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PLUMBING NOISES IN WATER SUPPLY AND SEWAGE SYSTEMS

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Abstract

The main subject of the thesis is to analyze and find solution for plumbing noise problems in water systems in a dwelling. Acoustical parameter inside the residential areas is one of the most significant factors when designing comfort environment for living. Noises that are caused by water supply and sewage systems are one of the common reasons of occupant complaints. That is why it is important for a HVAC engineer to be able to design acoustical appropriate systems and, in case of any violations that result higher noise level, identify a problem and suggest a noise reduction solution.

Analysis of noise problems requires knowledge in sound properties field and in water system field. Due to that in this thesis sound theory and water systems will be considered. For practical example three storey building will be analyzed where occupants complain about plumbing noises. After studying the noise problem and considering residential circumstances the best solution for the dwelling will be suggested.

All the main noise sources, factors that can influence sound level, and ways to reduce noise in water systems will be described. This thesis can be used as a theoretical background for future investigations about noises in water systems and as an example of plumbing noises analyzes.

Subject headings, (keywords)

Drain noises, water hammer, noise transmission, faucet sounds

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CONTENTS

1. INTRODUCTION

Nowadays the requirements for comfort parameters in buildings have become stricter and the requirements for sound level in buildings are not exceptions. Since sound can influence humans' health and productivity it is highly important to consider this factor when creating a comfortable environment for living and working areas.

In spite of this fact there is a significant number of old houses where the noise problem disturbs occupants. Moreover, even in new buildings plumbing noises can be found right after finishing the construction.

Very often people don't pay enough attention to this issue because in most cases plumbing noise level can't cause pain effect immediately when it is found. But as occupants start to spend significant amount of time in the space with a plumbing noise problem it turns out that noise annoys during the day and interferes with sleep during night.

In this bachelor's thesis the main object of research are water supply and sewage noises in dwelling in terms of sound properties. As a part of the research different sources and literature materials will be considered from various countries in order to get familiar with previous achievements in this field and for studying any possible solutions to the issue. Then there will be a practical part of measuring plumbing noises in a typical dwelling in Mikkeli (Finland) and noise problem investigation part. After analyzing the noise problem, conclusions with recommendations for particular dwelling will be suggested. Recommendations will be based on theoretical and practical parts of the research so that they can be applied to dwelling circumstances.

In this paper the reasons of the sound appearance will be shown, an example of existing noise problem in an apartment will be given, the information about the water supply and sewage system in that building will be considered. Next step will consist of making sound measurements and finally suggesting solutions according to the type of the problem. The illustrations of what kind of system was in the dwelling while measurements and what changes are suggested will be provided.

Although there are a lot of internet sources that tell us information about mentioned topic, there is no one reliable source that summarizes reasons, methods, solutions and comparisons with national standards at once. That is why this bachelor’s thesis could be useful for future investigations and water systems reconstructions and as a theoretical background for improving water supply and sewer systems.

2. AIMS AND METHODS

In this thesis, the primary aim is to find out why undesirable noises appear and transmit in water supply and sewage systems and how to prevent them. It is important to get familiar with the definition of sound in general. That is why the information about sound as physical phenomena will be provided first. Afterwards, it is necessary to explain how people perceive sound and what factors are important for humans’ hearing.

Since in this thesis is focused on water supply and sewage system noises, it is necessary to inform the reader about basic information of water systems, most common materials, general designing principles. When talking about plumbing noises it is essential to identify different noise source. That is why the types of the most common noise generators and reasons for theirs’ performance will be studied.

Further, there will be a briefly description of several noise transmission cases in water systems and then observation of ways to reduce noise according to the type of the problem. As a conclusion of the theoretical part the comparison of the reduction influence of each method will be shown and the most significant factor that should be taken into account when designing systems and the most efficient method to decrease plumbing noise level will be underlined.

As a practical part of the thesis another aim is to find the reason of the existing plumbing noise problem in multi-store building and suggest possible solutions for reducing the noises. To achieve this aim sound measurements of noise levels will be arranged of a multi-storey apartment with different using faucets cases that are in the apartments above. Afterwards, sound parameters will be calculated that are based on measuring results. Then they will be analyzed and if there any violations in the water systems, reasons and factors will be considered in order to find a possible solution.

3. THEORETICAL BACKGROUND

2.1 What is sound?

Sound is what we hear. It is a result of the vibrating air in the surroundings. Vibration passes through the air and creates different levels of air pressure (higher and lower) through air compression and decompression. These vibrations travel across the air in the form of sound waves. Sound can travel through water, wood, metal as well and through any other elastic medium. Various valuable terms describe the features of sound. These features have impact on how it affects hearing and health, how it is measured, and how it can be controlled. In terms of plumbing noises topic, it is necessary to get familiar with following parameters. /1./

Intensity (or wave amplitude, volume) is a measurement of the height of the sound wave or in other words unite for the loudness. The unit for sound volume is decibels [dB]. Table 1 gives examples of common sound levels for several noise sources that people can hear in everyday life. The human ear responds to a great range of sound intensities from 0 dB (threshold of hearing) to 130 dB (threshold of pain). Person can perceive sound with more than 135 dB but it will immediately cause damage for health. /2./

TABLE 1. Typical Sound Levels /2/

Type of activity	Intensity, dB(A)
Civil defense siren	130
Pile driver	110
Motorcycle	90
High urban ambient sound	80
Light traffic	50
Whisper	30

Frequency is the characteristic that represents how often the wave repeats itself in one second (1/s). It is measured in the number of cycles per second [Hz]. The lower the number the deeper or more bass the sound. Table 2 describes frequency ranges of various sources. The interval between 20 and 20000 Hz covers most audible frequencies although humans hear sounds best from 1,000 Hz to 5,000 Hz. These numbers are just averages: some people hear pitches as low as 15 Hz; others can hear frequencies significantly higher than 20 kHz. It is a scientific fact that the older person gets, less sensitive he becomes to high frequencies. /3./

TABLE 2. Some frequency ranges /3/

Source	Lowest frequency, Hz	Highest frequency, Hz
piano	27.5	4186
female speech	140	500
male speech	80	240
compact disc	0	22050
human hearing	20	20000

The sound audible range can be divided into 10 octave bands that represent specific spectrums of frequencies and eliminate other ones in between. This partition is done in order to simplify sound measurement processing and analyzing. These frequencies are following: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 and 16000 Hz. Sometimes the frequencies are separated into one third octave bands for more accurate data. There are lower, upper and middle frequency one third octave bands. For instance, 1000 Hz is middle octave band and it’s lower and upper one third bands are 800 Hz and 1250 Hz respectively. It is possible to calculate octave band sound level when knowing one third octave bands and vice versa. /4./

There are also some other parameters that are used to define and measure sound as humans or devices hear it. In terms of plumbing noise issue it is important to become familiar with sound level pressure and weighted decibels system.

The vibrations that represent sound are identified as slender variations in pressure. The range of sound pressures begins with a very weak pressure causing wispy sounds and increases to noise so loud that it causes pain. The zone where the same sound loudness can be determined has the same sound pressure level (SPL). SPL is a ratio of the absolute sound pressure and a reference level (usually the threshold of hearing or the lowest intensity sound that can be heard by most people). By international agreement, the reference sound pressure has value of 20 μPa. The unit of SPL is usually decibels [dB] but also can be expressed in Pascals [Pa]. SPL can be calculated using formula 1. / 4./

$$L_p = 20\log\left(\frac{P}{P_{ref}}\right) \quad (1)$$

where L_p is sound pressure level (dB), p is sound pressure (Pa), p_{ref} is reference sound pressure, Pa.

If there are several sources of sounds, it will be needed to calculate the total sound pressure level. Sound levels can’t be simply added to each other since the relationship is logarithmic. The equation number 2 should be used. /4./

$$L_p = 10\log\left(\sum_{k=0}^{n} 10^{Lpk/10}\right) \quad (2)$$

where L_p is total sound pressure level (dB), L_{pk} is sound pressure level of source k (dB), n is number of sound sources.

It is discovered that two sound sources that have equal sound pressure levels will result increasing the total pressure level in 3 dB. Another fact that was observed is that the bigger is the level difference between sounds the less sound pressure level to be added to the louder source. It means that 3 dB is the maximum supplement in relation to the greater sound source. /4./

If the difference between sounds is more than 10 dB, the quieter sound is not takes into account. It is important in terms of sound measurements where background sound exists. If the measured noise has smaller sound pressure level difference compared to background noise by 10 dB, then the evaluation of measured sound pressure level should be reduced. The figure 1 shows values that should be added to the louder source in relationship of sound pressure level difference./4./

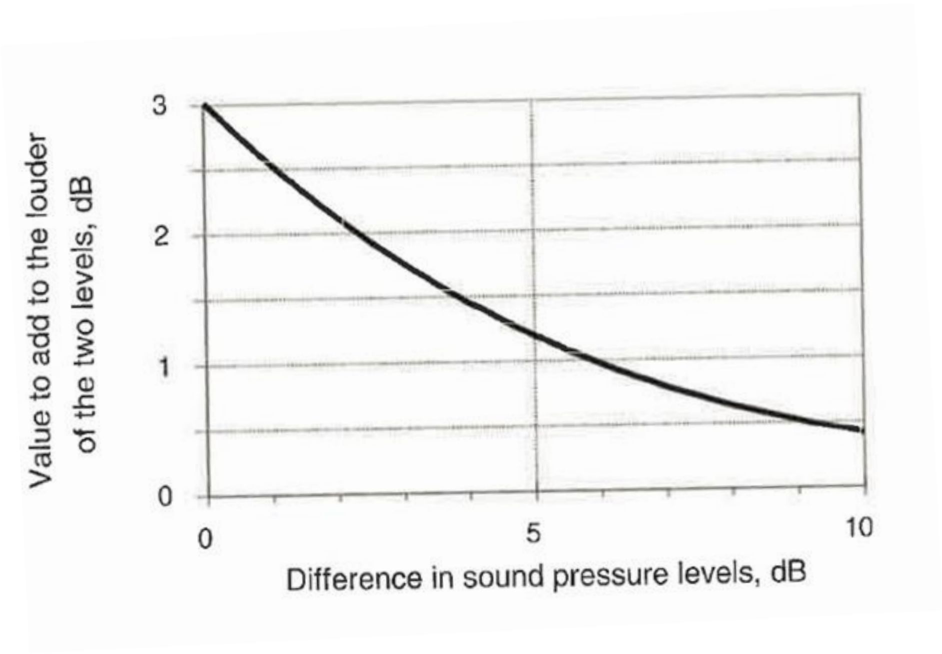


Figure 1. Curve for combination of two sound pressure levels /4/

Since sound measure instruments can capture much larger borders of frequencies than humans can, there is different weighting systems for how devices and humans perceive sounds. A-weighted decibels, abbreviated dB(A), are an expression of the relative loudness of sounds in air as perceived by the human ear. In the A-weighted system, the decibel values of sounds at low frequencies are reduced compared with unweighted decibels. Human ear is less sensitive at low audio frequencies, especially below 1000 Hz, than at high audio frequencies. B-,C-, Z-weightings are used for those noise measurements where it is needed to take into account very high or very low values that can't be perceived my human ear. /3./

2.2 How do humans perceive sounds?

As it was already mentioned, normally humans hear sounds that have sound pressure level interval from 0 to 120 dB and frequency range between 20 and 20000 Hz. When it comes to perception of sound changes people can identify about 3 dB difference. If the difference reaches 10 dB people hear this difference like the sound becomes twice higher or lower. The table 3 provides information about humans' sound difference perception.

Table 3. Relationship between perceived loudness and sound pressure level /4/

Change of sound pressure level, dB	As people perceive change of loudness
1-3	Very small change
5	Evident change
10	Twice as loud
20	Great change

Figure 2 is an Equal Loudness Curve. The vertical axis is intensity and the horizontal axis is the frequency of a sound on a logarithmic scale. The contour lines are lines of equal perceived loudness for sounds at different frequencies. For example, a sound at a frequency of 30 Hz and a measured relative intensity of 80 dB (the purple point) has the same perceived loudness as a sound at a frequency of 1000 Hz and a measured relative intensity of about 30 dB (the red point). /3./

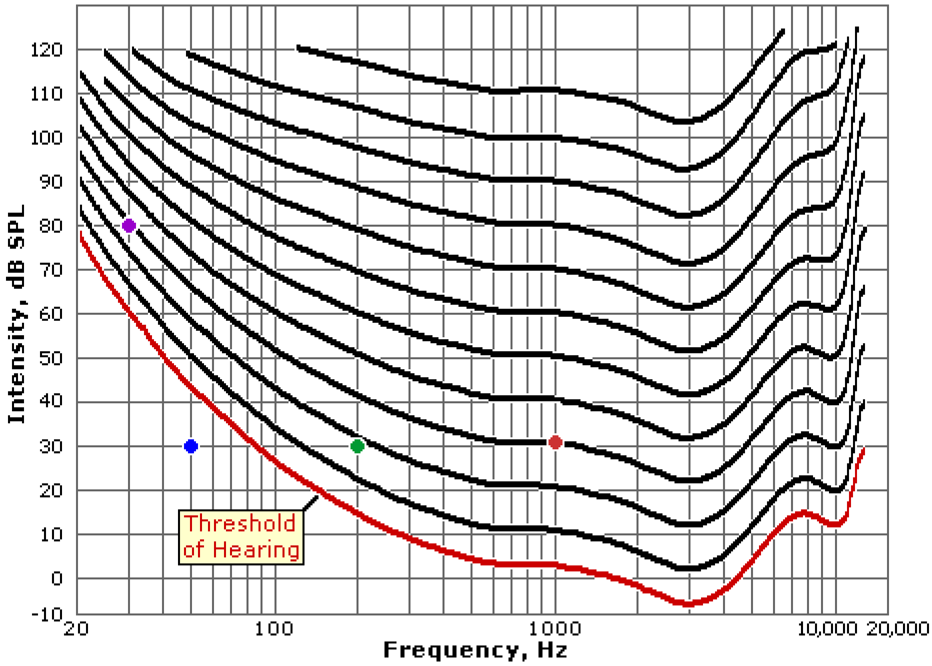


FIGURE 2. Equal loudness curve /3/

If people could hear equally well at all frequencies, the contour lines would be flat because the same measured sound intensity would be perceived to be equally loud regardless of the sound frequency. In fact, people do not hear as well at low frequencies. Therefore, the relative sound intensity has to be much greater for a low frequency sound to be perceived to be as loud as a sound at a frequency that we hear well, such as 1000 Hertz. /5./

The bottom red line in the graph is the threshold curve of human hearing. People don’t hear sounds that are below the threshold of hearing level at each frequency. For example, at a frequency of 50 Hz, people cannot hear a sound at 30 dB (the blue point). However, at a frequency of 200 Hz and intensity of 30 dB (the green point) a typical person would have no problems hearing the sound. /5./

Decibels are measured on a logarithmic scale: a small change in the number of decibels indicates a significant change in the amount of noise and the potential influence on a person's hearing. It is also necessary to take into account surround circumstances. The distance between sound source and objective and presence of reflected sound materials will influence the perception. Figure 3 depicts the changes of sound pressure level with distance and availability of reflected sound waves.

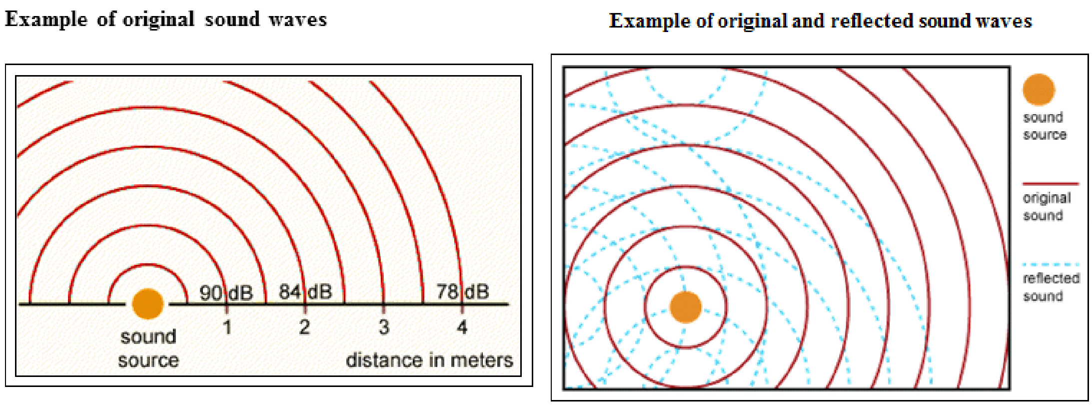


FIGURE 3. Sound pressure levels of original and reflected sound waves /5/

The duration of a noise is a crucial element for its perception and the discomfort or pleasure that it causes, without forgetting its level which may vary over time. Although hearing loss reason because of the too high sound level in surroundings is one of the most common occupational illnesses, it is often ignored because there are no visible effects. It usually develops over a long period of time, and, except in very rare cases, there is no pain.

There are some time limit recommendations for humans if the sound exceeds 85 dB. Table 4 shows that for every 3 dBs over 85dB, the permissible exposure time before possible damage can occur is cut in half. Thus, the quieter the sound, the longer humans can listen to it safely. If the sound is quieter than 80 dB, it will not result damage even if it is listened for a long time. /6./

TABLE 4. Time limits according to the volume of the sound /6/

Sound Pressure Level, dB	Sound pressure level, Pa	Permissible Exposure Time
100	2.00	15 min
97	1.42	30 min
94	1.00	1 hour
91	0.71	2 hours
88	0.50	4 hours
85	0.36	8 hours

2.3 Sound vs Noise

Noise is a kind of sound that can be described as remarkably loud one. In this regard, shouts are perfect examples of noise. They are characterized by unpleasant and annoying nature that can even lead to sensation of pain. Aside from hearing loss, noise can also induce severe cardiovascular symptoms of increased heart rate and can bring about psychological effects that manifest as anxiety, lack of concentration, and profound nervousness.

