Sound Levels, Noise Source Identification and Perceptual Analysis in an Intensive Care Unit

Master's Thesis in the Master's programme in Sound and Vibration

STAMATINA KALAFATA

Department of Civil and Environmental Engineering
Division of Applied Acoustics
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CHALMERS UNIVERSITY OF TECHNOLOGY
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Reproservice / Department of Civil and Environmental Engineering
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Abstract

Sound levels in hospitals have been reported to have risen since 1960s and are today much higher than the recommended levels given by the World Health Organization (WHO). This project is a cooperation between the University of Gothenburg with the Division of Applied Acoustics at Chalmers University of Technology and investigates the sound environment in two identical rooms in the Intensive Care Unit (ICU) in Southern Älvsborg Hospital (SÄS), Borås. One of the rooms is refurbished with regard to light, aesthetics and acoustics. The other room remains unchanged.

The aim of the thesis is to analyse in a comparative patient situation the distribution of resulting Sound Pressure Levels and to identify the noise sources and the perceptual characteristics of the sounds in the rooms. The A-weighted equivalent levels, minimum and maximum and the C-weighted peak levels were determined and the statistical distribution over time along with the number of "quiet"periods were calculated. A-weighted maximum levels of 45 to 55 dB and C-weighted peak levels of 65 to 70 dB occur for the majority of time during day and night with higher levels in the reference room. More and longer "quiet"periods occur in the refurbished room for the maximum and peak levels while the main activity is almost the same for both rooms. In order to identify different noise sources wave files that were recorded for two hours per day were analysed and compared. The noise sources are divided in two categories; sounds from medical equipment and sounds connected to human activity. The perceptual characteristics of the most common sound sources were analysed through HEAD acoustics Artemis software. Perceptible changes in loudness, sharpness, roughness and fluctuation strength occur in both rooms with higher values in sharpness and tonality for the refurbished room and in roughness and loudness for the reference room. In conclusion, there is an acoustical improvement in the refurbished room but further measures are needed to get down to the noise levels recommended by WHO.

Keywords: ICU, hospital noise, acoustic treatment, hospital psychoacoustics, levels statistical distribution, noise source identification, perceptual characteristics.

Contents

Acknowledgements

First, I would like to express my deep gratitude to my advisor Erkin Asutay for his invaluable guidance, advice and his promptness in answering all my questions. Also thank you for supporting me throughout the duration of my thesis and helping me put pieces together when I lost my motivation.

Special thanks to Kerstin Persson Waye and Mikael Ögren for giving me the opportunity to be a part of their team and for their invaluable feedback and advise. Additionally I would like to thank the whole acoustic team Michael Smith, Sofie Fredriksson, Irene Van Kamp and Oscar Hammar for their help and for creating such a pleasant environment. Thank you all for the motivation and the encouragement.

Thanks to all the people of the Division of Applied Acoustics and especially Börje Wijk, Gunilla Skog and Wolfgang Kropp for their help and guidance throughout the duration of my studies.

I would also like to thank my classmates for making the past two years an unforgettable experience. I will really miss them and I look forward to meeting them again.

Finally, my heartfelt thanks goes to my family who supported me unconditionally over the years and encouraged me to pursue this opportunity and make my dreams come true. My deepest thanks to my friends here in Sweden and back in Greece for supporting me and spending hours talking with me about sounds.

Stamatina Kalafata
Göteborg, November 2014

List of Abbreviations

ICU	Intensive Care Unit
WHO	World Health Organization
SPL	Sound Pressure Level
LAeq	A-weighted Equivalent Level
LAFmax	A-weighted Maximum Level
LAFmin	A-weighted Minimum Level
LCpeak	C-weighted Peak Level
L_{10}	Sound level exceed for the 10% of the time
HVAC	Heating, Ventilating and Air-Conditioning
RT	Reverberation Time
G	Sound Strength
C_{50}	Clarity
SAPSIII	Simplified Acute Physiology Score
JND	Just Noticeable Differences

1. Introduction

1.1. Background

According to Florence Nightingale (1859), “ unnecessary noise is the most cruel abuse of care which can be inflicted on either the sick or the well” [37]. The noise control in hospitals is a significant issue which has being largely neglected with the passage of time [38]. The sound environment in modern hospitals is very complex consisting of medical equipment, HVAC systems and sounds that are connected to human activity (staff, visitors and patients). In Johansson et al article [30] information from previous research [11, 12, 17, 40, 41] has been gathered showing that sound levels in modern hospitals have risen since 1960 reaching today 66 dB A-weighted equivalent levels with 80 dB maximum A–weighted levels during day time. The measured levels are much higher than the recommended by the World Health Organization (WHO) in the “Guidelines for Community Noise” stating that the sound levels should not exceed 30 dBA and 35 dBA during night and day respectively with maximum levels no higher than 40 dBA during night time [13].

Compared to other locations in the hospital, noise control in the ICU is a difficult task because of the medical equipment that is active all the time generating ongoing noise [33]. Apart from the alarms, the bleeping sounds and the mechanical noise from the equipment also sounds connected to human activity form the sound environment in the ICU room, as mentioned, indicating how complex and unpredictable it is. A study conducted by Busch – Vishniac et al. in 2005 [15] has revealed that noise plays significant part on both psychological and physiological condition of the patients while Biley (1993) reports that a noisy environment can cause stress, anger, confusion and distraction. Loud noises in hospitals are also linked to sleep disturbances [14]. Nightingale (1859), also, stated that “ sudden or sharp noise affects more than continuous noise and that anything that wakes a patient suddenly will put him in a state of greater excitement than any continuous noise no matter how loud it is”. Other negative physiological effects of noise on patients such as cardiovascular response, extended hospital stay and increased dosages of pain medication have been documented in previous research [40].

Having some information about some of the psychological and physiological impacts of the noise on patients, a subjective analysis is needed in order to investigate the perceptual characteristics of the ICU sound environment. Fundamental psychoacoustic metrics, such as loudness, specific loudness, sharpness, roughness, fluctuation strength and tonality have been used trying to stimulate the sound processing of the human hearing system [27] and to characterize the sound quality by quantifying the attributes of an individual sound that combine to give the overall impression of sound quality [45]. Although these metrics are widely used in sound product design, only one study has applied the metrics in hospitals sound environment. Hsu (2012)[27] in his study tried to evaluate the sound scape in the room from the psychoacoustics point of view using as references values from other studies that have been conducted for different products.

1.2. Objective

This thesis investigates the case of two identical ICU rooms in Southern Älvsborg Hospital (SÄS), Borås. One of the rooms has been treated with regards to lightning and aesthetics under the guidance of a team led by Professor Ingegerd Bergbom and senior lecturer Berit Lindahl and also acoustically treated by Saint-Gobain Ecophon AB.

Sound level measurements have been performed by Limes Audio AB in order to evaluate the sound scape in both rooms and see if there is an improvement after applying the acoustical treatment. Also wave files have been recorded and used in order to identify the noise sources that occur inside and outside of the rooms.

1.3. Scope

- To describe the effect of the acoustical treatment with regards to the properties of the room using the baseline measurements performed by Saint-Gobain Ecophon AB in order to use it as a background information.
- To analyze the distribution of resulting Sound Pressure Levels (SPL) in both rooms using a comparative patient situation.
- To identify the noise sources occur inside and outside the room with regards to number and duration of events as well as the perceptual characteristics.

1.4. Structure of thesis

The room acoustic properties of the rooms before and after the treatment are presented and discussed in Chapter 2 in order to describe the effect of the treatment using measurements of Reverberation time (RT), Sound strength (G) and Clarity (C_{50}).

In Chapter 3, the distribution of the resulting SPL that have been measured inside the rooms is analyzed. A-weighted equivalent levels, minimum and maximum as well as C-weighted peaks are plotted over time in order to evaluate the soundscape. Also the " quiet" moments inside the rooms with regards to number of events and durations are calculated.

The noise sources that form the complex sound environment of the ICU are identified and presented in Chapter 4. The noises coming from inside and outside the room are described analytically and the numbers of events together with the durations are calculated.

The next two chapters, Chapter 5 and Chapter 6, present the perceptual characteristics of the noise sources. First in Chapter 5, a general analysis of the perceptual characteristics of the most frequent and annoying sounds is presented and then a comparison between the two rooms with regards to psychoacoustics is presented in Chapter 6 in order to see if the acoustical treatment improved/changed the perceptual characteristics.

Conclusions drawn from the results and analyses and suggestions for future work are presented in Chapter 7.

2. Room acoustics evaluation

In the ICU room, the sounds build up increasing in that way the general noise levels. That is due to the hard surfaces and the reflections of the sound. Infection control and proper hygiene are a priority in ICU so the surfaces are often hard in order to be totally cleanable, avoiding fabrics and carpets [21]. The aim is to reduce the noise levels in the room so that the noise environment would be more comfortable for patients, visitors and staff. The two rooms under investigation are at the ICU of Southern Älvsborg Hospital (SÄS), Borås. The top view of the identical rooms is presented in Fig 2.1.

