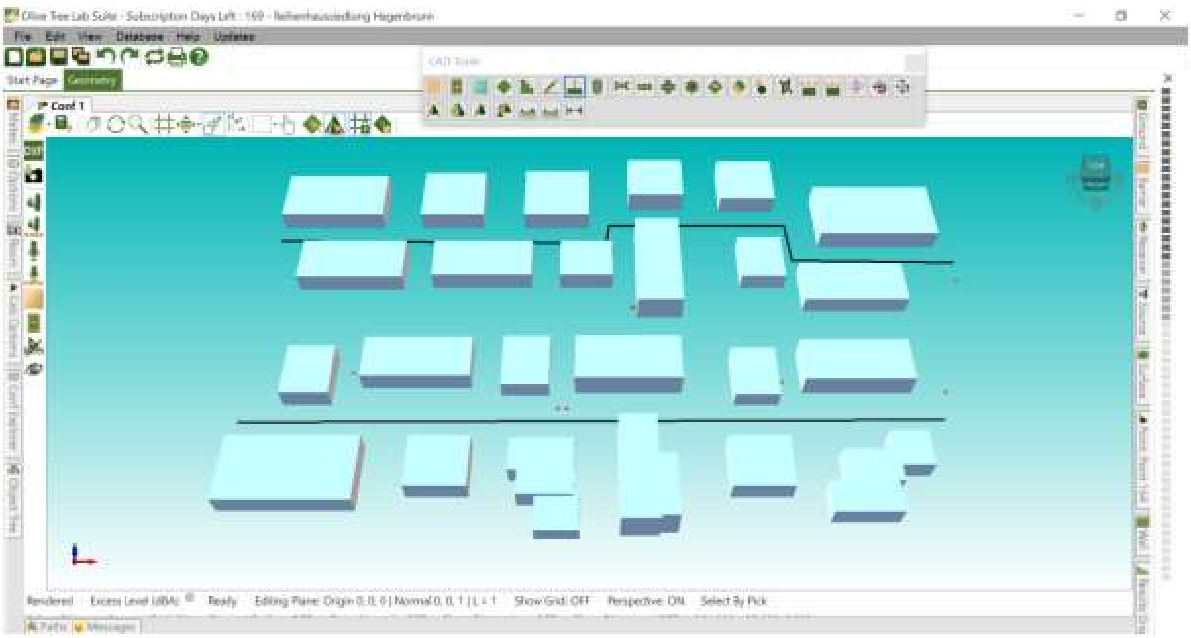

Figure 19 User interface of the program Olive Tree Lab with a simplified terraced house settlement

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 20 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 20 on the right.