Although, discomfort because of the sound is not required a high level of decibels. Some sounds that are usually not heard due to other louder sounds can result in certain situation an annoying effect. For instance, noises from ventilation system or plumbing of water wash basin tap commonly cause occupants' temper. This means that not only sound level matters but also frequency type.

Thus, noise is unwanted sound that is usually created by someone else (not by the listener) and is compared to sound which can easily be handled or listened to by everyone. This is the reason why noise is a type of sound that is less or least desired depends if the listener participates in sound making. When there's constant, loud chattering inside the classroom, a person might easily get annoyed and other one can handle it for a while.

In terms of vibration characteristics, sound is more regular while noise has a more irregular quality that is constantly fluctuating in a seemingly uncontrolled manner. Obviously, the sound with a higher dB value is louder. Stronger sounds that start from 80 dB can already be considered as noise. A crying baby can already reach as high as 115 dB. Most safe sounds are less than 100 dB. The higher the frequency and the more annoying the sound becomes. A crying baby can cause as annoying noise as working jackhammer sound (that has the 110 dB but lower pitch) because of the high frequency. /5./

Sounds that are combinations of harmonic frequencies make patterns that are pleasing to hear. They're musical. Random patterns produce noise. On the figure 4 it is shown how frequency of musical sound and noise differs with time.

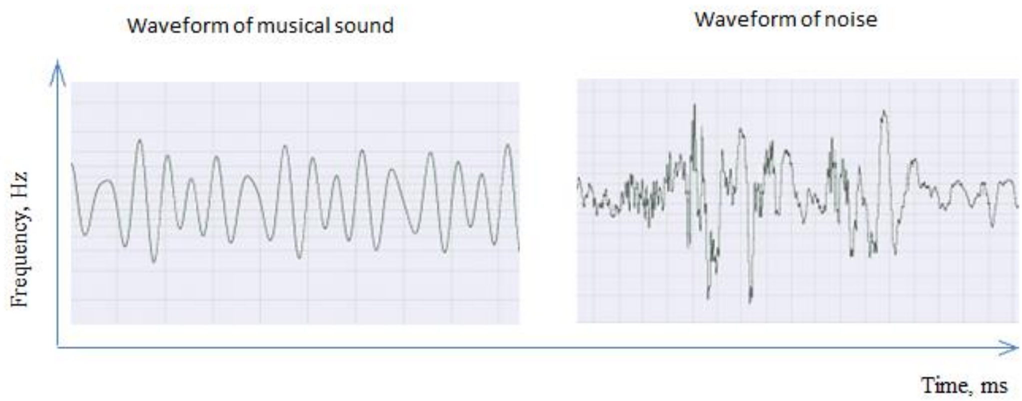


FIGURE 4. **Waveform of music sound and noise /3/**

2.4 Noises and sounds in our life

According to the survey Quality of life in European cities made by Flash Eurobarometer 366 in 2013, in 51 cities, more than 30% of respondents say they are not satisfied with the noise level in their city, while in 17 cities a majority of respondents are dissatisfied. /7./

Even though this survey describes the noise situation in general and how citizens perceive sound level throughout the day, it is highly important to take into account while talking about internal noises specifically.

The mean sound level in a dwelling is around 25 dB(A) and in the office building – 60 dB(A). These numbers depend not only on the type of the activities that are inside buildings but also on the general quality of building construction. If the building has a poor external insulation, the sound easily transmit from outside environmental to living or working areas and create higher noise level. In this case the quiescent level may reaches 30 dB(A) in dwellings and 75 dB(A) in office buildings. /5./

In order to evaluate in which case the background noise become too high, the noise-rating (NR) index is used. Figure & shows NR curves that determine SPL for different circumstances. For residential areas NR index should be 30. /4./

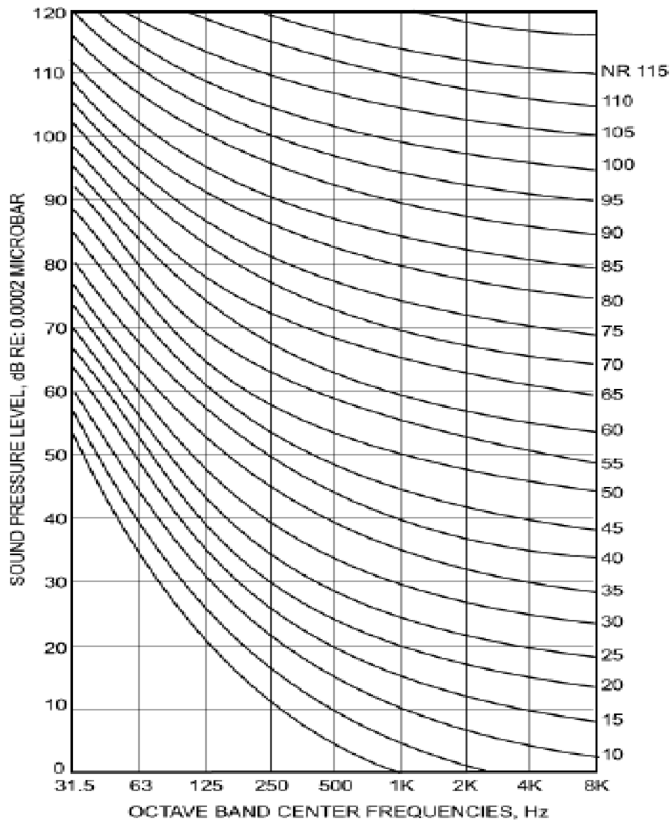


FIGURE 5. Curves for the rating noise, NR index /4/

When the sound level is above 40 dB(A) the perception of decrease or increase in the acoustic noise background of 10 dB(A) becomes greatly remarkable. The smallest difference that can be noticed by humans is at least 3 dB(A). In most cases 1 dB(A) difference won't be discernible.

Overall, noise perception depends on several factors such as loudness (measured in dB), frequency (measured in Hz), surrounding circumstances and the individual sensitivity to noise.

3 REASONS OF NOISES IN WATER SYSTEMS

Plumbing noise can be produced by different sources in water supply and in water sewage systems. Here are the most common noise problems sources:

1) faucets noise;
2) falling noise;
3) flow noise;
4) impact noise;
5) water hummer noise.

The most common case of the plumbing noise is when the water goes through any faucet, for example when flushing WC. The noise appears anyway even if there are no violations of speed, pressure and other factors. The use of the flush is the source of noise that goes further into the construction and transmits to other rooms and lower apartments. It is normal to hear flushing sound in the bathroom where the flush happened but it is not acceptable to hear this sound coming from neighbor's apartment or in other living areas of the flat. In the figure 6 the WC noise transmission to other flats is shown. Figure 6 illustrates how WC flushing noise transmits to other room and lower floor spaces.

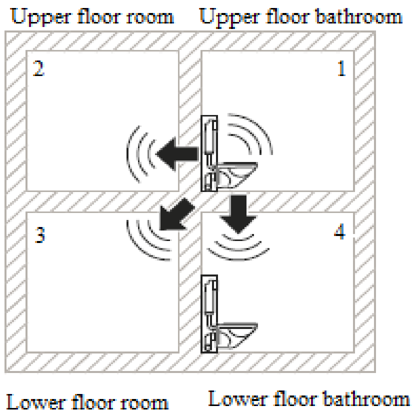


FIGURE 6. Example of flush noise. /8./

The flow noise is caused by the water as it flows along a horizontal pipeline and falling noise is generated by water as it falls down vertically inside a pipe. Between horizontal and vertical pipes there are always connections (bends) that can also create noise as water hits the bend (impact noise). In these cases falling energy is largely converted into sound energy. When considering these noise sources it is highly important to look closer at speed, slope and diameter of the pipe since these parameters are responsible of the inside the building water system processes./8./

Another frequent reason for noise disturbance is water hummer. It mainly occurs when a tap or valve is suddenly closed or during changed in water velocity, causing hydraulic shock (great pressure increase inside the pipe) waves to be transmitted through the pipe. Water hammer can also cause pipes to move if they are not well attached, resulting in even louder sound and vibrations./8./

4 NOISE TRANSMISSION THROUGH BUILDING

Once plumbing noise is generated, it is transmitted in a dwelling through airborne and solid-borne ways. Airborne sound is defined as sound waves which spread through air. Vibration of the solid object is also considered as an air borne sound. Solid-borne sound is acoustic noise which emanates from something solid. Often the main path of plumbing noise transmission is solid-borne. Wherever piping, pumps, and fixtures are mounted rigidly to a wall stud, floor joint, or other component of the building structure, sound and vibration are transmitted into the building. Plumbing noise can travel large distances and be radiated by walls, ceilings, and floors. On the figure 7 the example of airborne and solid-borne sounds is explained. /8./

As the noise travels, it can convert from one type of sound to another. Structure-borne noise may cause vibrations in a structure that will release airborne sound. In most cases the lightest parts of the structure result vibrations and, furthermore, airborne sound like joints and attachments. Airborne noise may also change into structure-borne and back to air-borne. The process of sound type changing from airborne to structure-borne and vice versa is called ‘transmission’ of sound energy./8./

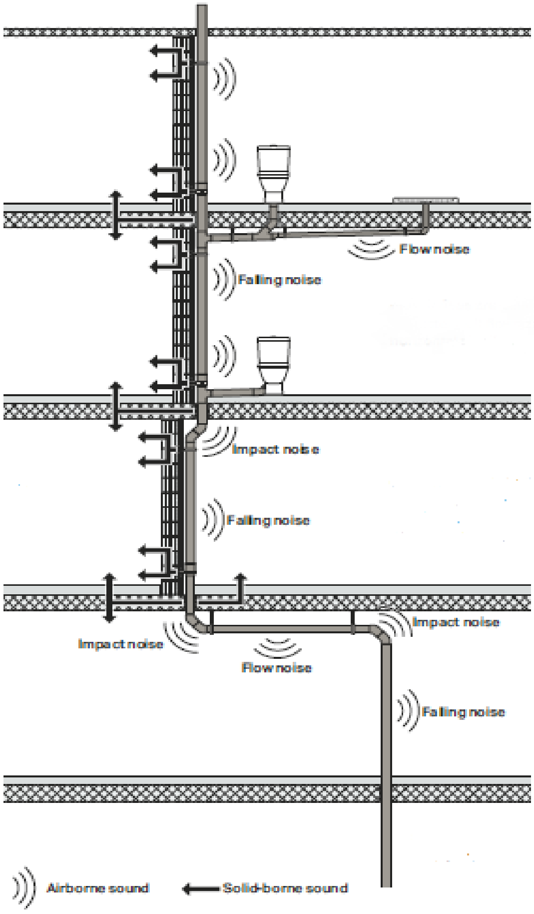


FIGURE 7. Airborne and solid-borne sound transmission /8./

The type of material is really important in noise transmission. Sound spreading is more common in iron and copper pipes (compared to plastic) as metal amplifies the noise. When considering airborne and solid-borne sound transmission, it is necessary to take into account several factors such as mass and stability of the structure (since vibrations cause noise where the structure has its most unsupported and light parts) and existence of air gaps in the walls or ducts (that cause appearance and spreading of airborne noise). /8./

5 WAYS TO REDUCE NOISE LEVELS

As it was already mentioned there are different reasons and sources of noises in water systems. According to the type of the reason or source the right way to reduce noise can be chosen. In general, all the variants of noise reduction measures can be divided into two groups in terms of the building operation stage. In the first group there are factors (methods) that have to be taken into account while designing the building. In the second group there are ways to reduce the sound that can be used during the construction stage as well and in some cases when the building is already utilized by occupants.

The first factor that must be considered during designing stage is water pressure. Water pressure has a great influence on noise cases such as water hammer and faucet sounds. The speed at which water flows from the opened outlet depends on the amount of pressure which exists at that time in the system. The higher the pressure, the louder is the noise inside pipes and noise that is generated by water flowing through faucets. Thus, while making calculations the right pressure has to be determined for the water supply system of the building.

In the water systems it is necessary to have high enough pressure for delivering water to the highest points to compensate pressure losses and for firefighting. That is why the reduction of the pressure in the whole water supply system is not a solution. Installation of decompression valve after water meter can handle this problem. Decompression valve automatically reduces the high incoming pressure from the main service line to provide a lower pressure for distribution line inside the house. It also allows to regulate water pressure inside distribution pipe with adjusting pressure in the range from 170 kPa up to 500 kPa. Thus, decompression valve could be a problem solving option if the key factor of plumbing noise is pressure. /9./

One more important factor in designing water supply and sewage systems is the material of pipes. The type of material has an impact on the noise level inside pipes when the water flows to the faucet in supply system and when it is collected in sewage system (flow, fall and impact noises). In Finland it is common to use PEX (cross-linked polyethylene), multi-layers (composite) pipes, and copper pipes in design of water supply systems. For water sewage systems in Finland the most common used materials inside building are different kinds of plastic pipes and cast iron. Copper pipes are also used but more rarely in some cases like for draining the waste water from washing machine. /10./

According to the research on plumbing noises that was performed in Canada by MJM Acoustical Consultants Inc, in water supply system plastic pipes cause less noise than copper pipes when used under the same conditions. By replacing copper pipes with plastic ones it is possible to archive up to 10 dBA reduction of plumbing sound. However, in the water sewage system the situation is different. The research disclosed that copper and cast iron pipes are quieter than plastic pipes. Replacing copper pipes with plastic ones resulted an increase of noise up to 8 dBA and replacing cast iron with plastic caused additional 10 dBA./9./

In the second group, two factors are related to the installing process and can be changed after the building process is completed. The first one is the way the pipe is attached to the frame of the building. Normally in the multi-stores buildings inside partitions' space is used to place the pipes. In most cases, these partitions are made of wood or metal frame and two layers of drywall from both sides. Preferably there should be as less connections between a pipe and a frame as possible in order to avoid sound and vibration transference. But when it is necessary metal attachments are used for fixing the pipe to the wall. In case of inadequate attachments noise causes problems since vibration from the pipe transmits through the metal attachment to the frame and then transforms into airborne sound.

The Canadian research showed that pipe inserts between pipes and the metal attachments significantly decrease the sound level in water supply systems. Depending on the type of the material inserted between the pipe and the metal attachment up to 19 dBA reduction can be reached in the wood frame case and up to 13 dBA reduction in the metal frame case in water supply systems. The example of pipe fixing with and without pipe insert is shown on the figure 8. /9./

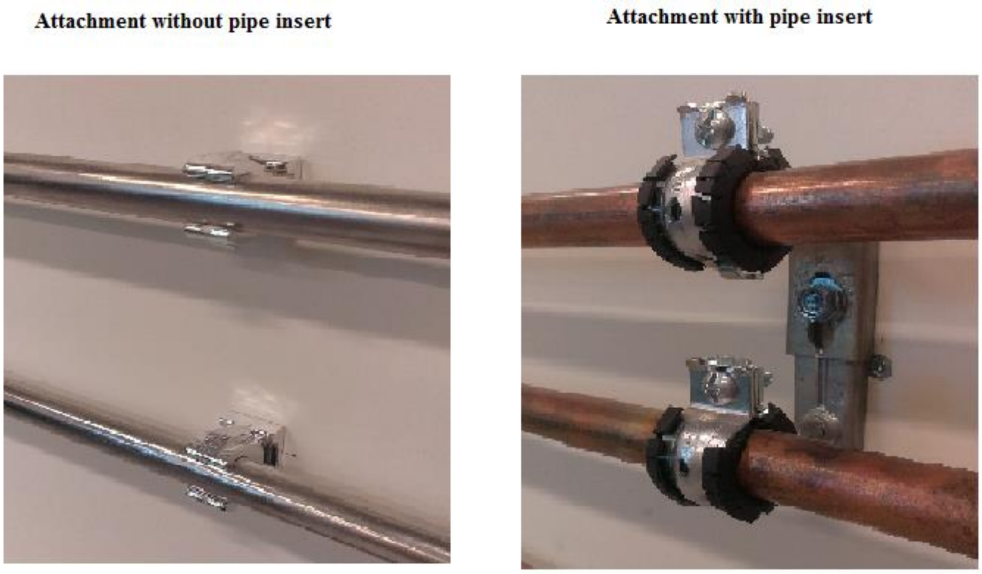
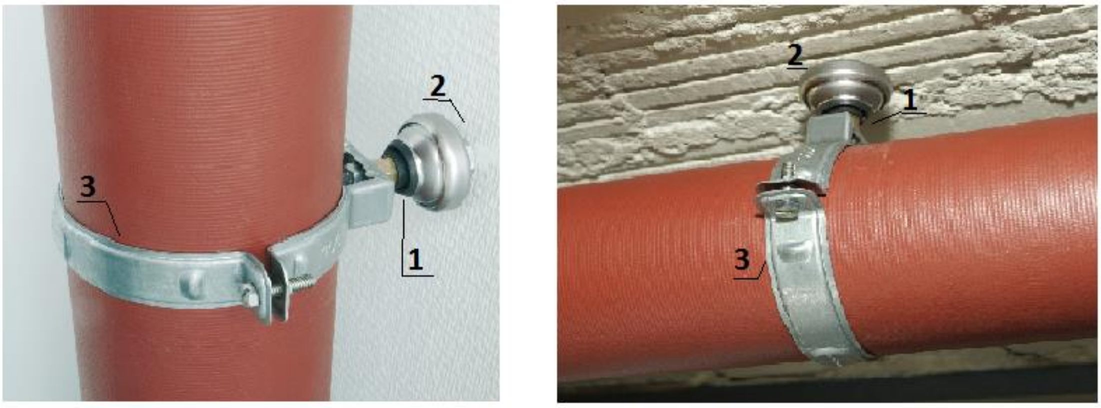


FIGURE 8. Supply pipe attachments without and with pipe insert

Nevertheless, in the waste water systems attaching vertical pipes to the frame or drywall should be avoided since it produces noise. Sometimes plumbers fix sewer pipes with wood blocks that also helps to secure pipeline. But installing a piece of wood between the pipe and the frame can result increasing sound up to 15 dBA in water sewage systems /9/.