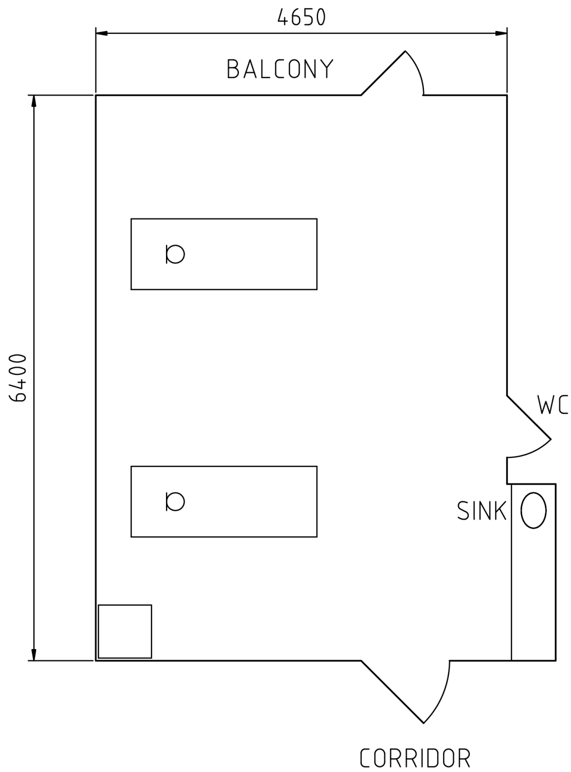

Figure 2.1.: Floor plan of the two identical rooms.

2.1. Description of the rooms

Dimensions: 4.65 m X 6.40 m X 2.70 m
The two rooms are two-bed rooms with a plastic floor and hard gypsum/concrete walls. The outer wall has two windows and a balcony door. The wall toward the corridor has a door and a small bay window. On the other wall there is the bathroom door, a sink, two small cabinets and a computer. There are no textiles or carpets in the rooms except a curtain that is located between the two beds. This information applies to both the refurbished and the reference room. Both rooms had initially the same design and furnishing.

2.2. Acoustic treatment

Acoustic treatment has been applied in one of the rooms by Saint-Gobain Ecophon AB in order to improve the sound environment. The other room remained unchanged. The two rooms under study are located next to each other.

2.2.1. Reference room

The first room remains unchanged and it is considered as the reference room. The ceiling is a wall-to-wall suspended 13 mm gypsum board with a 20 mm fibrous absorbent material with a few centimetres gap behind as shown in Fig 2.2.

Figure 2.2.: The reference room of the ICU at Borås hospital in Sweden.

2.2.2. Refurbished room

The whole area of the ceiling is covered by suspended plaster ceiling having a 20mm absorbent layer with a few centimetres gap behind. Extra panels of fibrous absorbent Ecophon Labotec Ds were placed and mounted with plaster rails on the ceiling covering most of the surface of the ceiling, except the surface close to the walls. An Ecophon Extra Bass layer has been added in the corners for extra bass absorption as seen in Fig 2.3.

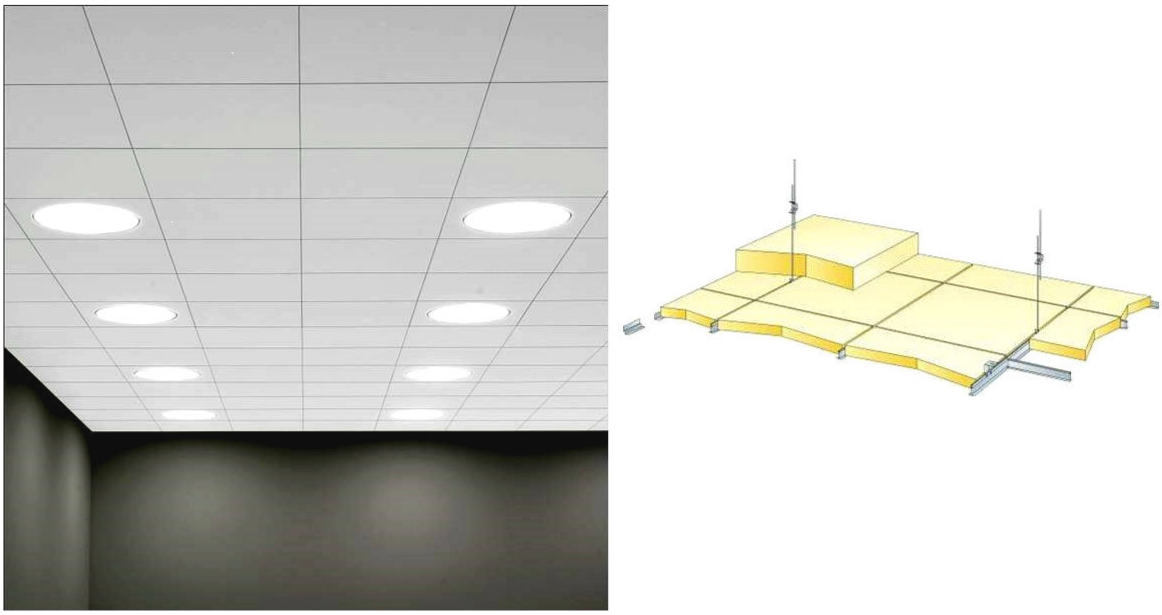

Figure 2.3.: Detail of the ceiling placed in the refurbished room of the ICU at Borås hospital in Sweden. Ecophon Labotec Ds ceiling is showed on the left picture and Ecophon Extra Bass layer on the right picture.

The refurbishment includes changes in lightning and aesthetics. The renovation was planned and performed by a team led by Professor Ingegerd Bergbom and senior lecturer Berit Lindahl and includes improvement in lightning in order to follow the rhythms of natural day and night light and also changes in colouration and furnishing[29]. Fig 2.4 shows the refurbished room after the treatment.

Figure 2.4.: The refurbished room of the ICU at Borås hospital in Sweden.

2.3. Measurements

2.3.1. Method

Acoustic measurements have been performed in order to evaluate the ICU sound environment by measuring three different acoustic parameters before and after the acoustical treatment. These parameters are the reverberation time (RT), the strength (G) and the clarity (C_{50}). All the acoustic measurements have been performed by Saint–Cobain Ecophon AB in collaboration with WSP Environmental in the ICU of Borås Hospital. All the room acoustic measurements have been performed according to the SS EN ISO 3382:2003 [8] and the SPL measurements according to SS EN ISO 10052 [7]. The SPL have been measured in both rooms during different phases of the intervention. Furnished / unfurnished, with and without the suspended ceiling, with or without the extra bass etc. In this study, we concentrate only on one case. Both rooms are furnished with the refurbished room been renovated and reference room unchanged. The measurements have been performed for seven microphone positions and two loudspeaker positions according to Fig 2.5.
Data is saved for 24 hours with 30 sec intervals. Saved data is equivalent, maximum and minimum level of frequency weighting A, C and also without frequency weighting.

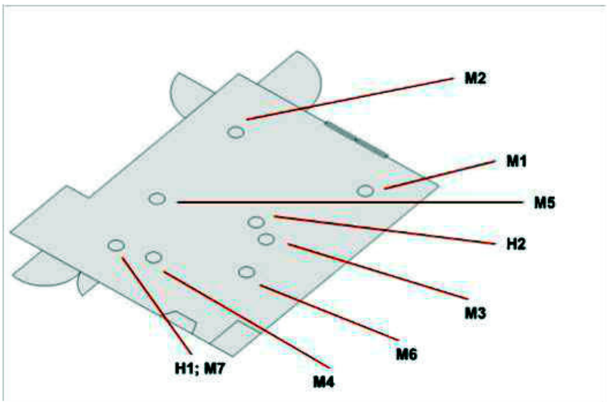

Figure 2.5.: Microphone (M) and loudspeaker (H) positions for room acoustic measurements.

2.3.2. List of the equipment

- Calibrator Brüel & Kjaer 4231, S/N 2123158, Calibration Date 2009-09-11
- Amplifier Lab 1300C, S/N 20613, Calibration Date 2010-05-26
- Loudspeaker Elton cube, Calibration Date 2010-05-26
- Sound Level Meter Norsonic 140, S/N 1402712, Calibration Date 2009-09-25
- Microphone Norsonic 1209/12104, Calibration Date 2009-09-25
- Microphone Amplifier Norsonic 1230, Calibration Date 2009-09-25
- Software Morset WinMLS 2004

2.4. Description of the room acoustics metrics

2.4.1. Reverberation Time (RT)

The Reverberation Time (RT) is crucial for describing the acoustic quality of a room or space. It is the time it takes for the sound to decay 60 dB after the sound source has been turned off. This decay is usually measured over the first ten (T_{10}), twenty (T_{20}) or thirty (T_{30}) dB and then extrapolated to the full 60 dB range. In order to evaluate the reverberation time of a room, the knowledge of the volume and the sound absorption coefficients of the surfaces and the materials in the room, must be used. The reverberation time is a metric that can give us good information about the suitability or quality of a room depending on the intended use [32].