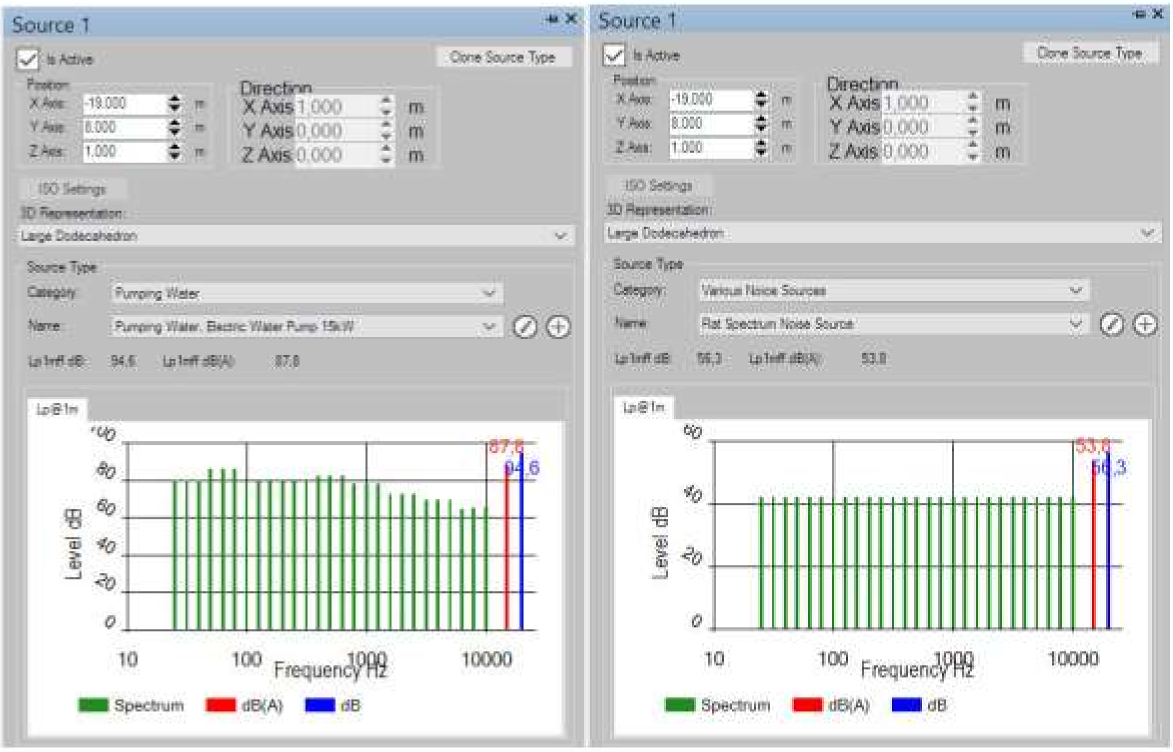

Figure 20 Input mask of an exemplary sound source (left: frequency-dependent sound source, right: frequency-independent sound source)

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 21 shows the input mask of a noise barrier. In this view the height of the absorption coefficient can be viewed.

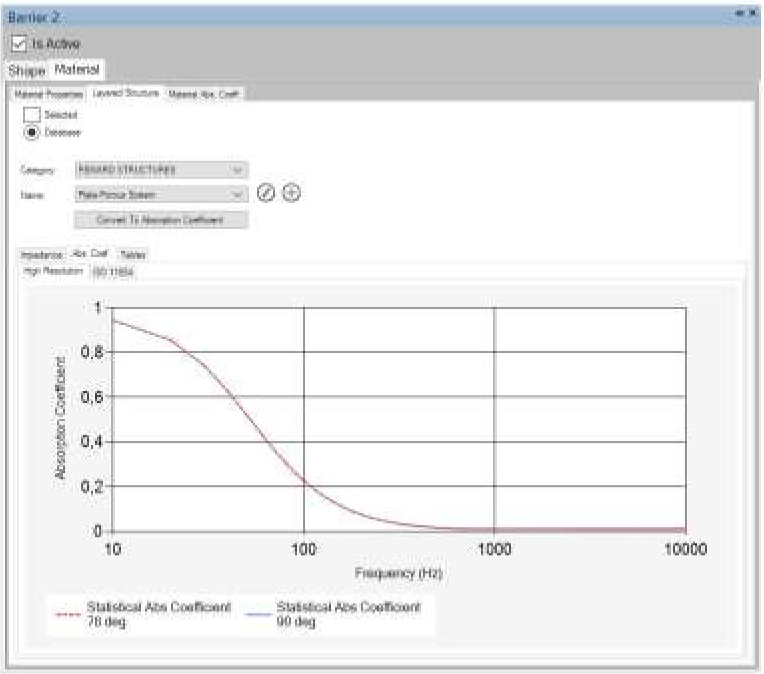

Figure 21 Input mask for a noise barrier

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 22.