Although in some cases it is necessary to attach vertical drain pipe due to big length or other installation circumstances. Then in order to decrease any residual contact noise the bracketing system should preferably be installed on the heaviest wall which further absorbs the noise. When choosing optimal locations of vertical pipe attaching in a multi-storey building, it is important to avoid residential areas as much as possible. /11./

Another way that can help to reduce noise transmitting is to put rubber gasket between supporting bracket and the wall attachment like it is shown on the figure 9. The rubber gasket prevents structure borne sound transmittance further to the building structure. /11./



1 - a rubber gasket; 2 - an attachment to the wall; 3 - a bracket (clamp) for pipe supporting

FIGURE 9. Sewer vertical and horizontal pipe attachments. /11. /

The second factor that has an influence on the noise level and can be corrected while utilizing water systems is the using insulation around pipes. Adding different type of the insulation like cellulose, batt, styrofoam material around the pipe can reach 5 dBA, 4 dBA, 8 dBA reduction of noise respectively.

Overall, water pressure is a significant factor in designing water supply systems and in preventing from the plumbing noise. It should be designed as low as possible and installation of decompression valves is the best way to control the pressure inside the distribution and connection pipelines. The type of pipe material plays an important role as well. The use of plastic pipes in the water supply systems is the best way to reduce plumbing noise, although, in water sewage systems it would make the sound louder. The way of attaching the pipe to the frame is the most essential factor in decreasing the noise level. The method of wrapping the insulation layers around pipes also helps to reduce noise level.

6 MEASUREMENTS DESCRIPTION

6.1 Background and aims of the measurements

The chosen building for the measurements is located in Mikkeli, Raviradantie Street. All buildings along this street were built during the period 1975-1985 and were renovated in 1994 year. The design of the floors is identic – on each floor there is the same amount of flats that has the same number of rooms and the same equipage of faucets in kitchens and in bathrooms.

One of those buildings has been chosen since the dwelling characteristics are typical for the area of the research. The building itself was built in 80's. Three storey building is common for this town and the flat design doesn't have any special parameters. The number of faucets is standard as well – WC, wash basin, shower in bathroom and sink in kitchen.

Two occupants from the chosen building corresponded a permanent plumbing noise level during day and nighttime. Their flat is situated on the first floor and it contains two bedrooms, kitchen area and a bathroom. The plan of their flat is shown on the figure 10. Both occupants complained about the plumbing noises they can hear from apartments above while using bathroom and when being in the kitchen area. The occupant from the bedroom 2 can also hear plumbing noises from the bathrooms above during night while being in her room.

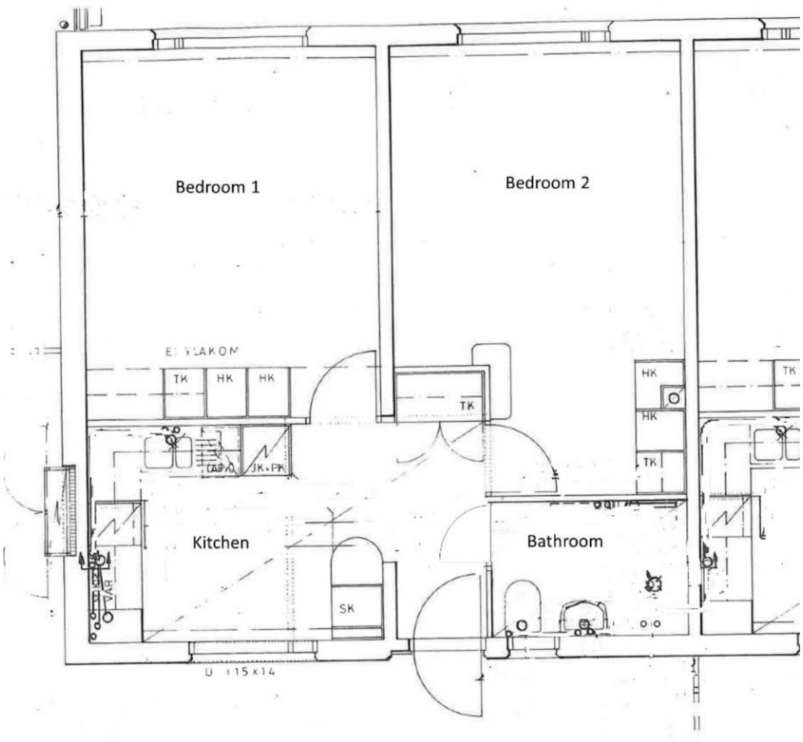


FIGURE 10. Plan of the apartment

The aim of the measurements was to determine the noise level in three areas of the flat when the bathrooms above where used and to find out when noises reach the highest level. For this purpose not only sound measurements were made but also water flow rates of the faucets were dimensioned for calculating water speed values inside water supply pipes.

6.2 Measuring process

All the measurements took place on the first floor of the building, inside the apartment of the occupants that corresponded high noise level in their flat. There were five parts of the measuring process with different faucets using cases. Measurements were made with the help of Nor140 Sound Analyser device. Each measurement duration time was fifteen seconds. The measuring place of the instrument was in the middle of the area on 1.5 m high as it is shown on the figure 11.

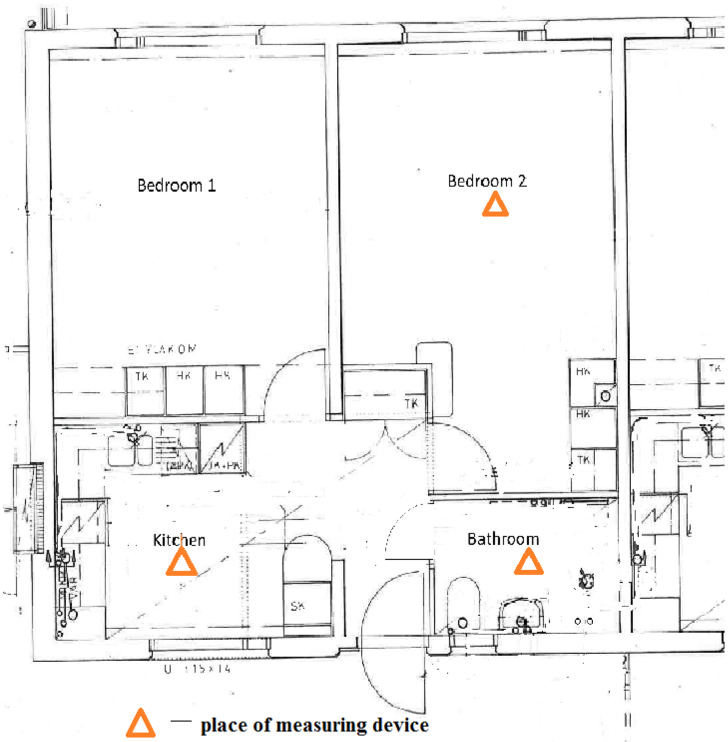


FIGURE 11. The layout of measuring places

In the first part, sound measurements were made when bathroom faucets were used on the second floor only. In the second part, the third floor bathroom faucets were used. In the third part faucets were used on the second and the third floors. These were sewage sound measurements so the noises have been coming from flushing the toilet or opening fulfilled wash basin.

The fourth part contained measurements of water supply noises coming from second, third and both floors. In this case of both floors using faucets, sound was measured when wash basin was opened on second floor and shower was opened on the third floor. The fifth part of the measurements consisted of dimensioning the water supply noise level in kitchen and bedroom 2 areas in the flat on the first floor when their bathroom was used in order to evaluate the quality of insulation in general inside the flat. In this case hot and cold water measurements were made separately for checking if there are any parameter differences between cold and hot water supply systems.

Before water system sound measurements it was needed to measure background sound in order to identify afterwards what sounds belong to the plumbing noises and what sounds belong to other sources from outside or inside. Background noise was measured in the bathroom, kitchen and bedroom 2.

6.3 Highlights of the measurements

The average values for background noise are 34 dBA, 32 dBA, 29 dBA in the kitchen, bathroom and bedroom respectively. The average sound level in the flat was 32 dBA.

The noises created by flushing WC and opening fulfilled wash basin from the second floor had the same loudness– 46,5 dBA in bathroom. Values measured in kitchen and bedroom were almost the same as well when using WC and wash basin on the second floor – 44 dBA and 36 dBA respectively. During these measurements the door to the bathroom was opened. When measuring the same case but with the closed door the noise level reduced by 11 dBA in the kitchen and 4 dBA in the bedroom.

In the second part of the measurements the same faucets were used on the third floor. In this case the noise difference between flushing WC and using wash basin was more evident. The average value of noise created by WC was 32.4 dBA in the flat. The average value of wash basin plumbing noise was up by 4 dBA. Nevertheless, third floor mean values were lower than mean values from the second floor by 6 dBA.

It is interesting to note, that the plumbing average noise level in the third case (when 3rd floor WC and 2d floor wash basin were used) was almost the same as in the first part of the measurements. In the bathroom the plumbing noise measurement showed 47 dBA, in the kitchen 36 dBA, in the bedroom 34 dBA.

In water supply measurements the values from three different cases were similar as well. The average wash basin plumbing values were 42 dBA, 38 dBA, 42,5 dBA when wash basin tap was opened on the second, third and both floors respectively. The additional water supply measurement was made with the open shower tap on the third floor and the opened wash basin tap on the second, but the result didn’t change comparative to two opened wash basins.

The fifth part consisted of cold water supply measurements and hot water supply measurements. It was made so in order to find out if there any difference between cold and hot water supply parameters since the consumption of cold water is usually much higher. The results were almost the same – maximum 2 dBA difference between cold and hot water values. Interestingly, the noise from the wash basin was around 2.5 dBA higher than the shower noise when measured in the kitchen and bedroom.

7 ANALYSING THE RESULTS

The analysis of the measurement results will consist of several parts. In the first part sound pressure levels in the residential area over measuring time will be considered and compared to the National Code limits to check if they meet the requirements. Second part will provide more detail information about SPL in terms of one third octave bands. Then, SPL lines will be calculated in reference of octave bands and compared to the standard NR curve that represents normal SPL in residential area. Final part will consist of taking into account A-weighting system that represents human hearing features and identifying on which frequencies noises should be reduced. In case of higher supply noise results water speed calculations will be made.

In order to provide clear explanations of measurements results processing, bedroom location was chosen as an example of all calculations and analysis since bedroom is the most significant residential area in the flat where sound requirements are the strictest. Analysis will be made for all faucets used cases – sewage, supply and inside flat supply measurements. Diagrams with SPL measurement results for all cases can be found in Appendix 1.

7.1 Sewage measurements

Sewage measurements on the second, third and both floors will be considered first. In the last case with both floors, wash basin was used on the second floor and WC was used on the third floor. Table 5 provides information about average sound pressure level during 15 measuring seconds in A-weighting system that was received from the measuring device.

Table 5. Sound pressure level in case of sewage measurements

Location and faucets	L_{pAeq}, dBA
Background noise	27.8
2nd floor, wash basin	32.8
2nd floor, WC	36.2
3rd floor, wash basin	36.3
3rd floor, WC	29.9
2nd and 3rd floors, wash basin and WC	31

In accordance with The National Building Code of Finland C1 the sound pressure level in dwellings should be 33 dBA in kitchen and 28 dBA in other residential rooms and must not exceed 38 dBA and 33 dBA for the same areas respectively /12/. Before the measurements the sound wasn't louder than it should be (27,8 dBA). Although, it is clear that when faucets were used all measurement noises exceed the limit for bedroom where L_{pAeq} should be 28 dBA. For further investigation it is important to find out on which frequencies SPL is higher than the standards.

The figure 12 provides information about sound pressure levels in reference of frequencies. On the vertical axis the sound pressure level is shown in decibels. On the horizontal axis one third octave bands are shown. Using this table it is possible to determine on which frequencies the sound has the biggest loudness. Background sound is shown on the figure as well in order to compare noise situation before using faucets and after.

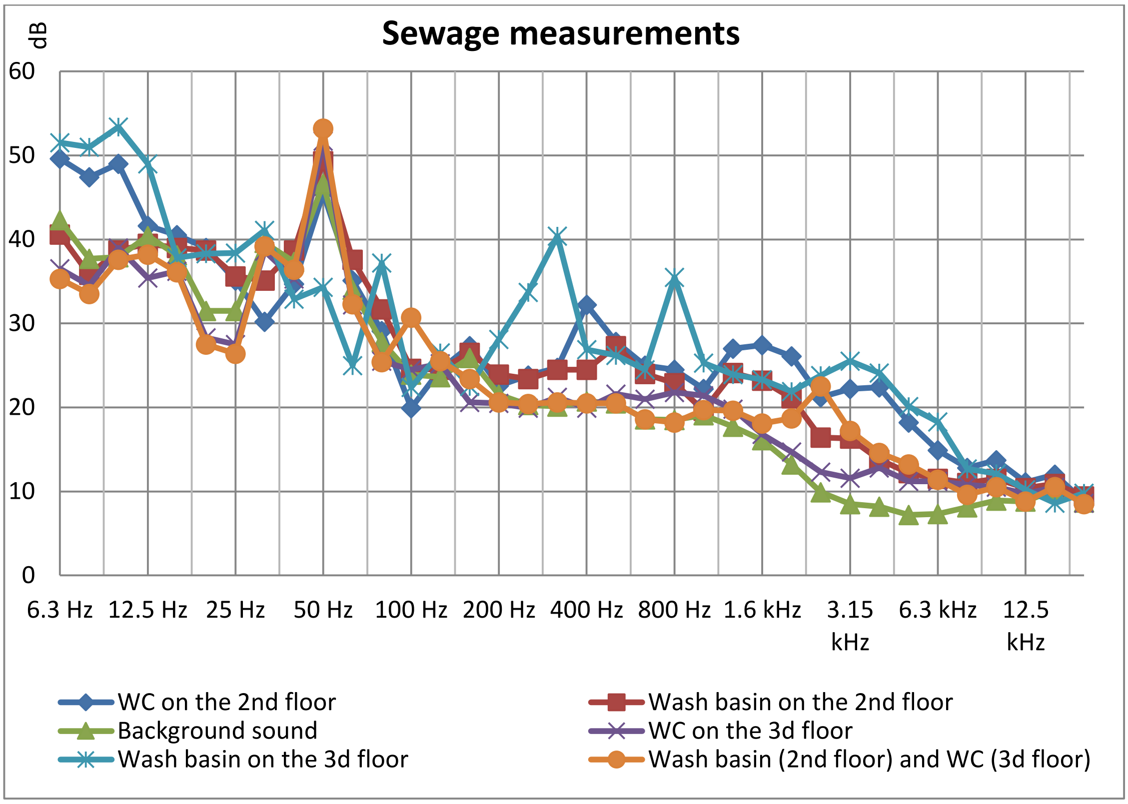


FIGURE 12. Sewage measurements and background sounds in the bedroom

These measurements were made with one third octave bands for having more precise results. Although for making analyzes and comparing with required standards it is necessary to calculate sound pressure levels with octave bands. Using formula 3 it is possible to calculate the general sound pressure level that is created on different octave bands. /4 /.

$$L_p = 10\log\left(10^{L1/10} + 10^{L2/10} + 10^{L3/10} + \cdots + 10^{Ln/10}\right) \quad (3)$$

where L_p is total sound pressure level of octave bands (dB), L_1 is sound pressure level . of first chosen (measured) octave band (dB), L_2 is sound pressure level of second octave band (dB), L_3 is sound pressure level of third octave band (dB), n is the number of octave bands.

Using formula 3 the octave band SPL can be calculated based on one third octave band results. Sound pressure level will be calculated for middle octave bands which will include upper and lower octave bands as well. Here is one example of octave band calculation. It is taken from the second floor measurement case when using wash basin.

Lower, middle, upper frequencies are 800 Hz, 1 kHz, 1.25 Hz and sound pressure levels are 22.9, 19.6, and 24.1 respectively. The sound pressure level of the octave band is calculated for the 1 kHz frequency (since it is a middle octave band).

$$L_p = 10\log\left(10^{22.9/10} + 10^{19.6/10} + 10^{24.1/10}\right) = 27.3 \text{ (dB)}$$

Thus, L_p is the sound pressure level of 1 kHz octave band that represents three octave bands at once. Using this formula, all measurement cases were calculated with octave bands. Thus, figure 13 shows same measurements but with octave bands. For other measurement cases in bathroom and kitchen areas these tables are shown in Appendix 1. The calculated information is given only for audible frequencies since these values are important in terms of the thesis topic.