2.4.2. Sound Strength (G)

The acoustic quality of a room or space is determined by the loudness, the level at which we experience one sound. With the strength index, G, one can estimate the room's contribution to the noise level relative to the sound level in free field (no reflections) with the same source.

$$G = 10\lg\left(\frac{\int_0 h^2(t)\,dt}{\int_0 h_A^2(t)\,dt}\right) dB \tag{2.1}$$

where $h_A^2(t)$ is the room impulse response for the direct sound component only in anechoic space [32]. In an ICU room a quiet and soothing environment is of great importance for the recovery of the patients. It is crucial to reduce the sound levels to limits that are recommended for these environments.

2.4.3. Clarity (C_{50})

Clarity measures the ratio of early sound reflections that support speech and late reflections that interfere with speech. This ratio is taken at 50 ms. It is used when we need to know the room's suitability for speech [32].

$$C_{50} = 10\lg\left(\frac{\int_0^{50ms} h^2(t)\,dt}{\int_0^{\infty} h^2(t)\,dt}\right) dB \tag{2.2}$$

There is a lot of activity in the ICU during day and night which also includes random and unpredictable events. It is important for the staff and generally the people who are involved in these activities to be able to have perfect communication and also to identify the nature and the origin of the sound sources and the patient's needs [21]. Moreover, having the perception of a better sound quality may lead to a change in the behaviour of staff and visitors keeping their voice levels low [38].

2.5. Results

The results from the measurements in the two ICU rooms are presented in Fig 2.6, Fig 2.7 and Fig 2.8.

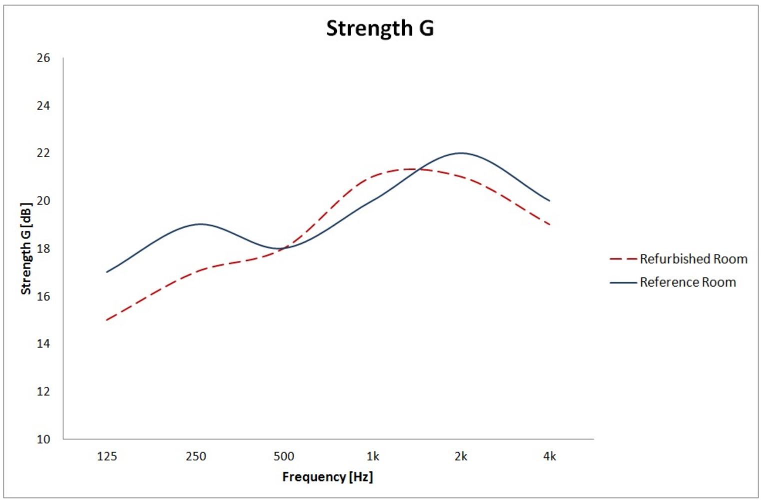

Figure 2.6.: Measured Sound Strength (G) in the reference and the refurbished room.

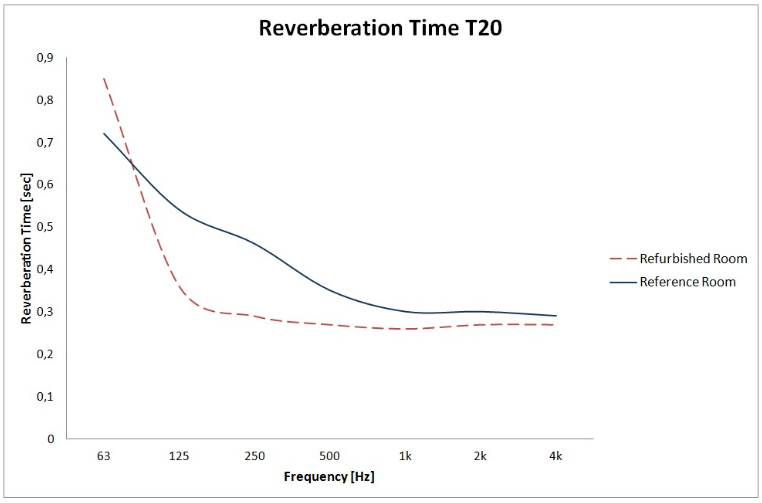

Figure 2.7.: Measured Reverberation time (RT) in the reference and the refurbished room.

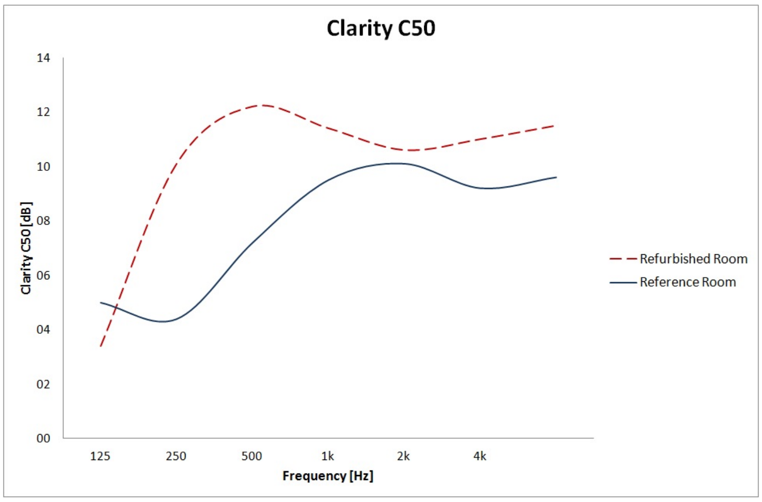

Figure 2.8.: Measured Clarity (C_{50}) in the reference and the refurbished room.

In Fig 2.6 one can see that the strength in the refurbished room is 2 dB lower at frequencies between 125 and 500 Hz and also 1 dB at 2-4 kHz. Since the aim is to reduce the existing sound levels in the room that means that the lower strength the better. Strength is inversely proportional to the absorption and since the absorption of the room has been increased the sound strength is reduced [28]. As a result the sound environment in the new room is slightly improved but needs further treatment. The data used for strength are the average over all microphone positions and for all microphone heights.
Since the new room was treated by adding absorption the reverberation time (RT) in the refurbished room is lower than in the reference room, as shown in Fig 2.7. The RT in the new room is 0.28 to 0.38 with the higher value at low frequencies. For frequencies below 100 Hz the RT in the refurbished room is longer. For short RT (<0.4 s) the room is considered "dead" acoustically [5], with no obvious reinforcement from the room and this is a desired result. By choosing the right materials for the room we can control the RT so that the sound environment to be appropriate for patients and staff. By controlling the RT we can optimize speech intelligibility and limit the noise transmission. The RT is not directly related to SPLs. Rooms with short RT doesn't mean that have low SPL [16].
In Fig 2.8 one can see that clarity is higher in the refurbished room. The clarity of speech in the new room is improved for the whole frequency range with greater improvement at frequencies bellow 1 kHz.

2.6. Conclusions

A major cause for the increase of the sound levels in the rooms/corridors is the hard surfaces and reflective materials that are usually used in hospitals to avoid infections and to be able to clean them easily. All these hard, sound-reflecting, surfaces help the sound to propagate into the rooms and the corridors causing sounds to echo and overlap [21]. In the ICU the number of visitors and staff around the patients changes during day and night and the more serious the condition of the patient is the more people are around and eventually results to a noisier environment. Renovating one of the rooms by adding absorption, an improved sound environment has been achieved with lower strength and RT and higher clarity and so speech ineligibility. The refurbishment includes also changes in colouration, furnishings and lighting which can improve the image of the room leading to a more comfortable environment for patients and staff. By limiting the number of cables and changing the colors and the lightning of the room can affect psychologically the mood of patients and the behaviour of the staff during working times, make them in a way speak in a lower voice and be quieter in their everyday activities [38]. In concluding, this renovation has given satisfactory results in terms of visual and acoustic improvement of the room but further investigation needs to be done in order to confirm if the acoustical treatment is effective or not.

3. Distribution of the Sound Levels and "quiet" periods

A first characterization of the acoustic behaviour of the two rooms has been completed with room acoustic measurements by Ecophon. It is evident that the refurbished room is acoustically improved, compared to the reference room, in terms of sound strength, reverberation time and speech intelligibility. The next stage is to calculate and present the Sound Pressure Levels in both rooms and how they are distributed during day and night time. By day time the time period between 7 am and 9 pm is defined and night time is 9 pm to 7 am. Data from measurements, performed by Limes Audio AB, were analysed to determine the A-weighted equivalent levels, as well the minimum and maximum levels in the rooms and also the C-weighted peak levels, trying to determine the sound scape in these two rooms and then to investigate if the acoustic treatment gave the intended results.