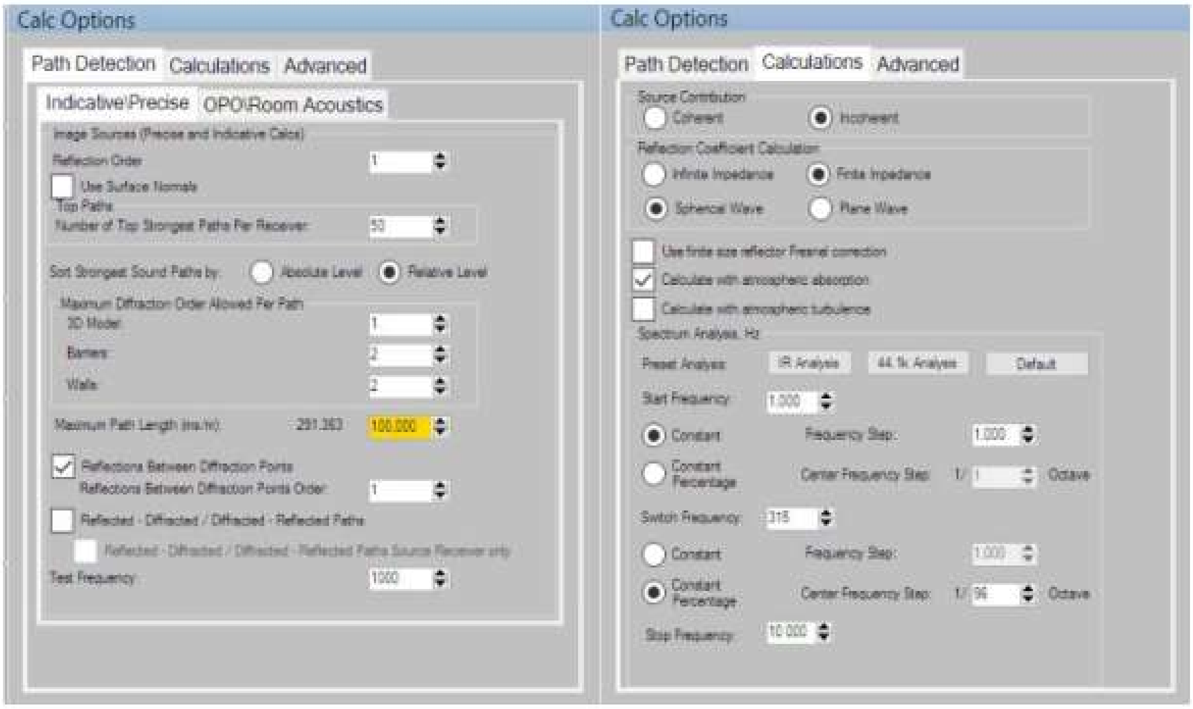

Figure 22 Calculation options

9 Interpretation

Figure 23 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.

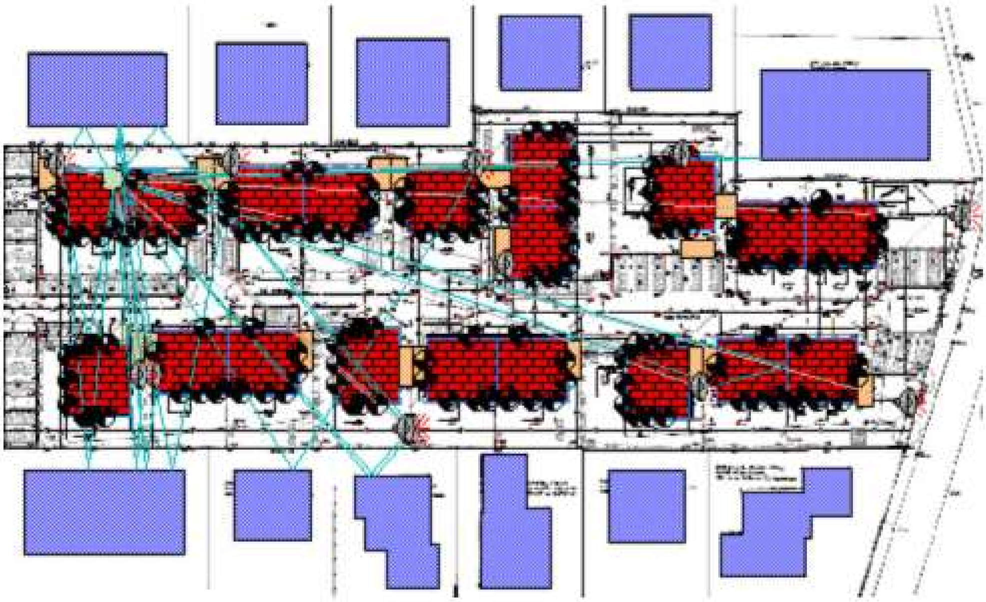

Figure 23 Influence of sound radiation on an immission point

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.

10 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.

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List of Abbreviations

§	Paragraph
A2/W35	Air inlet temperature = 2 °C, water outlet temperature = 35 °C
A2/W55	Air inlet temperature = 2 °C, water outlet temperature = 55 °C
COP	Coefficient of Performance
dB	Decibel
dB(A)	Decibel
DN	diamètre nominal (english: nominal diameter)
EN	European Norm
EU	European Union
FGl	Simultaneity factor
IMMI	Name of a software tool for the prognosis of sound and air pollutant immissions
ISO	International Organization for Standardization
L1 … Ln	Levels to be added
Lgesamt	Sum level
max.	Maximum
min.	Minimum
NÖ	Lower Austria (german: Niederösterreich)
ÖNORM	Austrian standard
OpenPSTD	opensource software development of the Pseudo-Spectral Time-Domain method
PHPP	Passive House project planning package
Qmax	Maximum connected load
Qnenn	Nominal power
S	Other areas of standards
U-value	Heat transmission coefficient

List of Units

%	Percent
€	Euro
°C	Degree Celsius
cm	Centimeters
h	Hours
kW	Kilowatt
kWh/(m²*a)	Kilowatt hours per square meter and year
kWh/a	Kilowatt hours per year
m	Meters
W	Watt