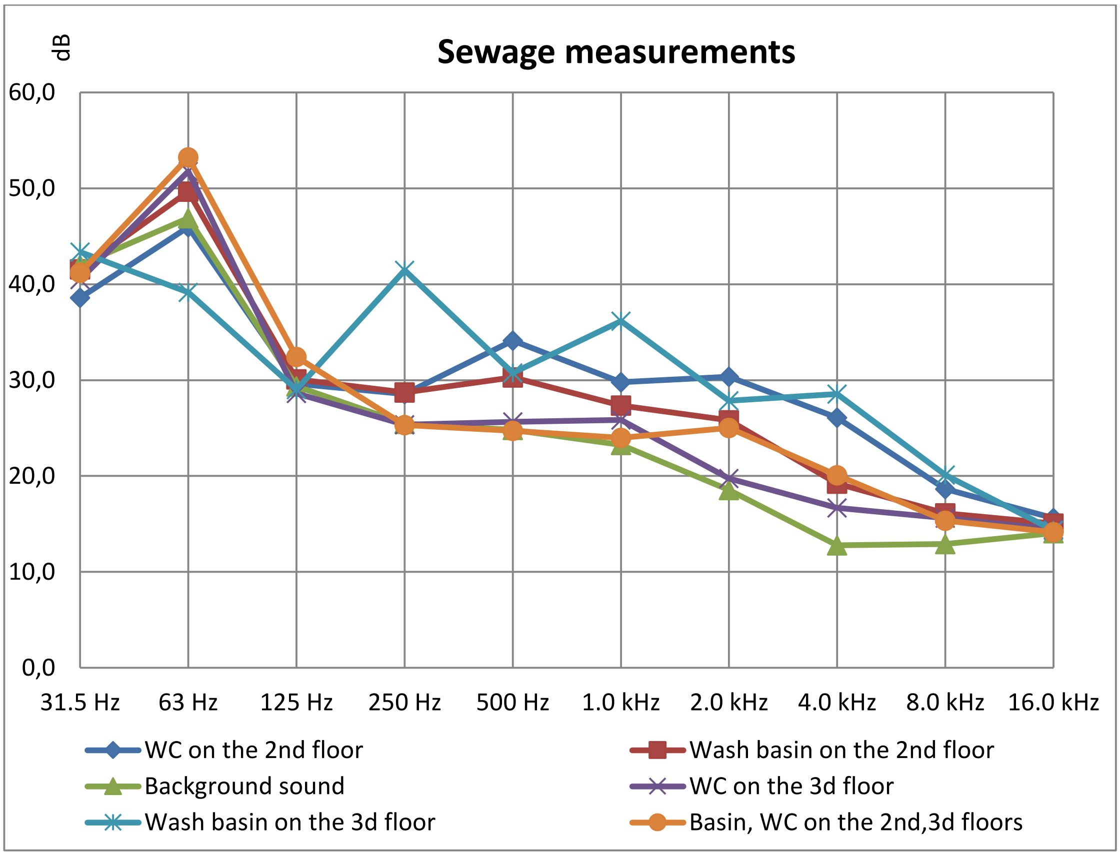


FIGURE 13. Sewage measurements in bedroom with octave bands

After calculating SPL with octave bands it is possible to check where sound pressure level exceeds standard values by comparing SPL lines of the measurements with NR index curve which represents standard SPL values in accordance with octave bands. For dwellings NR curves 25 and 30 are used. All NR curves can be found in Appendix 2. Figure 14 explains on which octave bands frequencies sound pressure level has to be reduced. NR index curve is marked with black color and it represents normal SPL for residential area. /4./

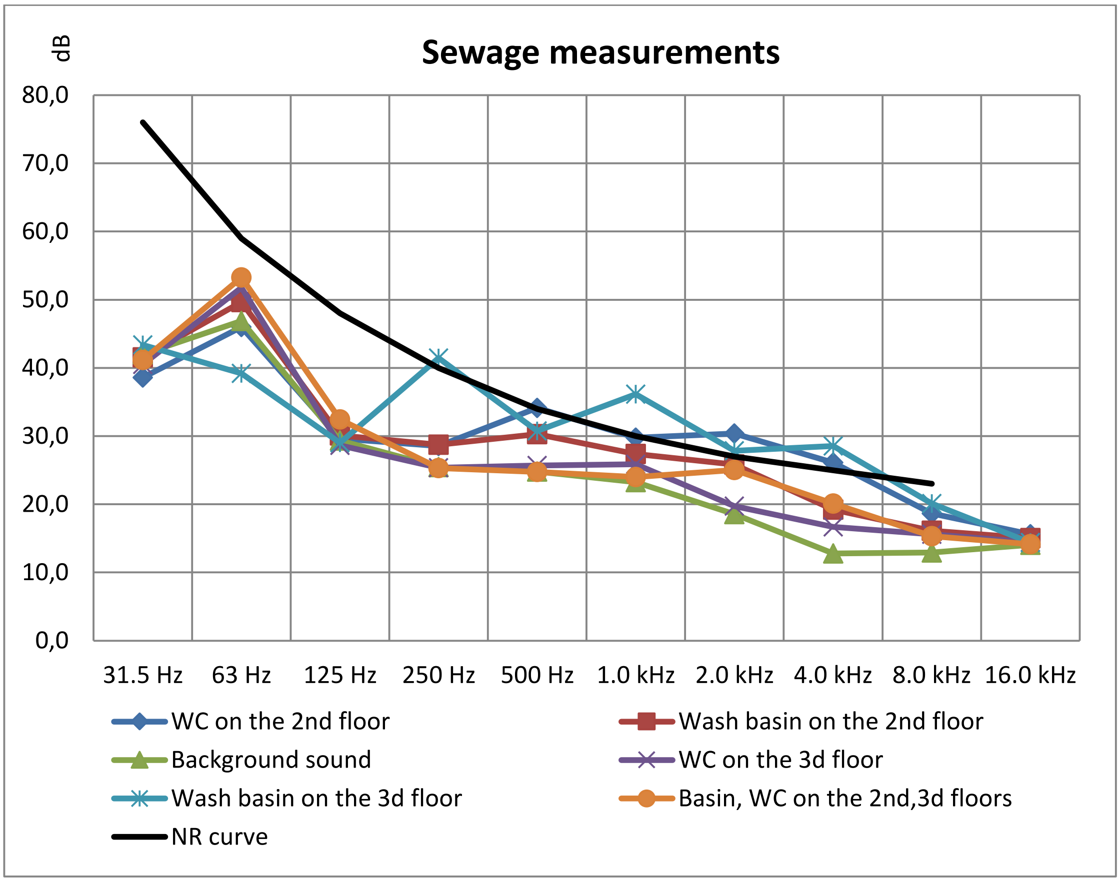


FIGURE 14. Sewage measurements in bedroom with octave bands and NR curve

7.2 Supply measurements

Table 6 provides information about average sound pressure level during 15 measuring seconds in A-weighting system that was received from the measuring device.

Table 6. Sound pressure level in case of supply measurements

Location and faucets	L_{pAeq}, dBA
Background sound	27.9
Wash basin on the 2nd floor	32.1

Wash basin on the 3rd floor	31.9
Wash basin on the 2nd and 3rd floors	33
Wash basin on the 2nd floor and shower on the 3rd floor	32.8
Wash basin (cold water) on the 1st floor	38.8
Wash basin (hot water) on the 1st floor	38.1
Shower (cold water) on the 1st floor	36.9
Shower (hot water) on the 1st floor	37.6

As it was mentioned before the sound level should be 28 dB in bedroom and before the measurements the background sound level met this requirement (27,9 dB). Although, when measurements started the results were higher than the standards again. Figure 15 provides detailed information about sound measurement results in bedroom when water supply faucets were used on the 2nd, 3rd and both floors.

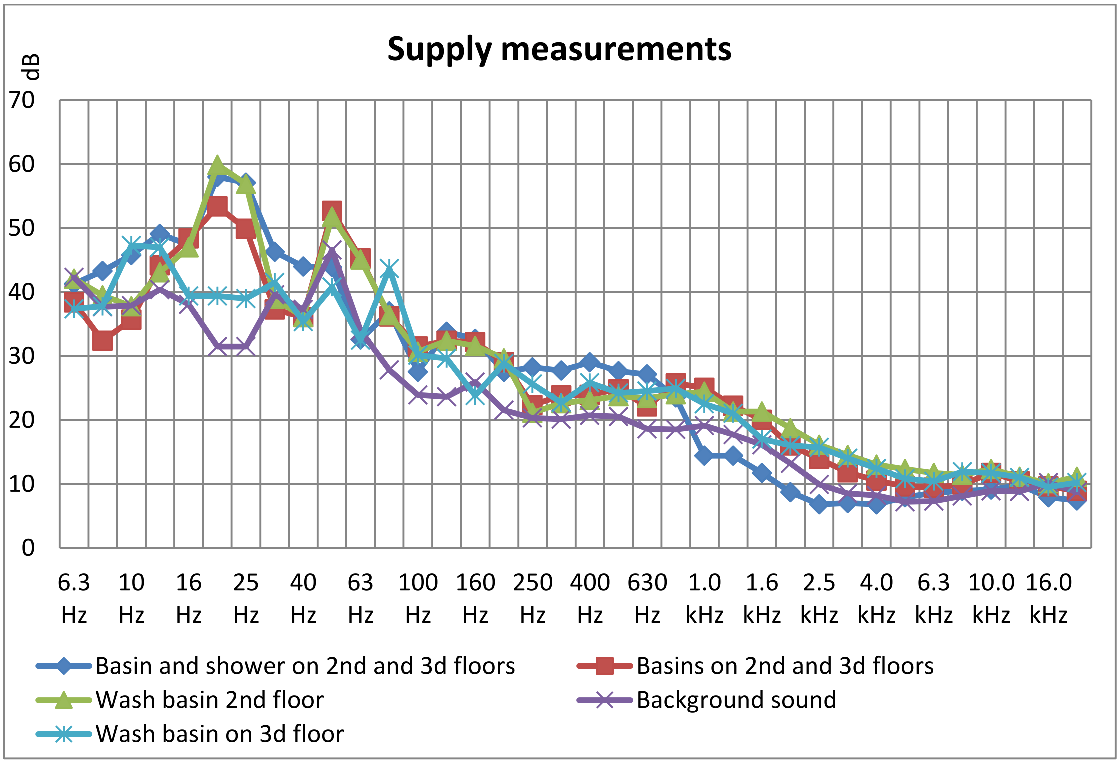


FIGURE 15. Supply measurements in bedroom with one third octave bands

Following the same analyzing method that was shown in the sewage measurement case, it is needed to calculate SPL on octave bands and compare with NR curve that represents standard values for living areas in dwellings. Figure 16 depicts this sound supply measurements and NR curve.

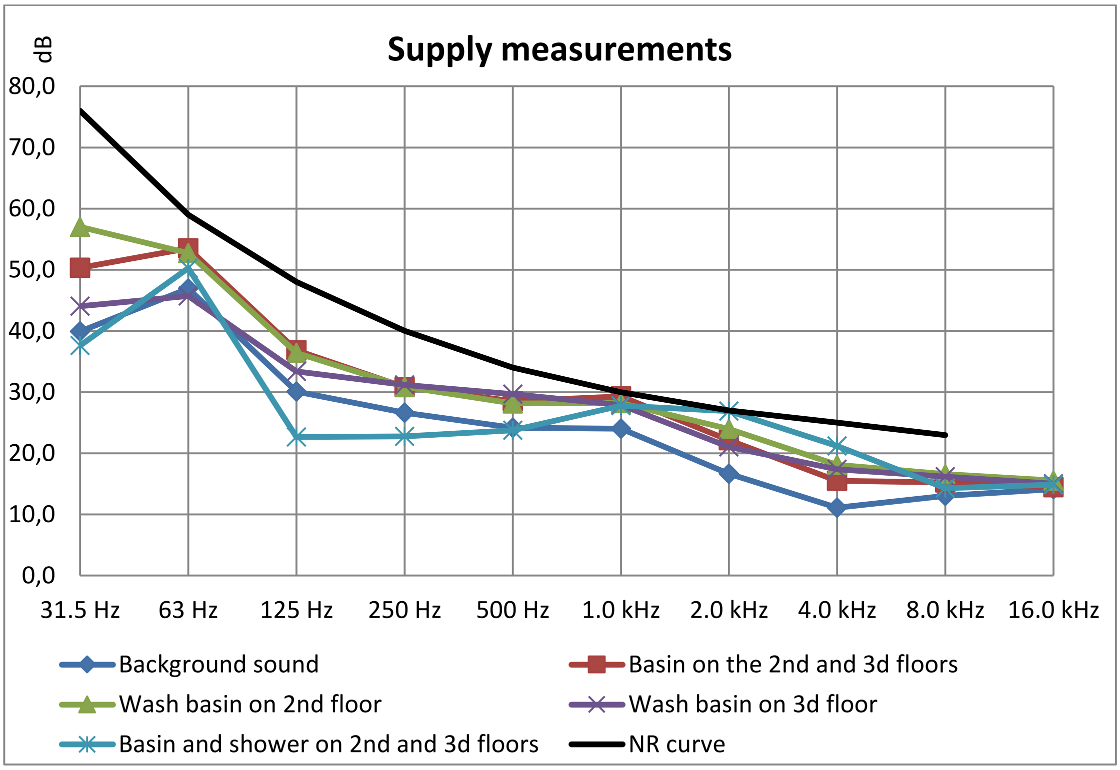


FIGURE 16. Supply measurements in bedroom with octave bands and NR curve

Same method and calculations were used for supply measurements that were performed on the 1st floor. Figure 17 shows original values with one third octave bands.

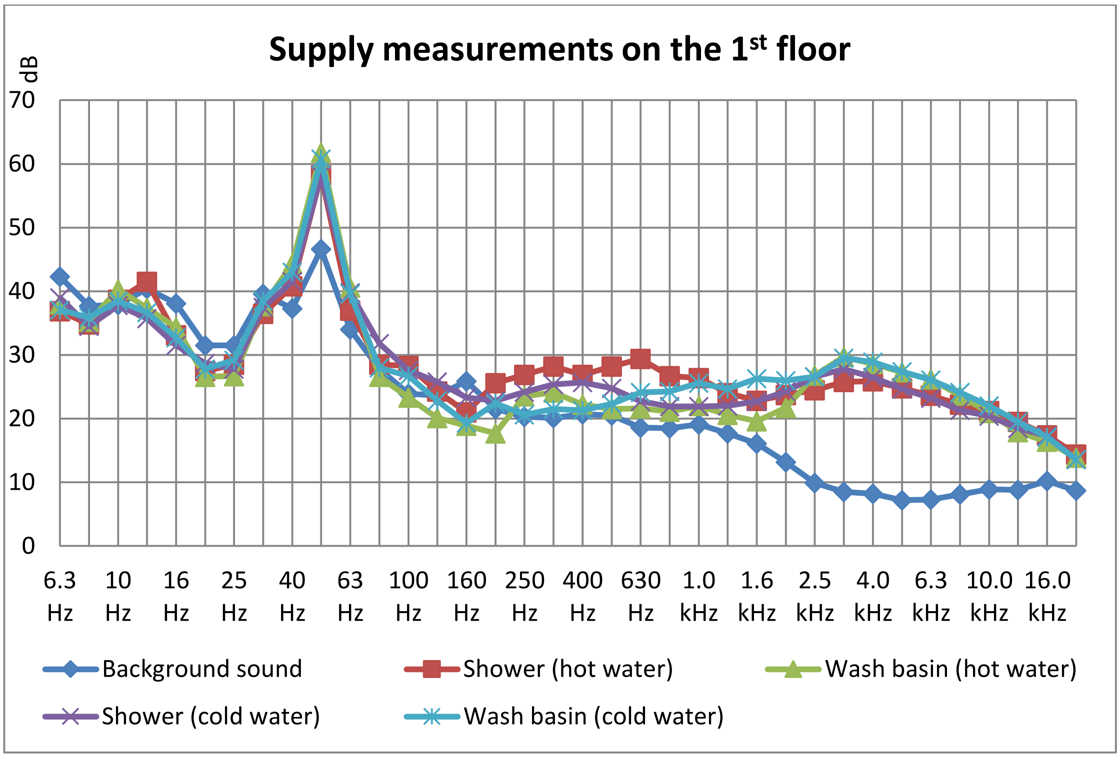


FIGURE 17. Supply measurements in bedroom with one third octave bands

Figure 18 shows SPL in bedroom after octave bands calculation with NR curve in 1st floor supply measurement case.

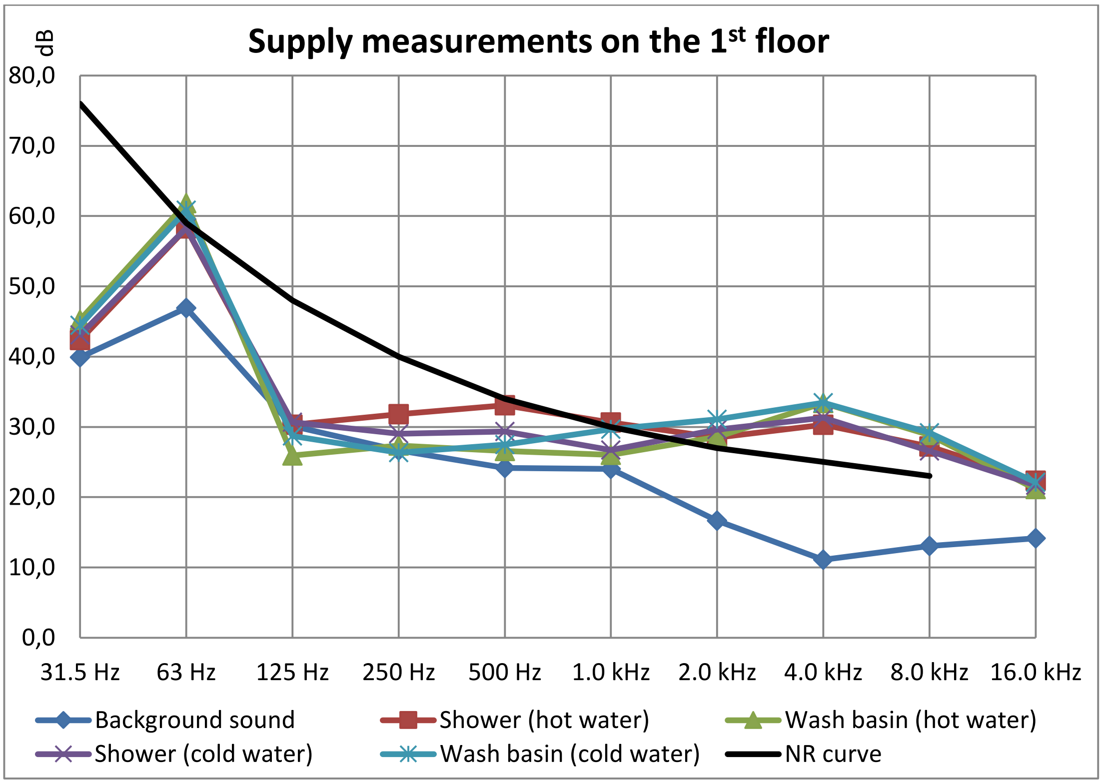


FIGURE 18. Supply measurements in bedroom with octave bands and NR curve

Thus, as it is easy to notice that in most cases SPL values are higher than the NR curve on frequencies between 500 Hz and 16 kHz. In terms of best frequencies ranges that human can hear, octave bands from 500 Hz to 4 kHz will be considered when choosing insulation type since in A-weighting system SPL is reduced on octave bands starting after 4 kHz.