3.1. Measurements

3.1.1. Measurements method

It is known that, in most cases, the sounds and noises we hear are not stable but vary with time. Microphones of BSWA MPA215 type were mounted above each patient (2 microphones per room) approximately 130-160 cm from the wall collecting the sound data day and night.The heights of the microphones are not the same for the two rooms.In the reference room it was placed 15 cm under the existing ceiling and in the refurbished room 5 cm under the new ceiling which means approximately 25 cm under the existing ceiling. The distances from the microphones to the beds could vary somewhat as the beds are mobile and also can be lifted. Sound data were continuously collected with a four channel type 2 sound level meter during day and night. The A-weighted equivalent levels as well as the maximum, minimum and the C-weighted peak levels were determined with a software called Sound Monitor and stored in a database.

The minimum and maximum levels have been measured using "fast"time weighting, which corresponds to a 125 ms time constant.The LAeq (A-weighted equivalent level) is used as an average sound level over the measuring time showing the total energy of the noise in the room [18]. LCpeak (C-weighted) is suitable for measurements of high sound pressure levels, showing the true peak of the sound (absolute pressure)[1].

The measurements have been performed over 30 sec intervals.

3.1.2. Weighting filters

Before proceeding to the analysis of the methodology, a short description of the frequency filters is given in this paragraph.

The perception of the sound depends on the angle of incidence and the duration, properties that are not included in the standard used for measurements. The reason that we measure SPL with frequency filters correction is in order to get subjective results for the sounds. These filters are the weighting filters with the commonest A and C filters that give the sound levels in dBA and dBC respectively [32]. In Fig 3.1 the frequency response curves of the filters are presented.

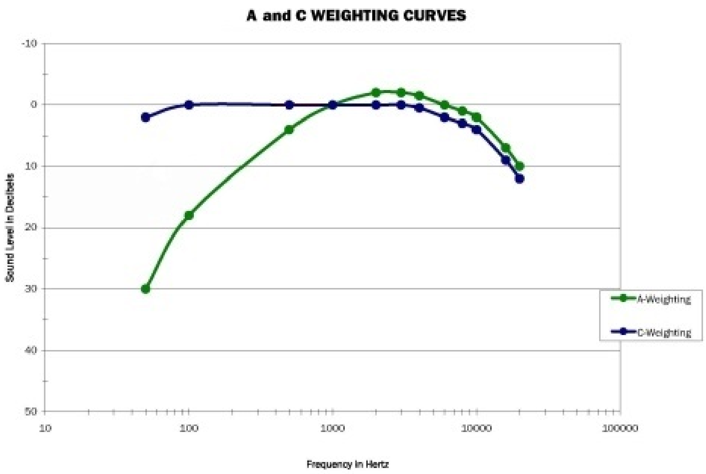

Figure 3.1.: Frequency response curves of A (green line) and C (blue line) filters. Picture adapted from [4].

A-weighting

Measuring with A-weighting scale the low frequency noise is filtered out following the response of the human ear. This filter is used for lower levels and describes quite well the damage risk of the ear. It is the most commonly used filter expressed in dBA [4].

C-weighting

The C filter is quite flat including much more of the lower frequencies than A. Follows the sensitivity of human ear at very high noise levels and it is expressed in dBC [4].

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000	16000
A-weighting	-26.2	-16.1	-8.6	-3.2	0	+1.2	+1.0	-1.1	-6.6
C-weighting	-0.8	-0.2	0	0	0	-0.2	-0.8	-3.0	-8.5

Table 3.1.: Weighting values (octave bands) for dBA and dBC values. Table accessed from [1] (November 2014).

The Table 3.1 shows the weighting values (octave bands) for the calculation of dBA and dBC values.

3.2. Methodology

In order to be able to compare the two rooms, a random sample of 5 patients of each room has been chosen. Each patient from the reference room has been matched with a patient in the refurbished room according to the use or not of respiratory machine and the Simplified Acute Physiology Score (SAPSIII) , which shows the severity of the patient's illness [34]. In most of the cases the ages of the patients were also similar. The comparison was conducted on two different time periods. For day time, the time period is 7 am to 9 pm and for the night time 9 pm to 7 am. Table 3.2 shows the patients pairs along with their data.

Pairs	ID	Room	SAPS	Respirator	Age
pair 1	72	Reference	52	yes	66
	63	Refurbished	52	yes	65
pair 2	111	Reference	67	yes	65
	62	Refurbished	65	yes	65
pair 3	49	Reference	56	yes	58
	50	Refurbished	65	yes	64
pair 4	118	Reference	36	no	58
	68	Refurbished	28	no	66
pair 5	101	Reference	43	no	32
	107	Refurbished	40	no	39

Table 3.2.: Table of the patient pairs presenting the patient ID, the room, the SAPS, the use or not of respirator and the age of the patients.

3.3. Results

3.3.1. Sound Levels distribution over time

For the SPL over time results, only one pair will be presented as an example and the graphs and results for all pairs will be presented in the Appendix. The choice of the pair to be presented is of no major importance, since the nature and the number of the events in the ICU are unpredictable and random, so pair No 5 will be the example to be presented with a SAPS not too high or too low. In Fig 3.2, 3.3, 3.4 and 3.5 the measured quantities versus time are presented.

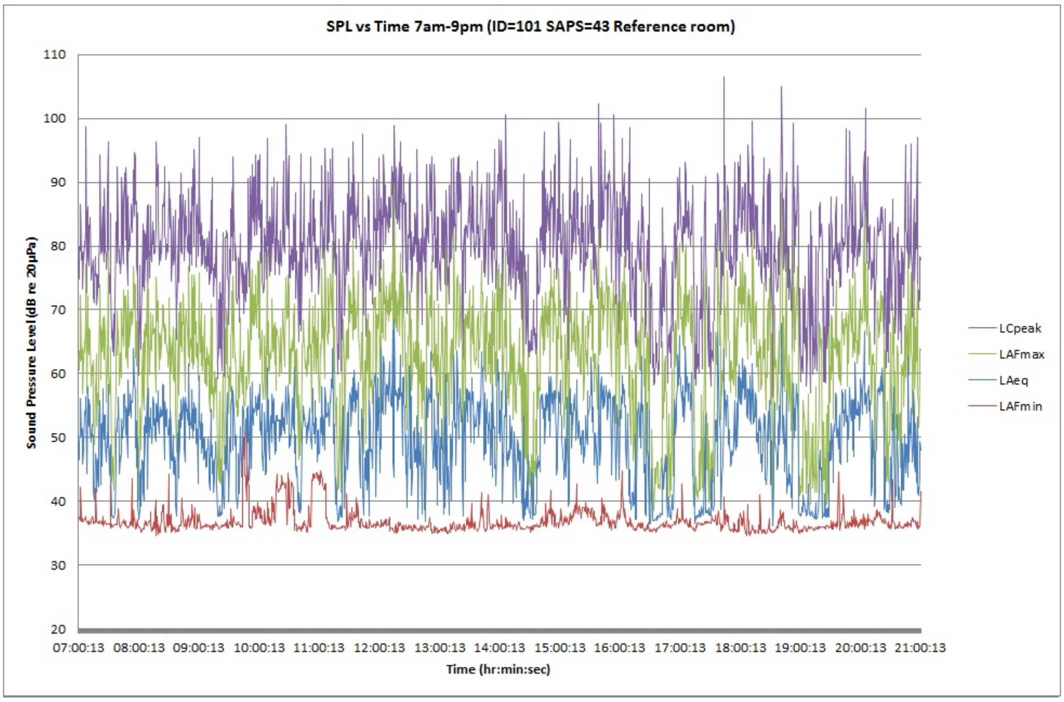

Figure 3.2.: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during day time.

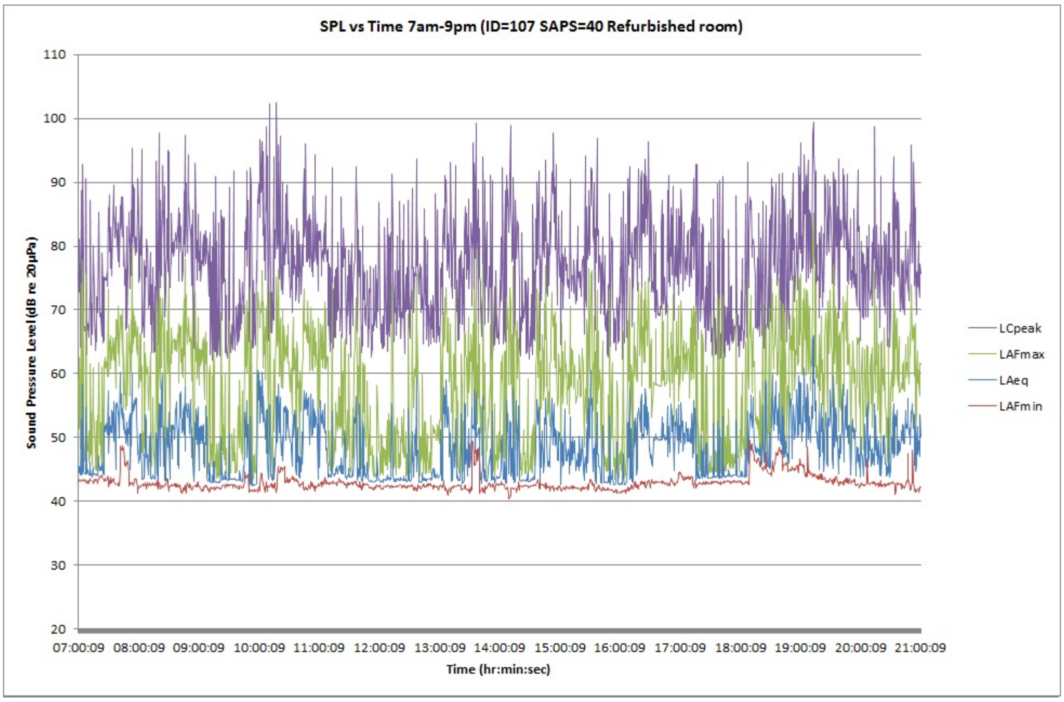

Figure 3.3.: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during day time.

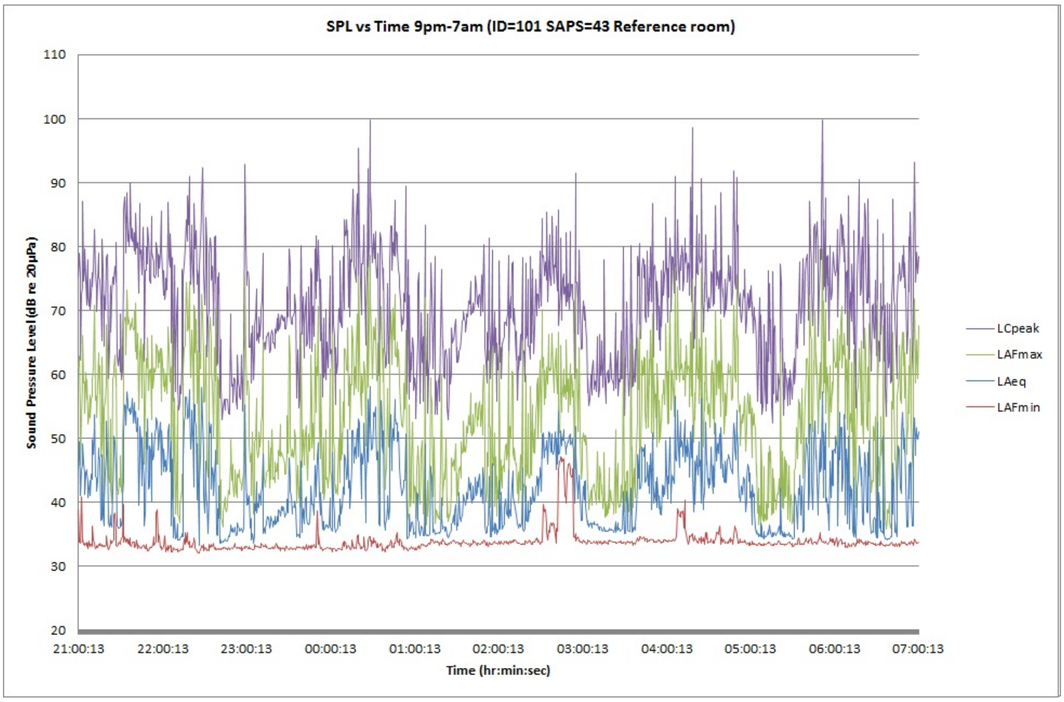

Figure 3.4.: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during night time.

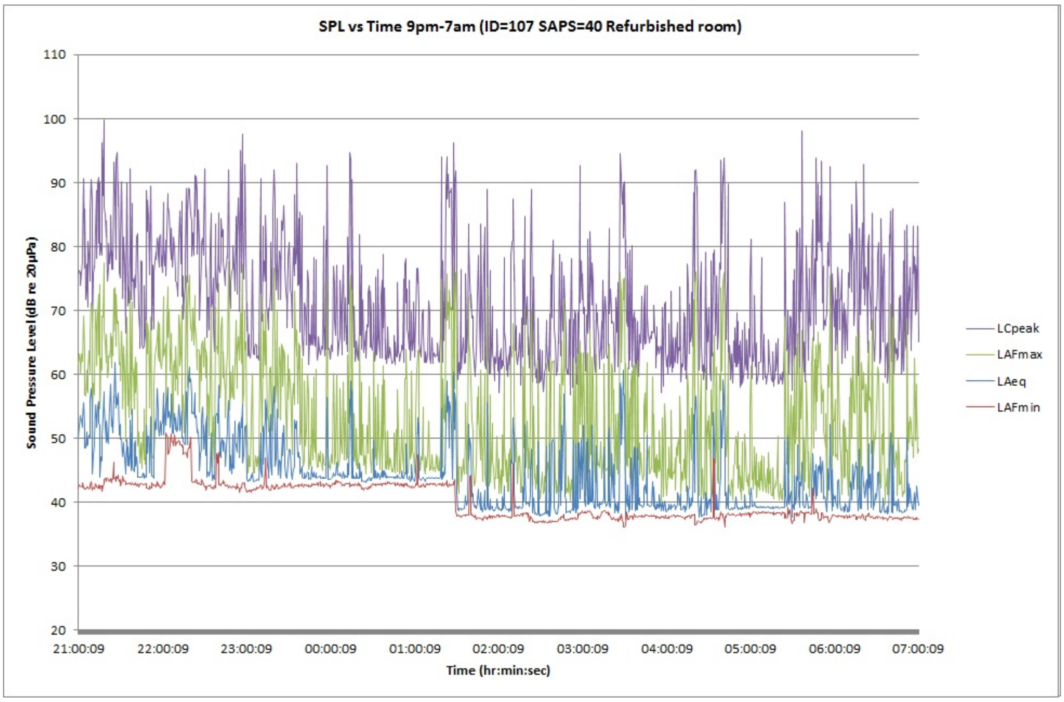

Figure 3.5.: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during night time.

The time periods for day and night are 14 and 10 hours respectively. That means that the time periods are very long and as one can see in the figures the levels are evenly distributed during day and night with no great difference. The most important thing that one can observe in these figures, is the short-term fluctuations of the levels indicating that the sound sources are coming from random, unpredictable events and can come and go at all times, affecting (and characterizing) the overall noise environment. It is not informative to analyse all the quantities; the most important information is that, generally, the levels exceed the recommended limits by WHO.

In Table 3.3 the LAeq and the L_{10} for each pair of patients and for the two time periods, are presented. L_{10} is the sound level exceed for the 10% of the time [6]. For example, if L_{10}=65 dB that means that for 10% of the total measuring time the sound level was above 65 dB.

Pairs	Day time				Night time			
	LAeq (dBA)		L_{10} (dBA)		LAeq (dBA)		L_{10} (dBA)	
	Refer. Room	Refurb. Room	Refer. Room	Refurb. Room	Refer. Room	Refurb. Room	Refer. Room	Refurb. Room
1	58.3	55.7	62.0	59.9	51.7	52.6	54.8	58.6
2	54.6	55.8	57.8	59.1	48.9	51.7	51.7	52.8
3	59.6	54.9	61.8	58.7	51.1	56.1	55.6	58.4
4	52.9	54.2	56.3	57.2	49.0	44.5	52.6	48.0
5	53.8	51.1	57.4	55.0	49.1	48.8	53.5	53.1

Table 3.3.: A- weighted equivalent level and L_{10} for both rooms for day and night time.

From Table 3.3 it is obvious that for all patients and time periods, the equivalent level is above 49 dBA with the levels to exceed 50 dBA for the 10% of the total time. One can see that there are small differences between the rooms with the reference room having slightly higher levels in most of the cases for day time and the refurbished room being slightly higher during night time.

3.3.2. Statistical Distribution of the Sound Levels

In order to have more complete information about the sound environment in the rooms, the statistical distribution of the levels has been obtained. The calculations represent the percentage of the time, over the two time periods, where the maximum equivalent and the C-weighted peak levels exceed values from 40 to 100 dB.