7.3 A-weighting system SPL changes

As it was already mentioned in theory background of sound part, sound measuring devices capture sound levels on greater range of frequencies and fix them much more precise than human ears do. That is why it is needed to find out on what are the noises that occupants hear while measurements. Thus, previous diagrams should be converted into A-weighting system that represents human hearing features.

Figure 19 explains how exactly sound level will change in A-weighting system. As an example it is shown on the supply measurements on 1st floor diagram. All the lines that shows SPL in different areas show the results that were received from the measuring device.

The dark red area shows where sound level will be reduced due to too low or too high frequencies that human hear less. Green area shows where increase of sound loudness starts and up to 0.6 dB should be added to the SPL value on these area. Orange area represents frequencies range that people hear most clearly. That is why up to 1.2 dB should be added to SPL values. Blue area has up to 1 dB addition to sound loudness.

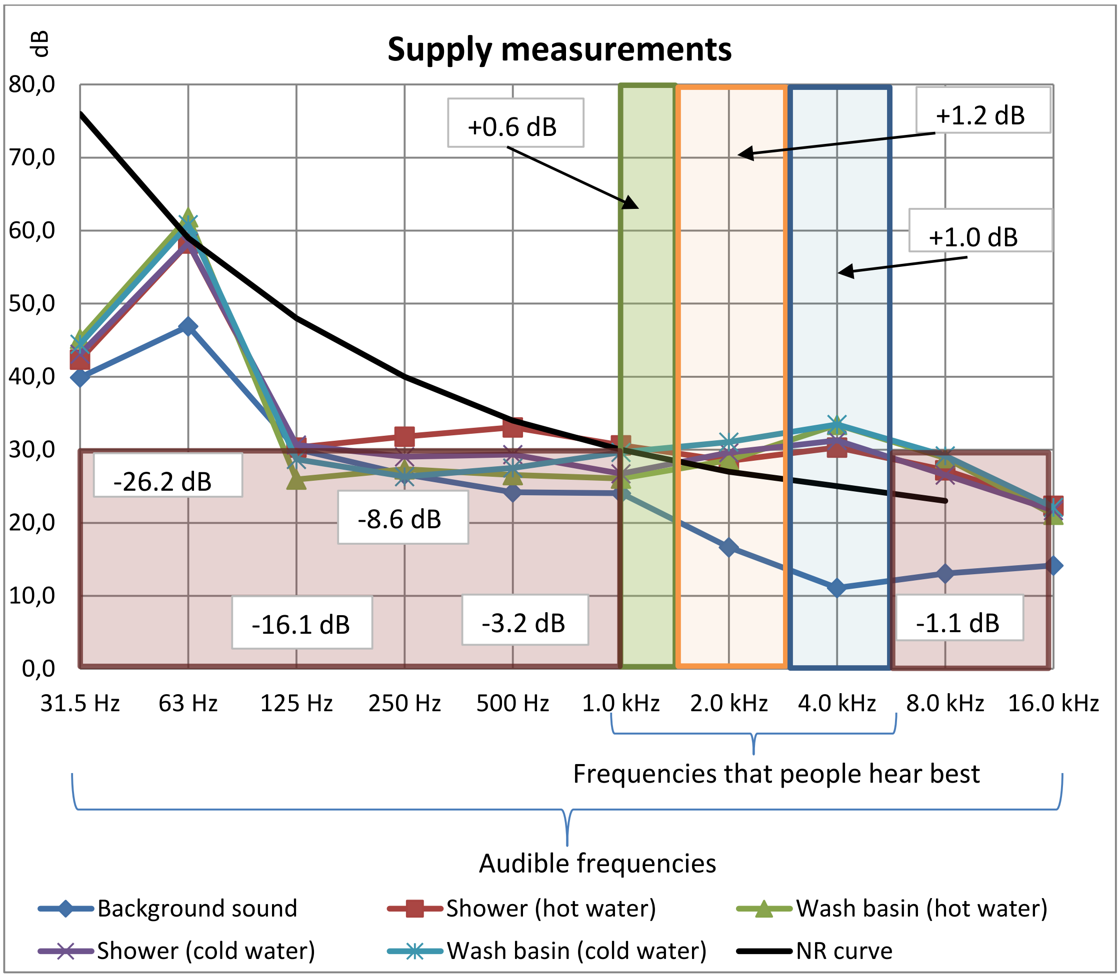


FIGURE 19. A-weighting system diagram with supply measurement example

This A-weighting system diagram is based on the table in Appendix 3. These changes are applied to all measurement cases. It means that it is important to pay attention to the SPL on the octave bands from 1 kHz to 4 kHz since main noises that humans hear are located there.

7.4 Water speed calculations

As part of measurement process, water flow rates of showers and wash basins on the second and third floors were measured when taps were fully opened. Water flow rates were 11 l/min, 13 l/min of wash basin and shower on the second floor and 9 l/min, 12 l/min of wash basin and shower on the third floor respectively.

In accordance with The National Building Code of Finland C1 the sound level in dwell-ings should be 33 dB in kitchen and 28 dB in other residential rooms and must not exceed 38 dB and 33 dB for the same areas respectively /12/. As measurements showed, in some cases the sound level of the apartment doesn't meet requirements.

In order to check if there are any violations of speed inside pipes it is necessary to calculate water velocities (v) with following formula (4)

$$v = \frac{q}{A} = \frac{4\,q}{\pi\,d^2} \tag{4}$$

where q is flow rate (m^3/s), A is area (m^2), d is diameter of the pipe (m).

According to the measurement results flow rates of wash basin and shower on the second floor were 0.18 l/s (11 l/min) and 0.23 l/s (13 l/min) respectively. The diameter of the supply wash basin pipe is DN 10 mm (inner diameter is 8,4 mm) and the material is copper. Knowing these parameters it is possible to calculate water velocity inside wash basin pipes.

$$v = \frac{4*0.18*10^{-3}}{3{,}14*(8{,}4*10^{-3})^2} = 3{,}25 \text{ m/s}$$

The diameter of the supply shower pipe is DN 12 mm (inner diameter is 10 mm) and the material is copper. The velocity inside shower pipes will be:

$$v = \frac{4*0.23*10^{-3}}{3{,}14*(10*10^{-3})^2} = 2.92 \text{ m/s}$$

According to the D1 Water supply and drainage installations for buildings the velocity inside connection pipes must be less than 3 m/s /13/. Thus, it is clear that water velocity of wash basin pipes is higher than it should be, meanwhile, shower water velocity meets requirements.

Identical calculations should be done for the third floor faucets. The designing parameters (material and diameters) are the same for wash basin and shower. Flow rate values are 0.15 l/s (9 l/min) for wash basin and 0.2 l/s (12 l/min) for shower.

$$v = \frac{4*0.15*10^{-3}}{3{,}14*(8{,}4*10^{-3})^2} = 2{,}7 \text{ m/s}$$

$$v = \frac{4*0.2*10^{-3}}{3{,}14*(10*10^{-3})^2} = 2.54 \text{ m/s}$$

8 NOISE PROBLEM DISCUSSION

As a first step of identifying the noise reason, all possible factors, that were described in chapter 3 (Reasons of noises in water systems), will be considered as a potential noise source. When identifying the noise reason, all measurement cases in each area (bathroom, kitchen, and bedroom) will be taken into account. The section 6.3 (Highlights of the measurements) provides information that is used in the further discussion.

When performing water supply and sewage measurements no faucet sounds were found. Flushing WC itself didn't cause higher than usual noise as well as opening wash basin tap or shower tap. This means that the faucet noise can't be the main reason of higher noise level in this apartment

Sewage measurements showed that after flushing WC or using wash basin on the second and third floors waste water flowing through drain pipes result noises that can be heard on the first floor. This means that flowing, impact and falling noises appear. In this measurement circumstances it is impossible to separate flowing, impact and falling noises from each other, thus, they are considered as one noise source.

It is interesting to note that the sewer noise level caused from the second floor was higher than from the third floor in most cases. This can be explained by the fact that there is poor sound insulation between second and first floor and in the dwelling in general. That is why sound easily transmits from the second to the first floor since there aren't any materials that could absorb noises. In case with the third floor there is bigger distance between floors and sound waves spread more on their way. Although, sewage measurements in bedroom showed that there was a case when plumbing noise from wash basin resulted 36.3 dB. This can be explained by the fact that in some cases velocity of water going vertically down from the third floor is high enough to compensate bigger distance and cause high sound loudness.

Water supply measurements showed that there were no violations among pressure parameters. When suddenly shutting up taps of wash basins and showers on all three floors there wasn't a water hammer effect. That is why water hammer can't be a reason of plumbing noises.

Although, it turned out that there was one violation of the water system parameters. Calculations showed that on the third floor water velocities of shower and wash basin meet the requirements. However, on the second floor there is higher velocity of wash basin pipes which can result additional noise and vibration of the pipes.

Overall, it turned out that in both sewage and supply measurements there were noise sources. In sewage measurements the reason of higher noise level was flowing water in vertical, horizontal pipes and in bends. In supply measurements main noise reason came from wash basin pipe on the second floor.

Possible solutions for sewage noise problem could be improving pipe attaching method or installing new type of insulation that will capture noise frequencies better than the existing insulation. For the supply noise problem possible solutions could be regulating water flow rates which is difficult to do when the building is already in operation or installing better insulation type. Thus, improving acoustical properties of the wall (so that the sound won't transmit inside rooms) can solve both problems in sewage and supply cases.

9 SUGGESTING SOLUTION

Before choosing insulation material it is important to get to know the type of existing structure of the pipe duct and how much decibels it is necessary to reduce. The existing structure of the pipe duct is a double-layer wall. There are wood studs, two layers of gypsum and mineral wool insulation layer between them. Because of their construction, most double-layer walls weigh less than solid walls which affects their transmission loss characteristics. More weight the wall has, more sound waves it can delay. Figure 20 explains where pipes are located and gives information about structure of the duct.

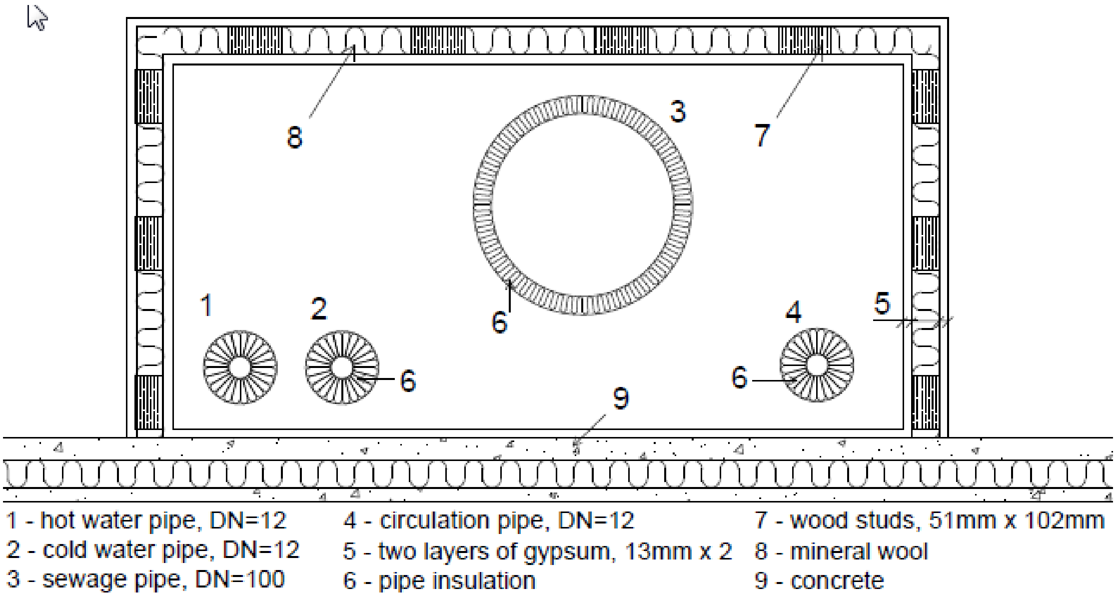


FIGURE 20. Pipe duct structure

Insulation around pipes is already installed, as well as insulation in between two layers of gypsum. Although, sound can still transmit inside the residential areas. The renovation solution can be installing a layer of new insulation material between those gypsum boards or installing other layer of material that will increase the wall weight. Before that the analysis of the noise properties will be provided in order to choose optimal solution. /14./

For calculations two measurement cases will be used: water and sewage measurement cases where L_{pAeq} values were highest. These two cases are chosen since in different types of measurements it is possible that the noise comes from different frequencies. To make sure all noises are taken into account and the sound solution will ensure acoustical comfort, sewage and supply measurements will be considered.

Table 7 provides information about octave bands sounds pressure level of water and sewage cases and calculations that determine plumbing noise parameters. First line shows SPL of the loudest sewage measurement in accordance of octave bands where wash basin was used on the 3rd floor. Second line shows SPL of the loudest measurements for supply case where wash basin was used on the 2nd floor and shower was used on the 3rd floor. Third line shows the NR curve 25 values that represent requirement sound pressure level in accordance with octave bands for bedrooms. Lines 1 and 2 will be compared with line 3 for identifying on which frequencies plumbing noises exceed the standard values. Lines 4 and 5 are the result of subtraction lines 1 and 2 from 3 line respectively. From the lines 4 and 5 the highest SPL values are chosen and shown in the line 6. Afterwards, in terms of human hearing features A-weighting system is taken into account. The line 7 represents how many decibels it is necessary to reduce so that occupants won't hear plumbing noises in the bedroom.

Table 7. Octave band SPL values of the loudest measurements

		Octave Band Center Frequencies, Hz					
		125	250	500	1000	2000	4000
1	Sewage, SPL, dB	29.6	28.6	34.1	29.8	30.4	26.1
2	Supply, 2nd and 3rd floors, SPL, dB	30.1	28.7	30.3	27.3	25.8	19.2
3	NR curve, dB	44	35	29	25	22	20
4	Needed reduction for sewage case, dB	-14.4	-6.4	5.1	4.8	8.4	6.1
5	Needed reduction for supply case, dB	-13.9	-6.3	1.3	2.3	3.8	-0.8
6	Maximum reduction, dB	-13.9	-6.3	5.1	4.8	8.4	6.1
7	Needed reduction in A-weighting system, dB	-	-	2.1	4.8	9.6	7.1

As it is seen from the line 7 SPL values that have to be reduced do not exceed 10 decibels. This means that the acoustical violations are not so great but they still result discomfort for occupants. Installing a new type of insulation in between two layers of gypsum is not necessary since needed reduction is not so essential meanwhile reconstruction of the duct will demand time and investments. Taking into account this and the fact that the building is already in operation so that any reconstructions should take as less time as possible, installing an additional layer of gypsum can be suggested as a solution. It will increase the weight of the wall and provide sound reduction enough for this case.

For checking if installing a layer of gypsum provides enough sound reduction, the formula 5 will be used. It provides information about transition loss in accordance with octave band frequency and material properties. /15/.

$$R = 20\,\lg(m) + 20\,\lg(f) - 49 \qquad (5)$$

where R is decibel reduction (dB), m is structure masse (kg/m^2), f is octave band frequency (Hz).

Below one example of decibel reduction calculation is given for 125 octave band frequency and gypsum layer that has 13 mm thickness (same thickness as other gypsum layers in the duct). The structure masse of the gypsum with 13 mm thickness is 9.5 kg/m^2 /16/.

$$R = 20\,\lg(9.5) + 20\,\lg(500) - 49 = 24.5 \text{ (dB)}$$

Thus, decibel reduction is calculated for all octave bands and all chosen cases. Table 8 shows octave band decibel reduction for chosen insulation type. Only 4 octave bands are shown in this table since these octave bands are heard best by humans and plumbing noises have to be reduced there.

Table 8. Octave band sound decibel reduction of additional gypsum layer

Noise reduction	Octave Band Center Frequencies, Hz			
	500	1000	2000	4000
R, dB	24.5	30.6	36.6	42.6

As it is shown in the table 8 the additional layer of gypsum will protect all noises at these octave bands. After these calculations it is possible to make a conclusion that installing an additional layer of gypsum will provide enough sound protection. Figure 21 provides information about duct structure after installing insulation layer between gypsum boards. This solution will prevent both air borne and structure borne noises from transmitting to bathroom and other rooms.

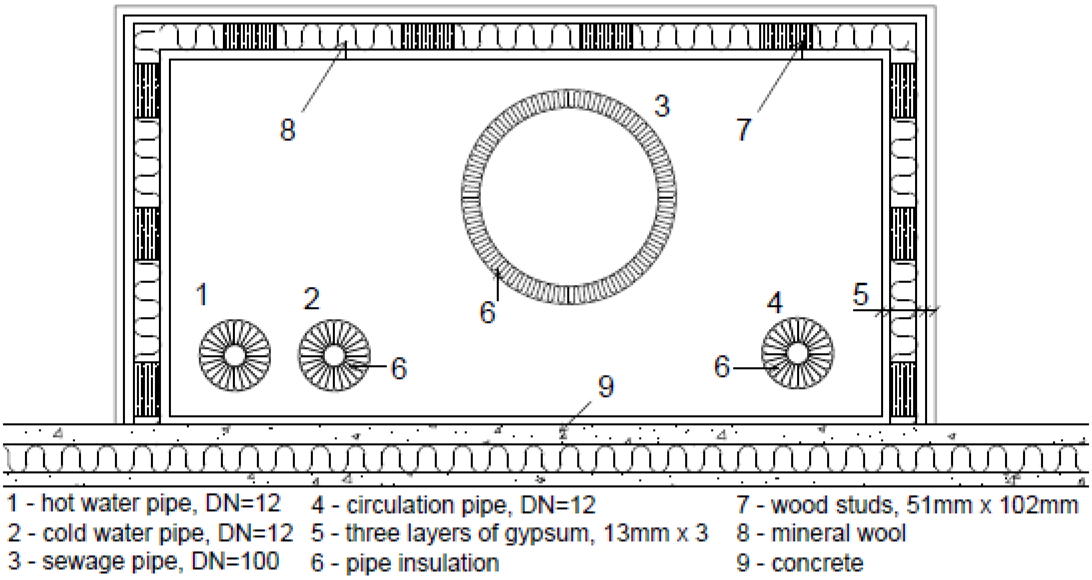


FIGURE 21. Pipe duct structure with three layers of gypsum

10 CONCLUSION

In accordance with all information that was mentioned above it can be concluded that finding a solution of a plumbing noise problem is a complex task that demands a lot knowledge of sound characteristics and water supply and sewage system field. There cannot be a one single solution that could be used in all cases when plumbing noises are detected. Each situation has to be analyzed and only after considering circumstances (like is a building in operation or not, its structure, background noise level and so on) the suggestions for improvements can be made.

Plumbing noises have to be taken into account during two stages: in building designing stage and in construction site stage. While the building is being planned it's important to consider all the parameters that can create and influence sound transmission: water flow rates, pressure inside pipes, water speed, pipe material, slopes. If these factors don't meet requirements after building is in operation it's difficult to regulate them and in some cases impossible to make any changes.

As it was already mentioned the most significant factor in installation stage is a way pipes are attached to the building structure. Using different methods of pipe attaching in accordance of pipe material and its appropriation (supply or sewage) can reduce noise level and protect building from vibration transmission. Another factor that can decrease plumbing noises is using insulation layers around pipes and installing then as a part of a building construction.

In the case that was described in this paper the most appropriate solution of plumbing noises problem was installing new type of insulation since noises were found in both supply and sewage measurements, although, noise violations were not that great and it was necessary to keep in mind that the building was already in operation which means that hole water system can’t be changed and reconstruction should take as less time as possible. That is why installation of an additional gypsum layer was chosen as a solution. Calculations showed that 13 mm thickness layer of gypsum will provide acoustical comfortable environment in residential area.

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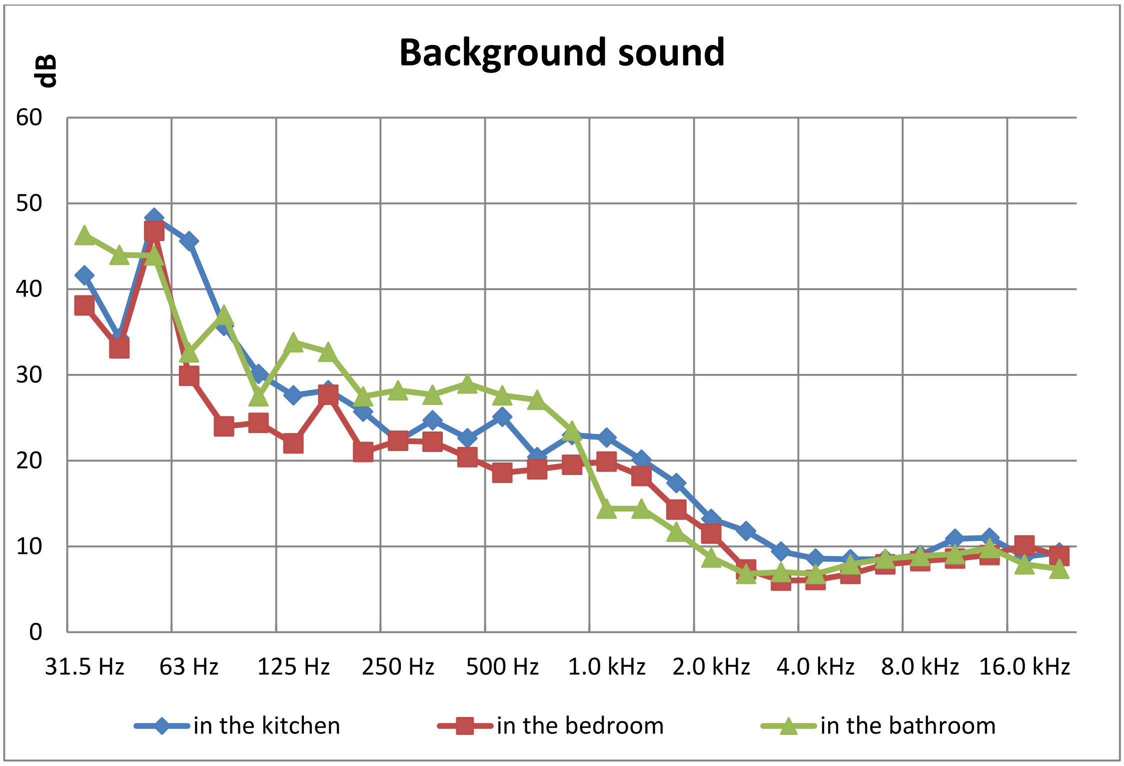
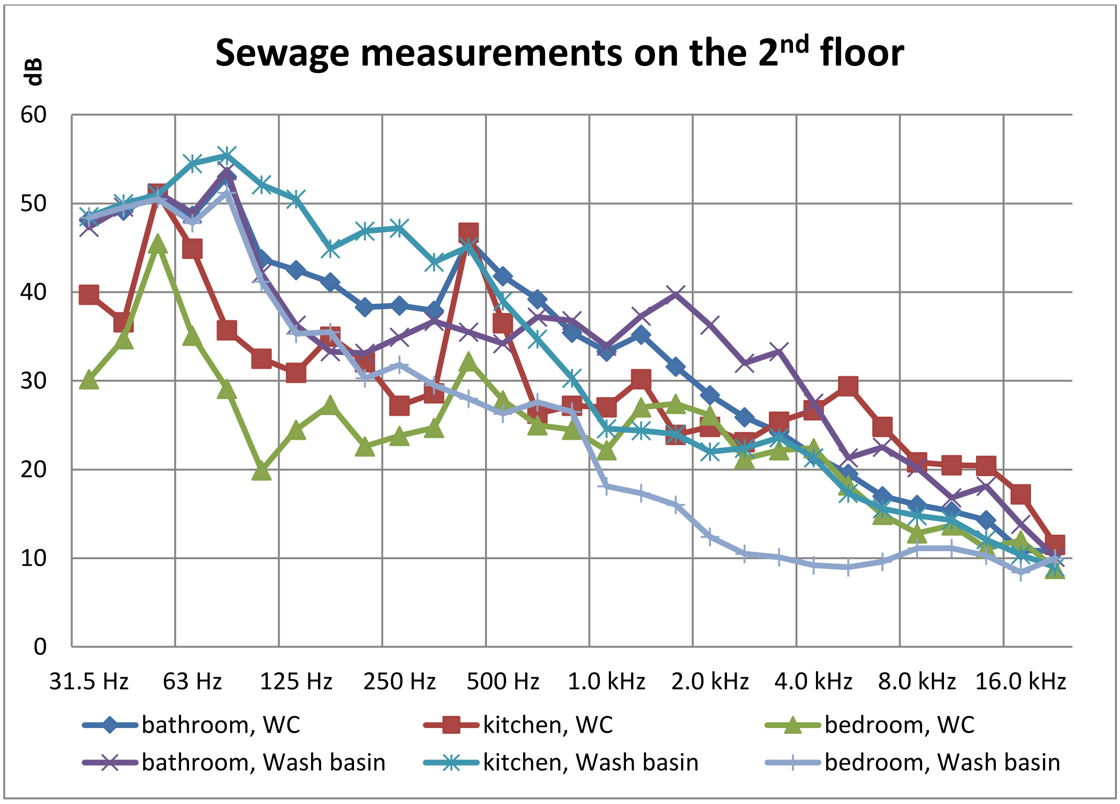
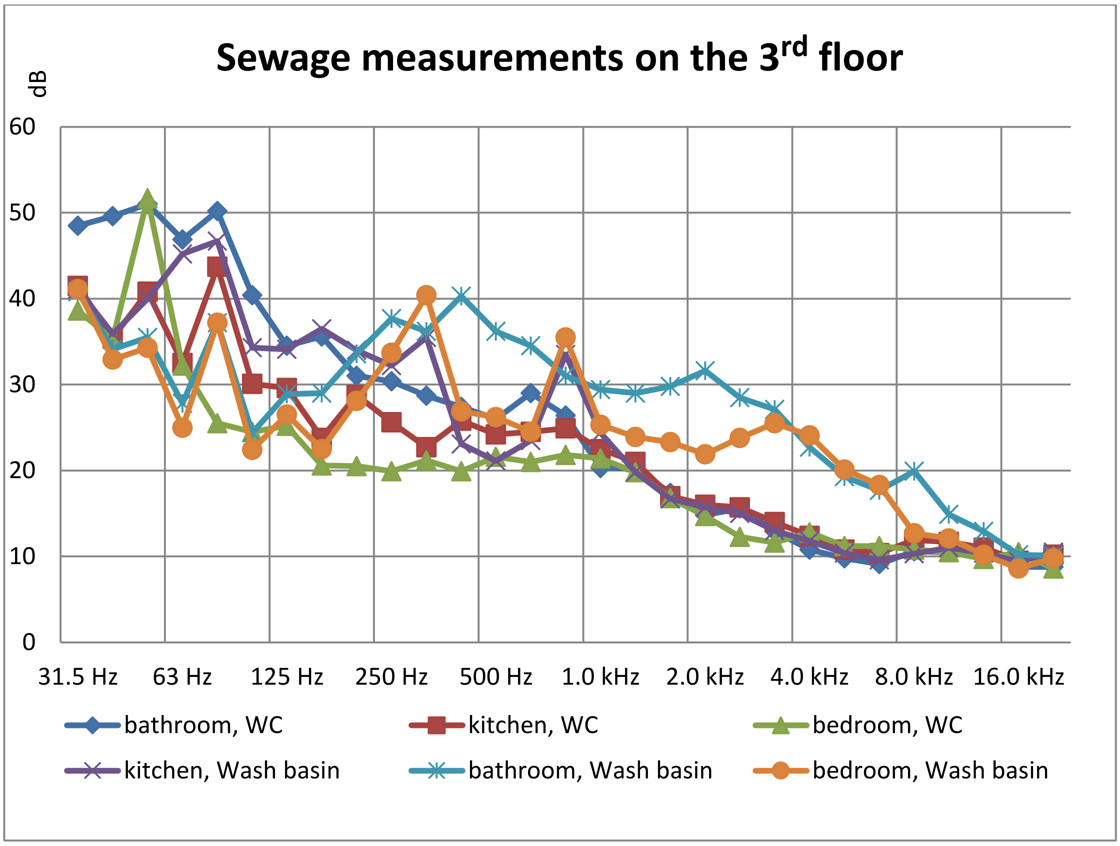
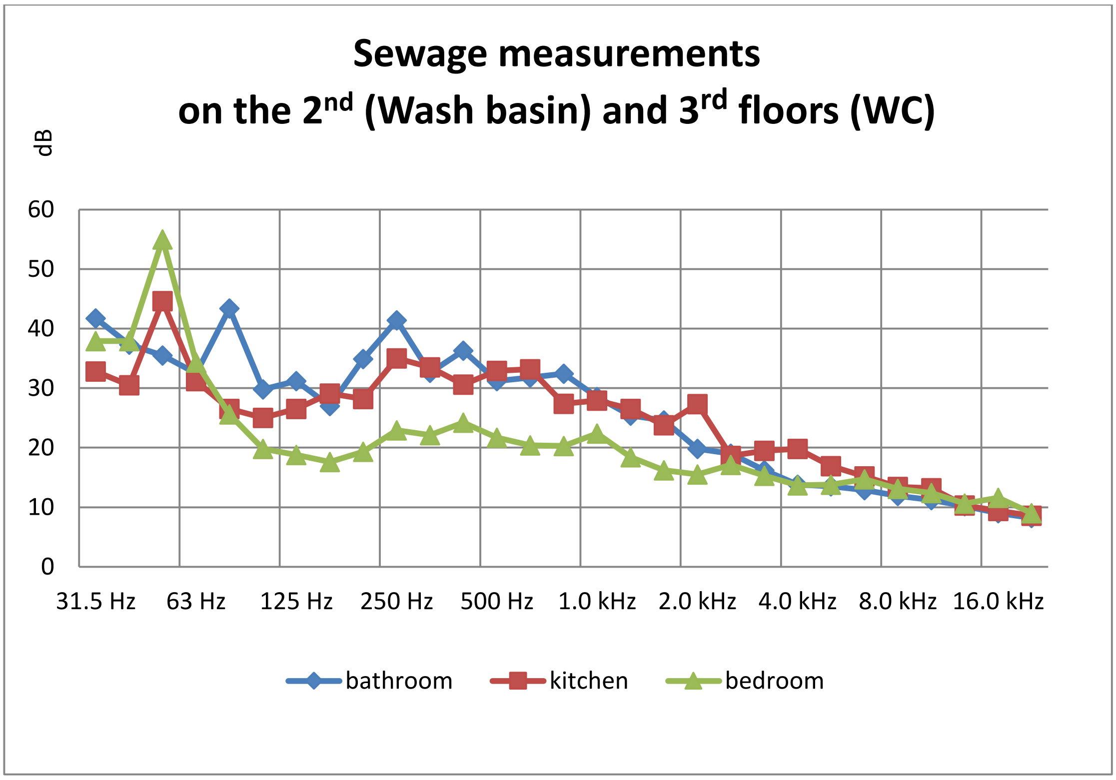
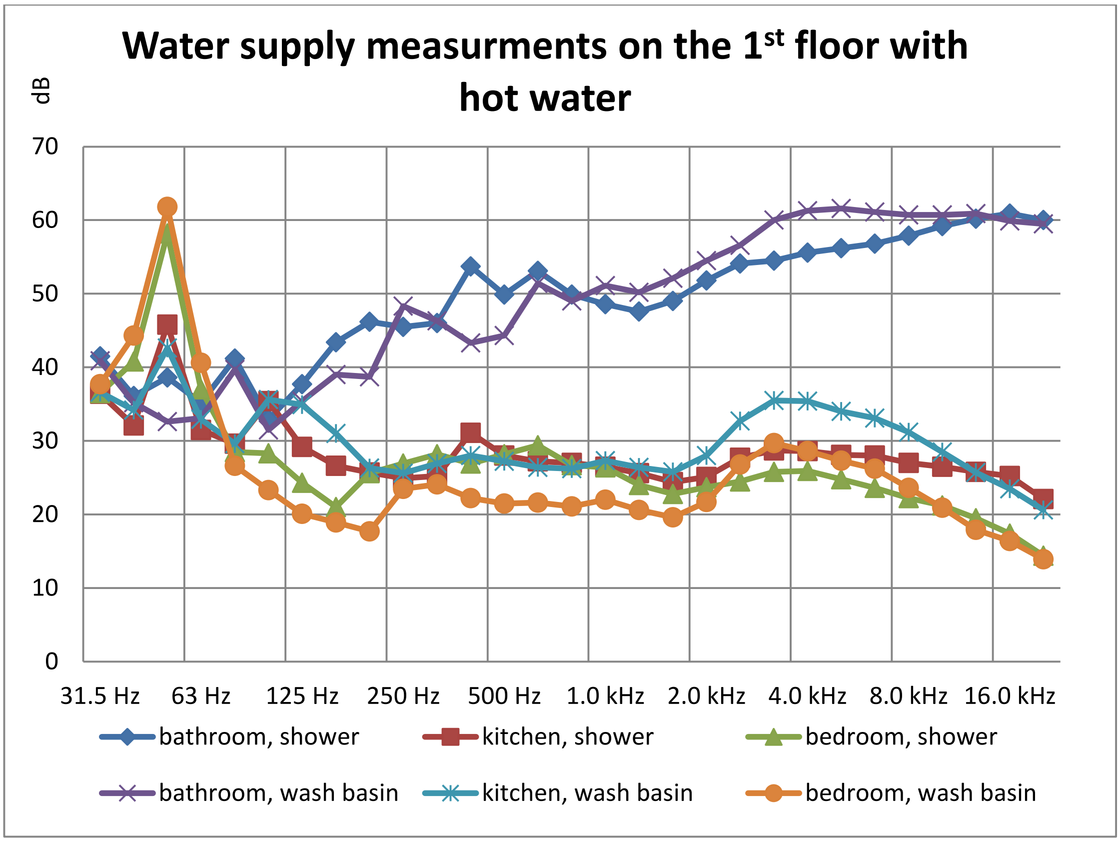
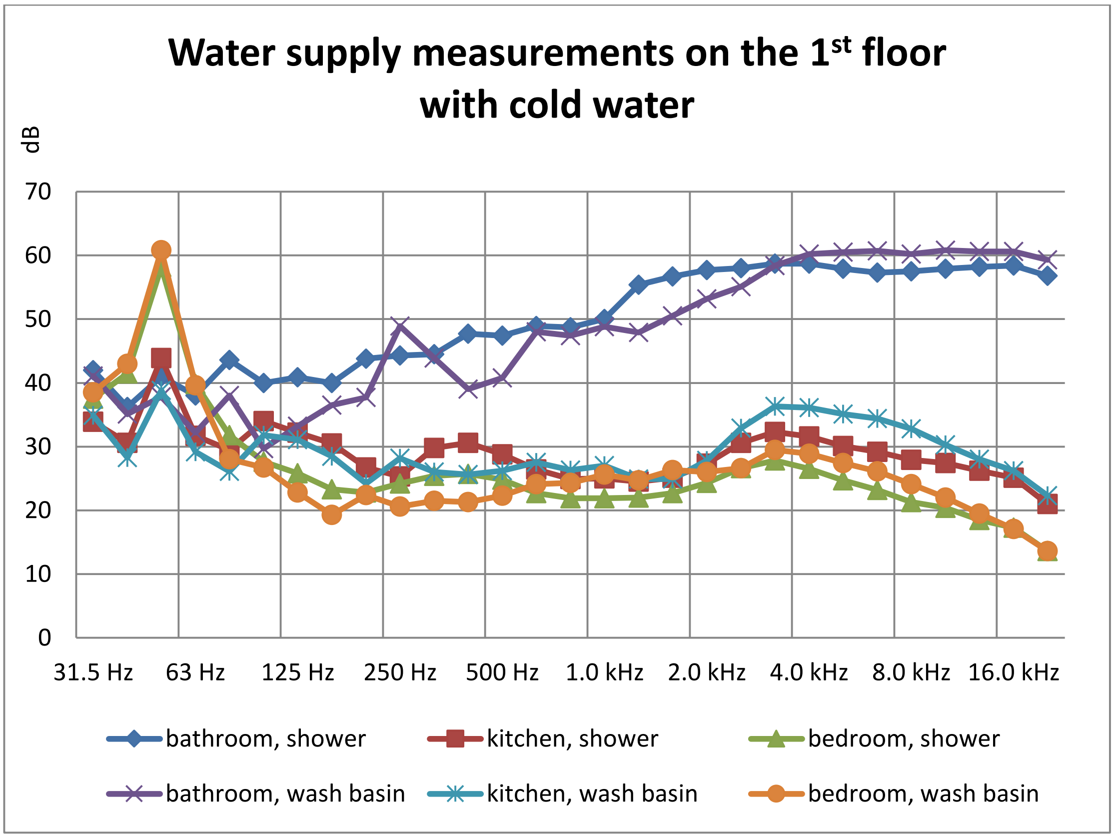