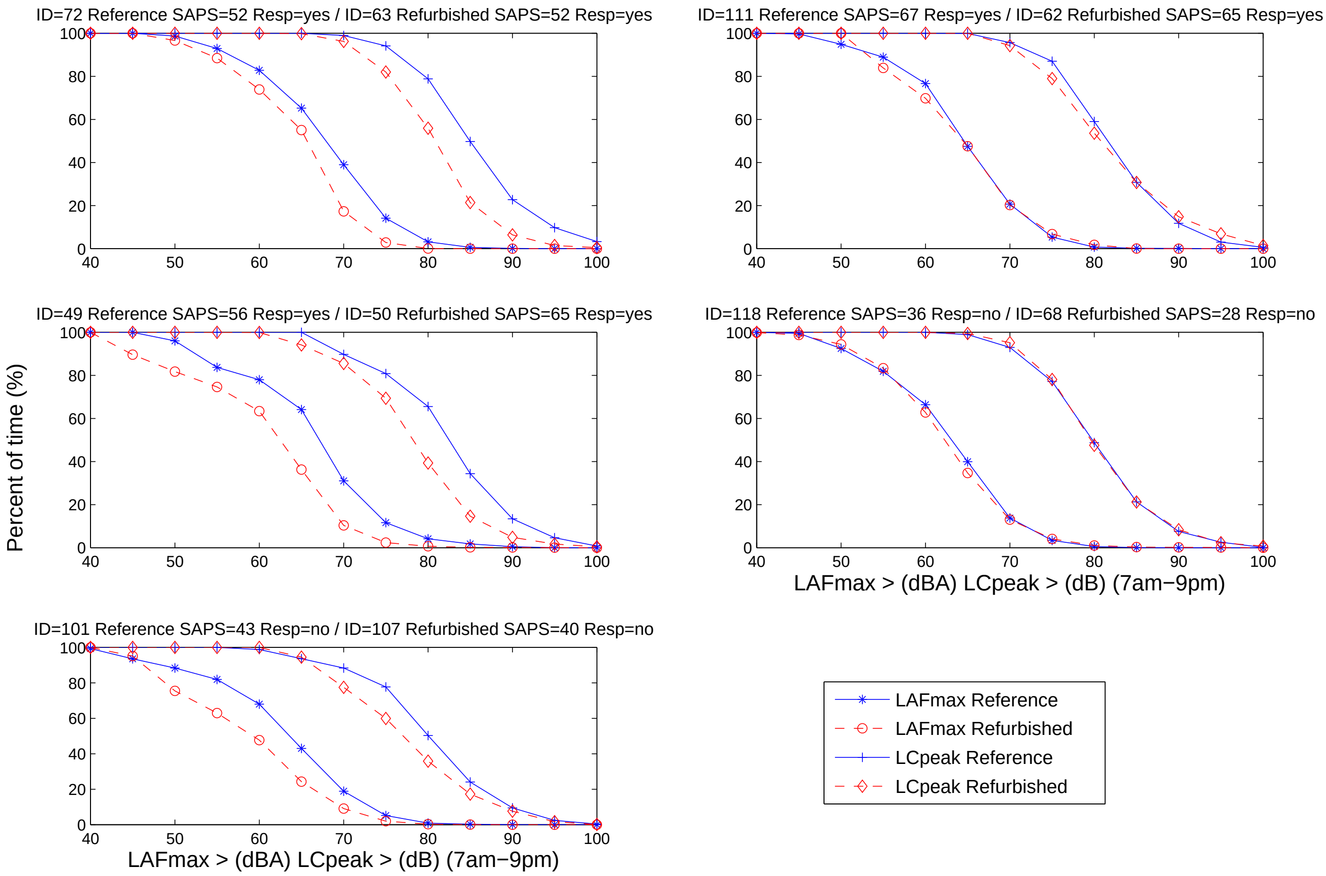

Figure 3.6.: Statistical distribution of A-weighted maximum levels and C-weighted peak levels in reference (blue solid line) and refurbished (red dashed line) room during day time.

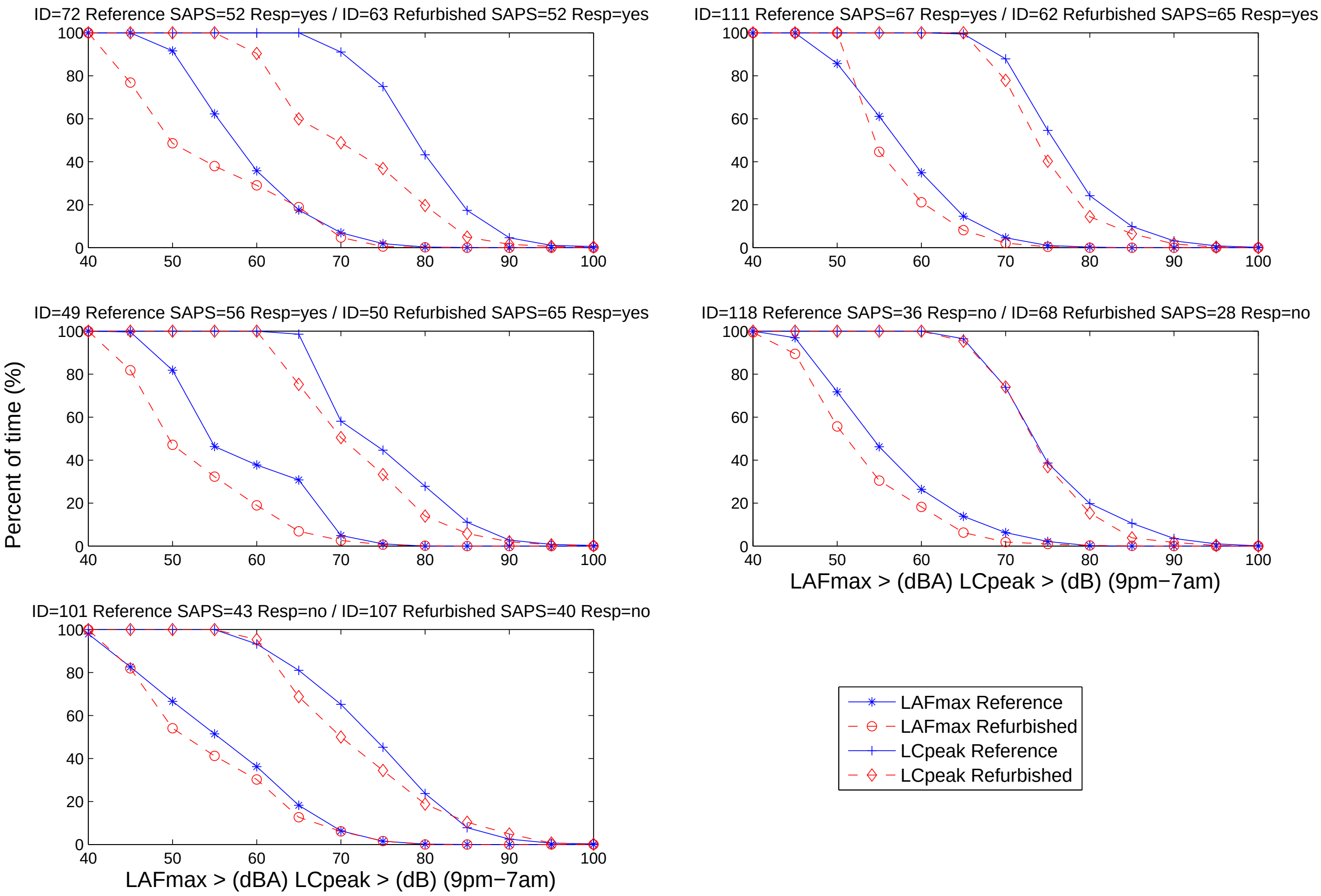

Figure 3.7.: Statistical distribution of A-weighted maximum levels and C-weighted peak levels in reference (blue solid line) and refurbished (red dashed line) room during night time.

From Fig 3.6 and 3.7 one can see that LAFmax is above 40 dB for 100% of the time periods for both rooms and for all pairs. The maximum and peak levels between 50 to 70 dBA and 70 to 85 dB respectively in the refurbished room occur in smaller percentages of time than in the reference room during the day for 3 out of 5 pairs. For the other two pairs the differences are very small with the refurbished room being slightly lower. C-weighted peaks of 65 dB occur for 100% of the day for both rooms and all pairs reaching even 85 dB for 20 to 50% of the time in the reference room. The overall picture given from the figures is that day time high levels occur in smaller percentages of the time in the refurbished room compared to the reference room.

Apparently during the night time the levels occur in much lower percentages of the total time due to less activity in the rooms. The shapes of the figures are very similar to the ones for the day time but are shifted to lower percentages. In the refurbished room the situation is clearly improved with the levels, both LAFmax and LCpeak, being lower most of the time. The higher levels though, for example LAFmax = 65 dBA and LCpeak = 80 dB, occur for more than 10% of the time in both rooms, which is too high for night time when the activity is less.

3.3.3. "Quiet "periods

From the previous investigation, we already described the equivalent, maximum, minimum and peak levels in both rooms. We concentrated on acceptable levels and the statistical distribution of the levels over two time periods. The high levels and the incidence with which they appear leads to the conclusion that the sleep patterns of the patients are disrupted so "restorative"times are in need [40]. Even though the levels are much higher than expected, it is important to investigate how many "quiet"periods occur in the rooms.

Following the same method that performed in a neurological intensive care unit by Ryherd and Persson Waye [40], the measurements of the equivalent, maximum and C-peak levels for each patient are gathered in tables according to the time period (day and night time). From these tables, the "quiet"periods have been calculated. By "quiet"periods, we mean the total number of the quantities of interest, which occur under a specific limit and for ≥ 5 minutes in a row. For example, setting a 45 dB limit for equivalent level, we are looking for at least 10 consecutive measurements (since the measurements have been performed with 30 sec intervals then we need at least 10 measurements to complete a 5 min period) with LAeq <45 dB. The same applies for all quantities.

The tables below show the amount of these "quiet"times in numbers of periods, mean and maximum lengths in minutes.

Number of periods ≥ 5 min										
	LAeq <45		**LAeq <50**		**LAFmax <50**		**LAFmax <55**		**LCpeak <75**	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	4	2	14	16	0	0	6	1	1	8
2	1	0	10	0	1	0	2	4	0	2
3	4	10	6	8	0	8	6	13	7	11
4	8	9	21	22	0	0	4	3	4	0
5	11	19	19	32	3	5	6	15	7	9
mean	**5.6**	**8**	**14**	**15.6**	**0.8**	**2.6**	**4.8**	**7.2**	**3.8**	**6**

Table 3.4.: Number of quiet periods ≥ 5 min in both rooms during day time (7 am-9 pm).

Mean length of periods ≥ 5 min (in minutes)										
	LAeq <45		**LAeq <50**		**LAFmax <50**		**LAFmax <55**		**LCpeak <75**	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	15.5	9.3	12.0	10.2	0.0	0.0	7.2	5.0	5.0	7.1
2	6.5	0.0	7.3	0.0	5.5	0.0	5.3	9.1	0.0	6.5
3	25.3	15.5	25.8	7.9	0.0	7.9	16.7	10.4	9.2	8.3
4	7.3	7.8	9.6	10.6	0.0	0.0	6.0	5.0	5.3	0.0
5	8.9	9.0	10.7	10.2	7.5	6.1	7.8	8.8	14.7	6.4
mean	**12.7**	**8.3**	**13.1**	**7.8**	**2.6**	**2.8**	**8.6**	**7.7**	**6.8**	**5.7**

Table 3.5.: Average length of quiet periods ≥ 5min (in minutes) in both rooms during day time (7 am-9 pm).

Maximum length of periods ≥ 5 min (in minutes)										
	LAeq <45		**LAeq <50**		**LAFmax <50**		**LAFmax <55**		**LCpeak <75**	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	32.5	10.0	49.5	32.0	0.0	40.5	9.0	5.0	5.0	13.5
2	6.5	0.0	12.5	9.5	5.5	0.0	5.5	11.5	0.0	8.0
3	60.5	35.0	112.0	13.0	0.0	13.0	30.0	25.0	16.5	19.5
4	14.0	17.5	26.0	48.5	0.0	0.0	8.5	5.0	6.0	0.0
5	21.0	16.0	33.0	27.5	10.0	7.0	13.0	18.0	10.5	10.0
mean	**26.9**	**15.7**	**46.6**	**26.1**	**3.1**	**12.1**	**13.2**	**12.9**	**7.6**	**10.2**

Table 3.6.: Maximum length of quiet periods ≥ 5 min (in minutes) in both rooms during day time (7 am-9 pm).

In Table 3.4 the periods of time longer than 5 min are presented in terms of numbers of periods. That means, and by looking at the averages, in the refurbished room there are more periods of silence, for every level than in the reference room during day time. In Tables 3.5 and 3.6 the silent periods are presented in terms of mean and maximum length of periods in minutes. From the averages, one can see that the differences in the mean values are not very big with the reference room having slightly longer periods. By looking at the maximum values, one can see that the differences between the rooms differ among the levels. For the LAeq level the reference room has longer maximum values while in the refurbished room there are longer periods with the LAFmax being lower than 50 dB. In the case of the LCpeak level the refurbished room has again slightly longer maximum "quiet"periods than the reference room.

Number of periods ≥ 5 min										
	LAeq <45		**LAeq <50**		**LAFmax <50**		**LAFmax <55**		**LCpeak <75**	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	19	10	18	7	0	15	20	19	1	21
2	1	0	23	0	0	0	8	16	9	16
3	14	9	10	20	2	1	18	3	17	5
4	21	21	19	12	2	0	19	25	23	16
5	16	27	18	23	9	11	16	20	15	20
mean	**14.2**	**13.4**	**17.6**	**12.4**	**2.6**	**5.4**	**16.2**	**16.6**	**13**	**15.6**

Table 3.7.: Number of quiet periods ≥ 5 min in both rooms during night time (9 pm - 7 am).

Mean length of periods ≥ 5 min (in minutes)										
	LAeq <45		**LAeq <50**		**LAFmax <50**		**LAFmax <55**		**LCpeak <75**	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	15.9	40.9	24.1	65.1	0.0	11.7	7.6	14.2	5.0	10.8
2	7.0	0.0	14.4	0.0	0.0	0.0	6.8	11.5	7.5	7.3
3	20.5	7.9	37.7	10.9	8.5	5.0	12.0	5.7	11.6	6.8
4	12.5	22.7	20.3	44.5	5.7	0.0	9.1	7.9	7.5	7.5
5	13.3	11.4	18.9	18.8	7.1	7.3	10.8	8.5	10.3	10.6
mean	**13.9**	**16.6**	**23.1**	**27.8**	**4.3**	**4.8**	**9.3**	**9.5**	**8.4**	**8.6**

Table 3.8.: Average length of quiet periods ≥ 5min (in minutes) in both rooms during night time (9 pm - 7 am).

Maximum length of periods ≥ 5 min (in minutes)										
	LAeq <45		LAeq <50		LAFmax <50		LAFmax <55		LCpeak <75	
Pairs	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**	**Ref.**	**Refurb.**
1	67.5	122.5	161.5	268.5	0.0	40.5	9.5	45.5	5.0	36.0
2	7.0	0.0	46.0	0.0	0.0	0.0	11.5	20.0	14.5	13.5
3	45.5	20.0	89.0	26.5	11.5	5.0	29.0	6.5	36.5	13.5
4	40.0	82.5	76.5	187.0	6.5	0.0	26.0	20.5	13.5	12.0
5	36.5	42.5	83.0	46.0	9.0	18.5	31.0	23.5	20.5	39.5
mean	**39.3**	**53.5**	**91.2**	**105.6**	**5.4**	**12.8**	**21.4**	**23.2**	**18.0**	**22.9**

Table 3.9.: Maximum length of quiet periods $\geq$ 5 min (in minutes) in both rooms during night time (9 pm - 7 am).

For night time measurements (see Tables 3.7, 3.8 and 3.9), the differences of the numbers of silent periods along with the mean and maximum values are smaller for the two rooms. There are more silent periods in both rooms, as expected, since during the night time the activity is less. The differences are not that big between the averages of the numbers of periods with the reference room having slightly more periods for the LAeq levels and the refurbished room being quieter for the LAFmax and LCpeak. The silent periods in minutes are longer in the refurbished room than in the reference room, with bigger differences in maximum duration for the LAeq <50, LAFmax <50 and LCpeak <75.

In Fig 3.8, 3.9 and 3.10 the averages of the numbers and the lengths of periods are presented. These figures present the LAeq <45, LAFmax <50 and LCpeak <75, for both rooms and for day and night time in a more illustrative way. The solid bars present the day time and the striped bars present the night time (blue for the reference room and red for the refurbished room).

From the figures one can see that the refurbished room has more and longer "quiet"periods for the LAFmax and LCpeak levels. In the case of LAeq, the values differ between the rooms with the reference room having less but longer periods for the day time but more and shorter for the night time. From the comparison of the five pairs of patients and by looking both the analytical tables and the figures, on can see that the averages for the LAeq levels between the two rooms cancel each other while there are clear differences for the LAFmax and LCpeak levels. This leads to the conclusion that the activity in both rooms is the same (since the patients of each pair have the same SAPS) but in the reference room the maximum and peak levels are markedly lower.