Background sound
dB
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
in the kitchen
in the bedroom
in the bathroom

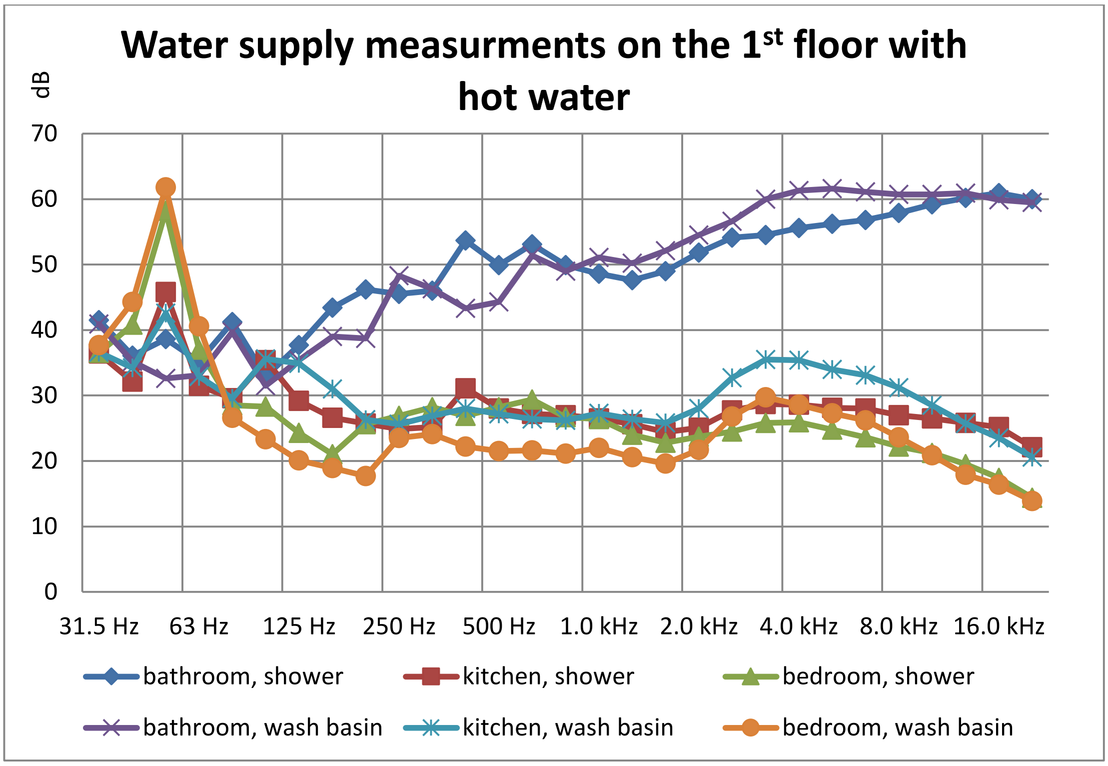

Sewage measurements on the 2nd floor
dB
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, WC
kitchen, WC
bedroom, WC
bathroom, Wash basin
kitchen, Wash basin
bedroom, Wash basin

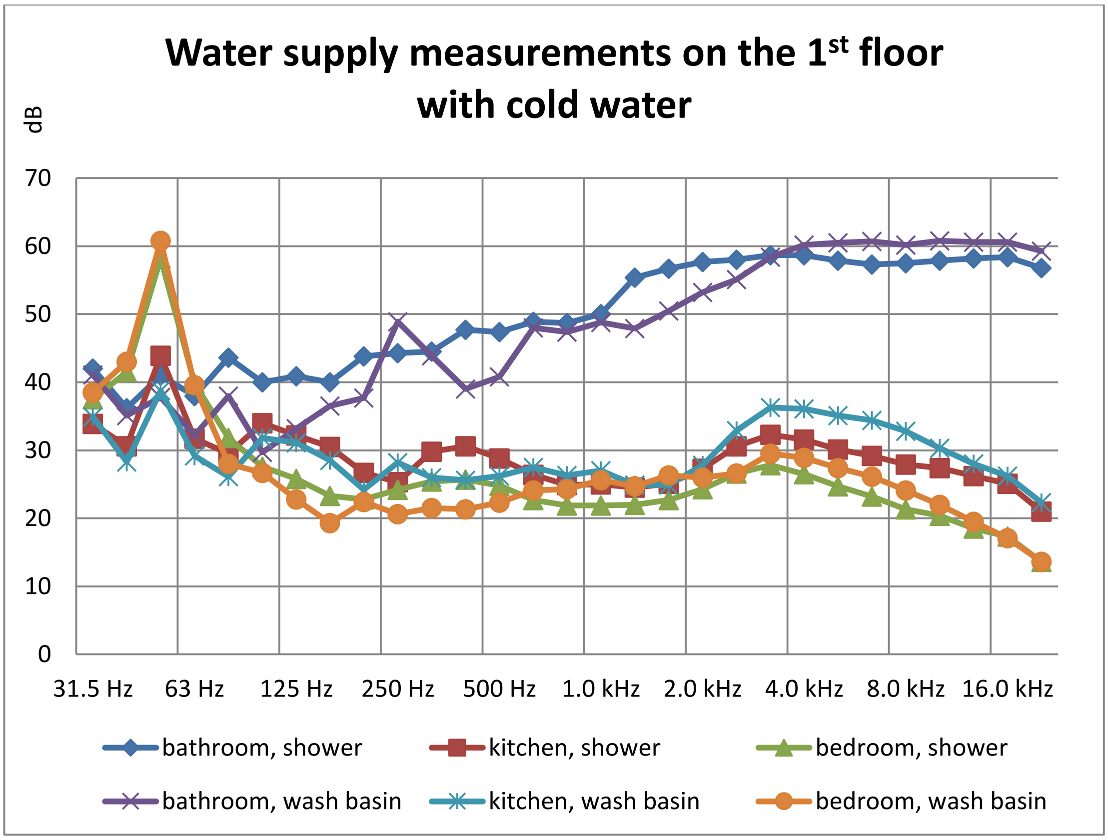

Sewage measurements on the 3rd floor
dB
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, WC
kitchen, WC
bedroom, WC
kitchen, Wash basin
bathroom, Wash basin
bedroom, Wash basin

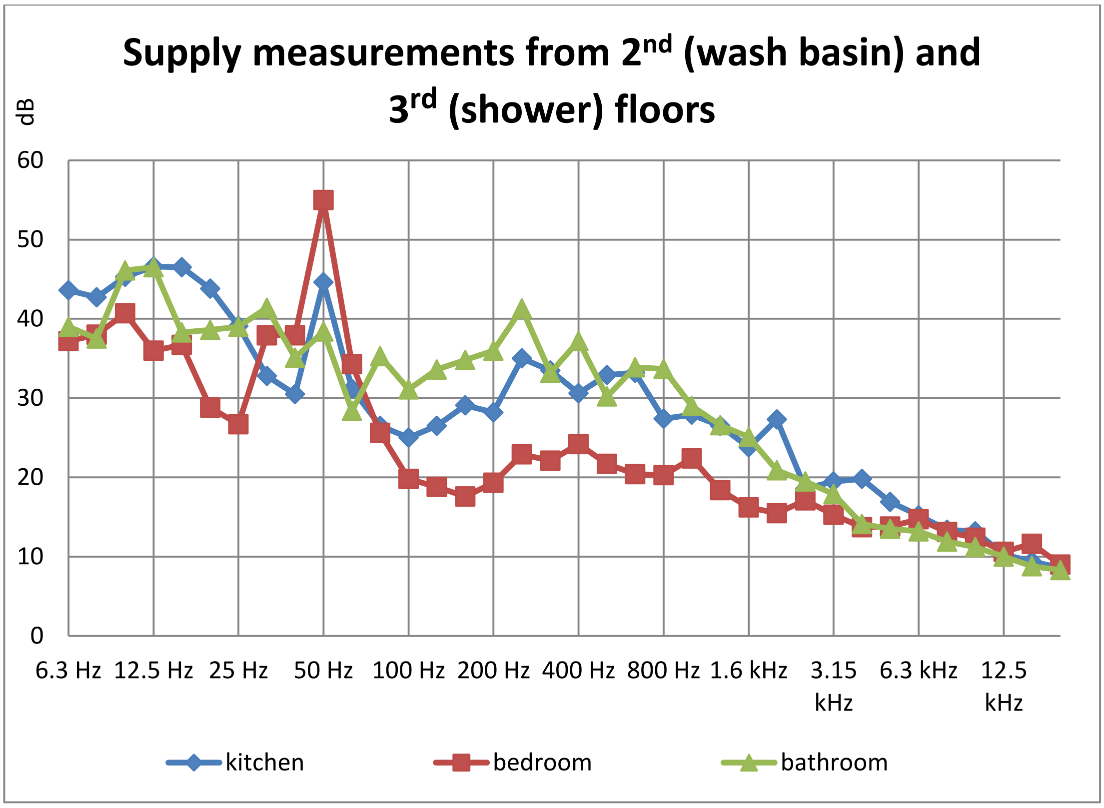

Sewage measurements
on the 2nd (Wash basin) and 3rd floors (WC)
dB
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom
kitchen
bedroom

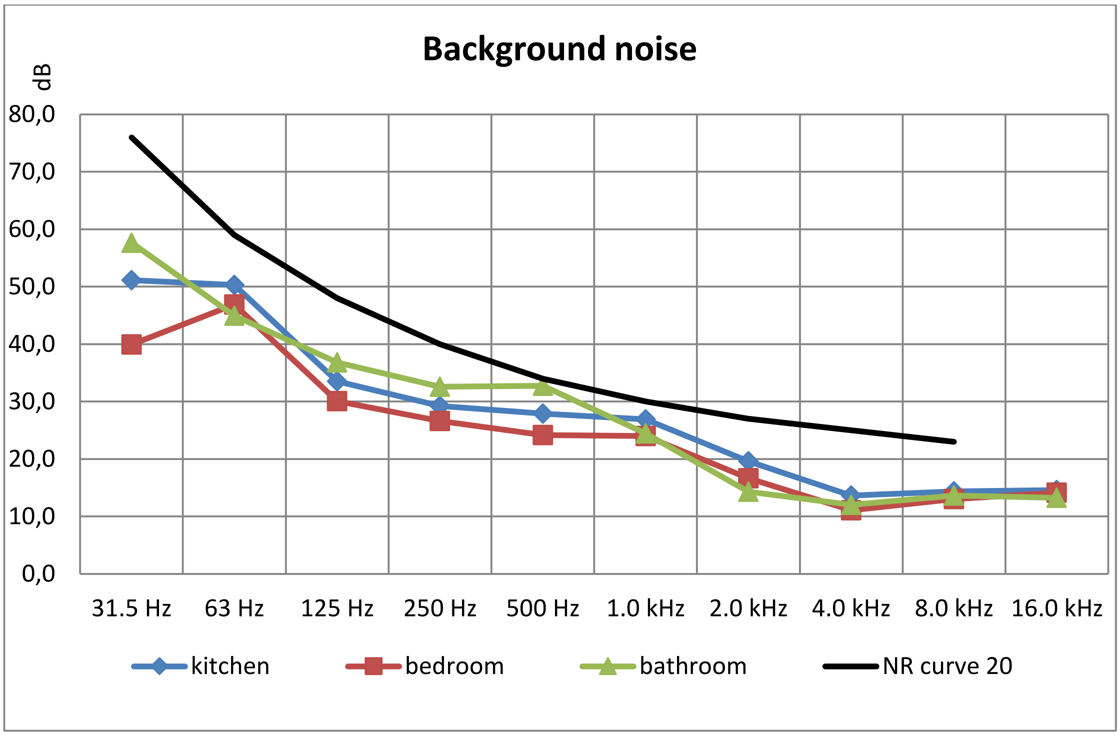

Water supply measurments on the 1st floor with hot water
dB
70
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin

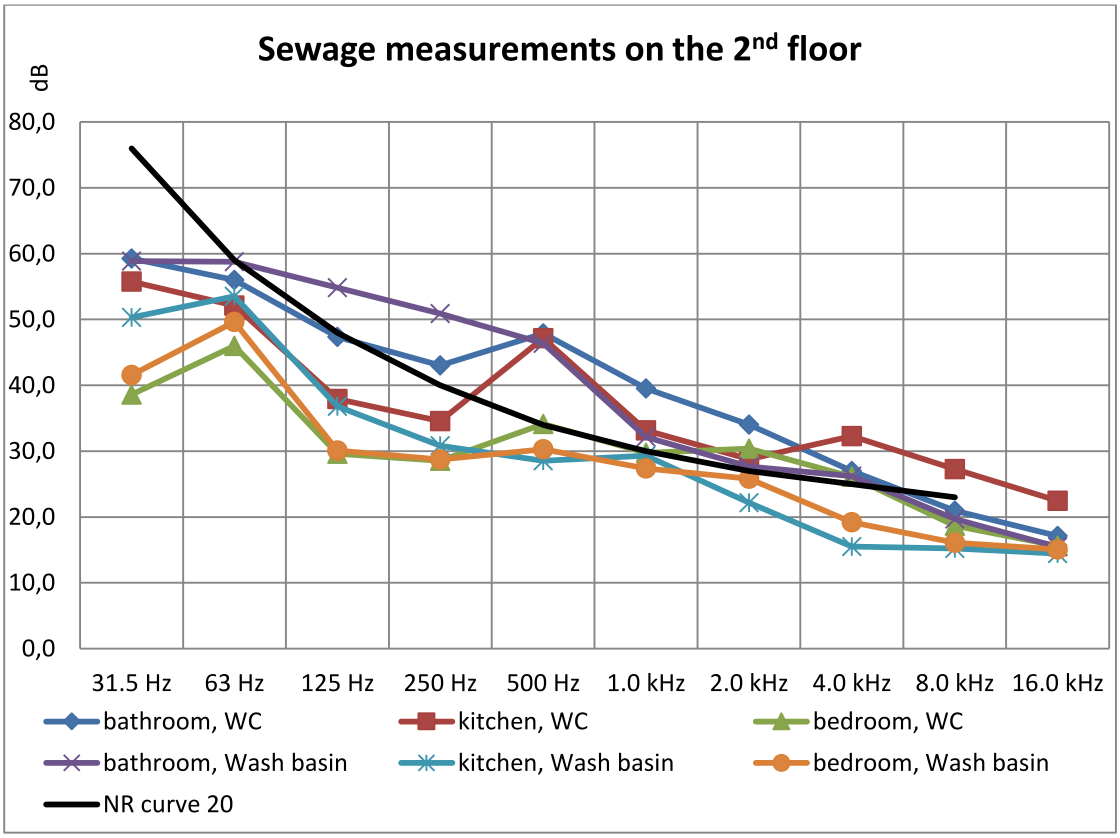

Water supply measurements on the 1st floor with cold water
dB
70
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin

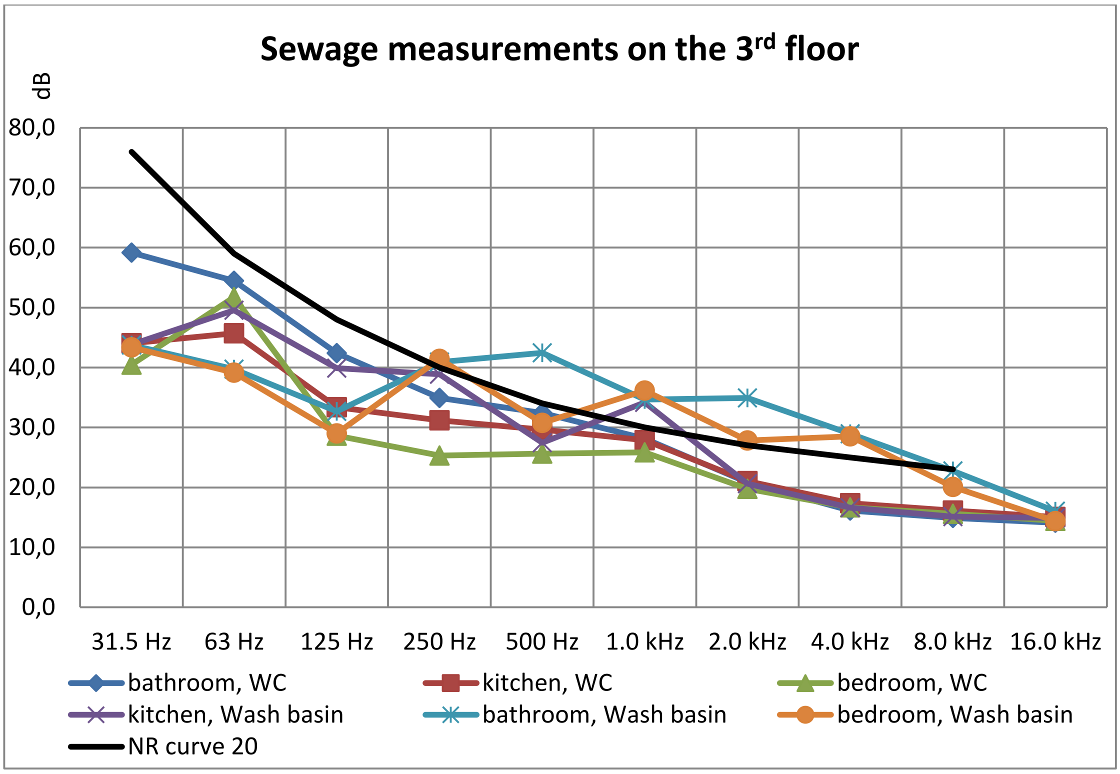

Water supply measurments on the 1st floor with hot water
dB
70
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin

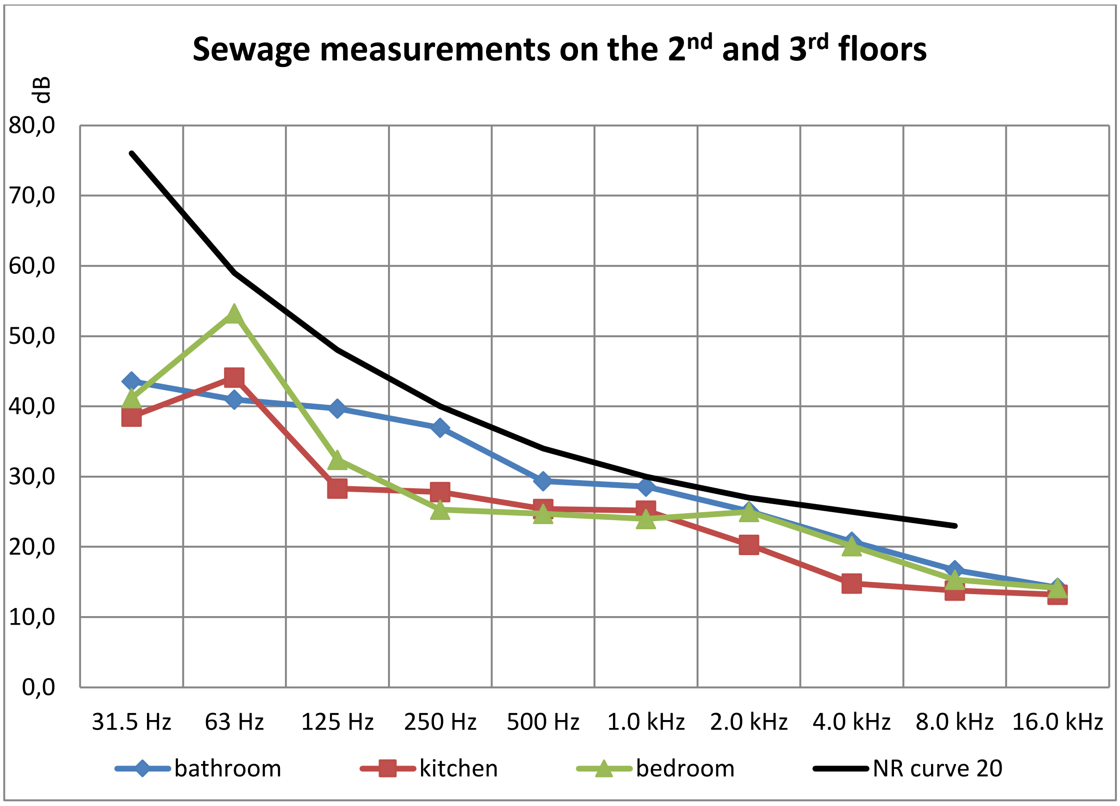

Water supply measurements on the 1st floor with cold water
dB
70
60
50
40
30
20
10
0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin

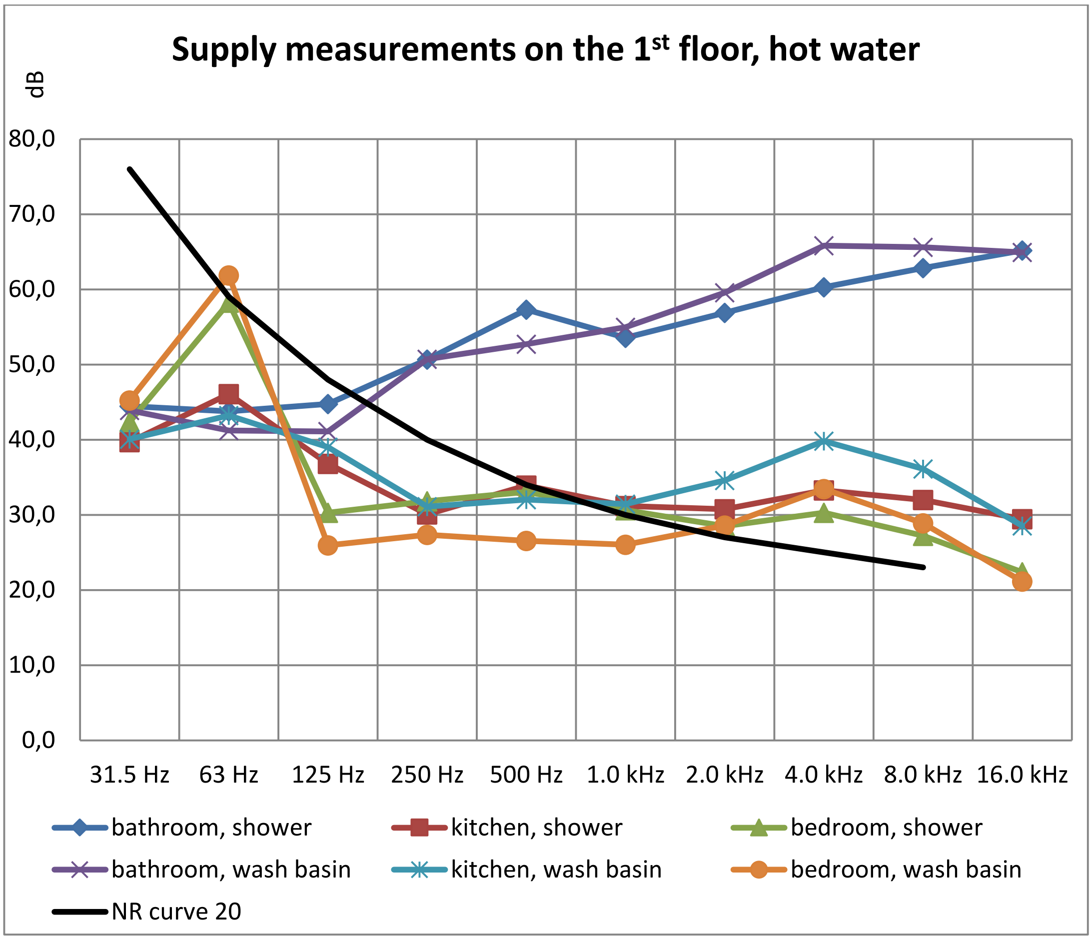

Supply measurements from 2nd (wash basin) and 3rd (shower) floors
dB
60
50
40
30
20
10
0
6.3 Hz
12.5 Hz
25 Hz
50 Hz
100 Hz
200 Hz
400 Hz
800 Hz
1.6 kHz
3.15 kHz
6.3 kHz
12.5 kHz
kitchen
bedroom
bathroom

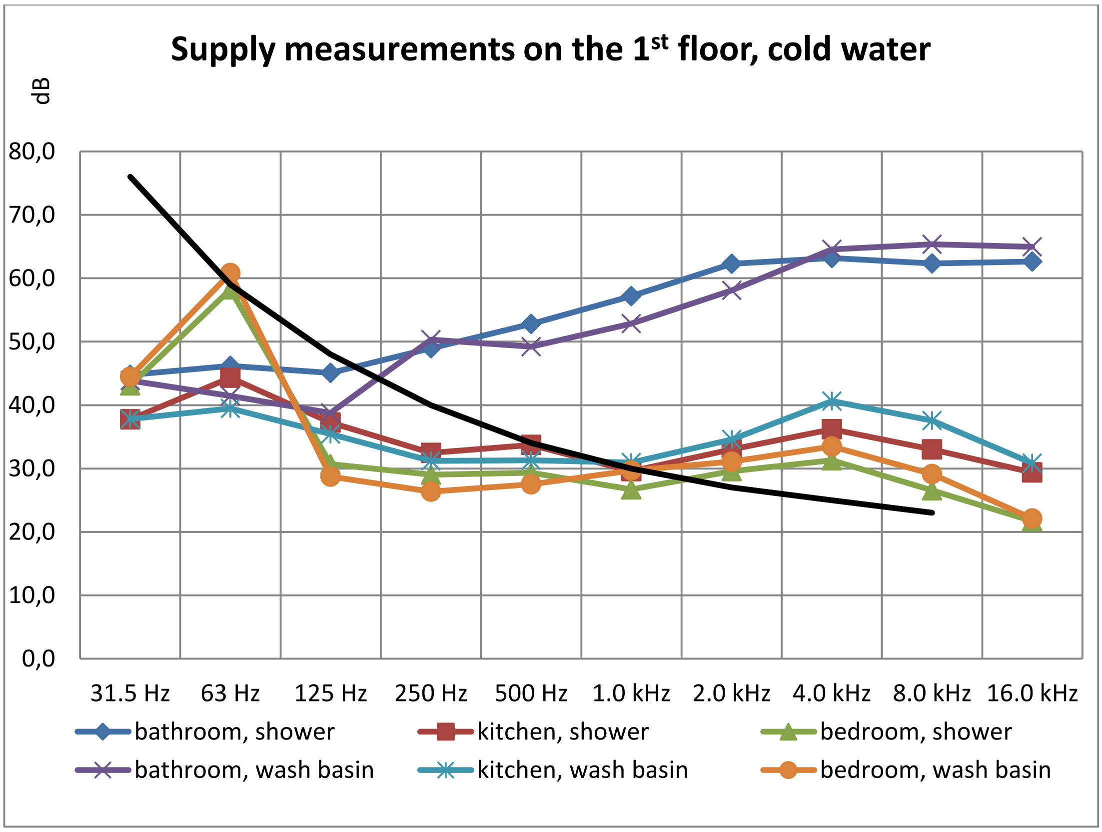

Background noise
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
kitchen
bedroom
bathroom
NR curve 20

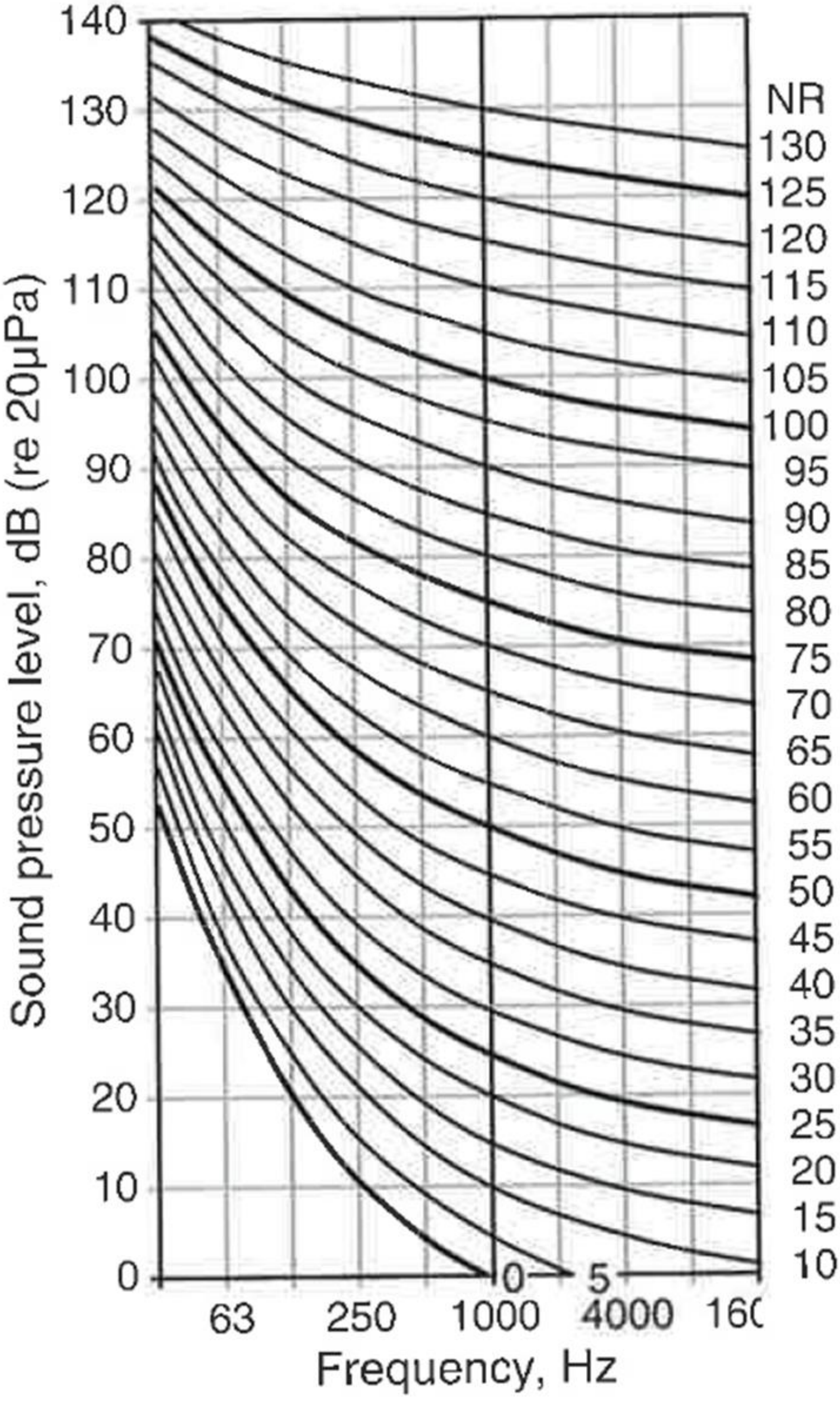

Sewage measurements on the 2nd floor
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, WC
kitchen, WC
bedroom, WC
bathroom, Wash basin
kitchen, Wash basin
bedroom, Wash basin
NR curve 20


Sewage measurements on the 3rd floor
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, WC
kitchen, WC
bedroom, WC
kitchen, Wash basin
bathroom, Wash basin
bedroom, Wash basin
NR curve 20


Sewage measurements on the 2nd and 3rd floors
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom
kitchen
bedroom
NR curve 20


Supply measurements on the 1st floor, hot water
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin
NR curve 20


Supply measurements on the 1st floor, cold water
dB
80,0
70,0
60,0
50,0
40,0
30,0
20,0
10,0
0,0
31.5 Hz
63 Hz
125 Hz
250 Hz
500 Hz
1.0 kHz
2.0 kHz
4.0 kHz
8.0 kHz
16.0 kHz
bathroom, shower
kitchen, shower
bedroom, shower
bathroom, wash basin
kitchen, wash basin
bedroom, wash basin


140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
Sound pressure level, dB (re 20μPa)
NR
130
125
120
115
110
105
100
95
90
85
80
75
70
65
60
55
50
45
40
35
30
25
20
15
10
0
5
63
250
1000
4000
Frequency, Hz

APPENDIX 4 A-weighting system /5/

Frequency (Hz)	*A weighting (dB)*	*B weighting (dB)*	*C weighting (dB)*
10	−70.4	−38.2	−14.3
12.5	−63.4	−33.2	−11.2
16	−56.7	−28.5	−8.5
20	−50.5	−24.2	−6.2
25	−44.7	−20.4	−4.4
31.5	−39.4	−17.1	−3.0
40	−34.6	−14.2	−2.0
50	−30.2	−11.6	−1.3
63	−26.2	−9.3	−0.8
80	−22.5	−7.4	−0.5
100	−19.1	−5.6	−0.3
125	−16.1	−4.2	−0.2
160	−13.4	−3.0	−0.1
200	−10.9	−2.0	0
250	−8.6	−1.3	0
315	−6.6	−0.8	0
400	−4.8	−0.5	0
500	−3.2	−0.3	0
630	−1.9	−0.1	0
800	−0.8	0	0
1,000	0	0	0
1,250	+0.6	0	0
1,600	+1.0	0	−0.1
2,000	+1.2	−0.1	−0.2
2,500	+1.3	−0.2	−0.3
3,150	+1.2	−0.4	−0.5
4,000	+1.0	−0.7	−0.8
5,000	+0.5	−1.2	−1.3
6,300	−0.1	−1.9	−2.0
8,000	−1.1	−2.9	−3.0
10,000	−2.5	−4.3	−4.4
12,500	−4.3	−6.1	−6.2
16,000	−6.6	−8.4	−8.5
20,000	−9.3	−11.1	−11.2