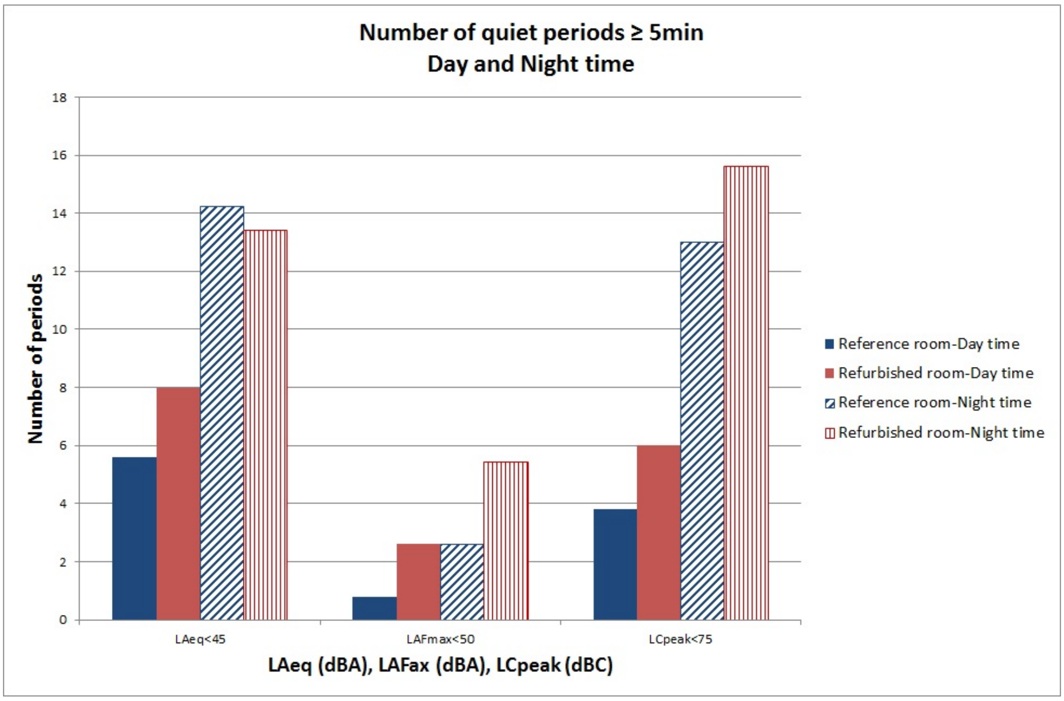

Figure 3.8.: Average values of the numbers of quiet periods for both rooms, for day and night.

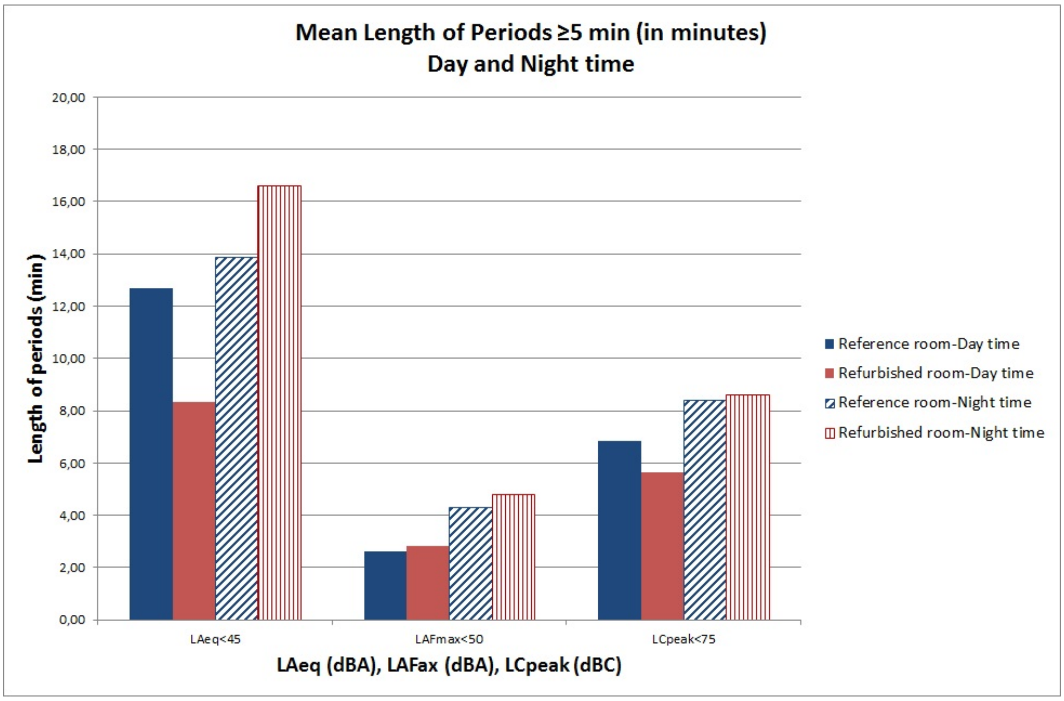

Figure 3.9.: Average values of the mean length of quiet periods (in minutes) for both rooms, for day and night.

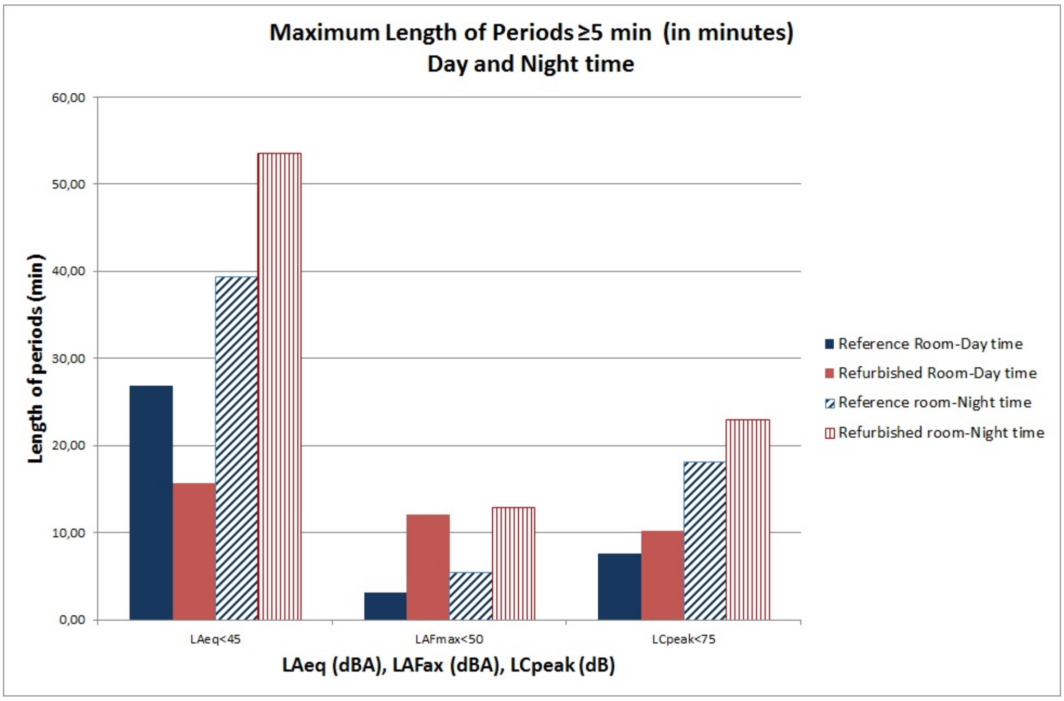

Figure 3.10.: Average values of the maximum length of quiet periods (in minutes) for both rooms, for day and night.

3.4. Conclusions

For both, the reference and the refurbished room, the levels are very high for the 100% of the two time periods. Keeping in mind the fact that random events occur in the ICU regardless of the severity of the patient, for all five pairs, the maximum equivalent levels are above 40 dB and the peak levels above 65 dB for almost 100% of the day and night time.

Generally, one can say that the refurbished room is quieter compared to the reference room and especially for levels between 45 and 75 dB for the maximum levels and 65 to 85 dB for the peak levels, but it still needs further improvement. All the figures for all cases are presented in the Appendix.

Taking into account all the previous information about the sound environment of the rooms and how high the sound levels are, as well as their distribution in time, the results from the 5 min period tables can verify and complete the analysis of the sound distribution in the rooms. The refurbished room has more and longer "quiet"periods than the reference room for the maximum and peak levels and for day and night time. The LAeq levels vary between the rooms with the reference room having less periods and the refurbished room longer periods in terms of length in minutes. In short, the reference room is louder in maximum and peak levels but with the main activity (LAeq) being almost the same in both rooms. Of course the number and the length of these periods is still not enough for the patients to rest since these periods are followed by high sound peaks that occur during day and night.

A preliminary study by Persson Waye and Ryherd (2013) on the effect of the interventions on the personnel showed that the refurbished room was rated less noisy, bleeping and hissing. The fact that the maximum and peak levels in the refurbished room are lower and occur in smaller percentages during day and night time, might lead to the hypothesis that the personnel is behaving differently in the room, moving and talking more quietly influenced by the visual interventions (aesthetics, lightning). Another hypothesis might be that the personnel talk more quietly because of the improved speech clarity [38].

4. Noise source identification

While Sound Pressure Levels are measured continuously with the equipment set by Limes Technology AB, as mentioned in Chapter 3, wave files have been recorded for two hours per day, one hour during day time (7 am-9 pm) and one hour during night time (9 pm-7 am).

The plan was to collect wave files every day for the same hours for day and night, but because of an equipment failure caused by unplanned power outages, half of the wave files have been recorded at 15:00 in the afternoon and 03:00 in the morning and the others at 12:00 in the afternoon and 00:00 at midnight. Since the aim is to identify the noise sources throughout day and night between the two rooms this time change is not crucial.

4.1. Method

4.1.1. Selection of recordings

In order to be able to identify the noise sources in ICU a good sample of recordings is needed. The recordings are divided in two different time periods, as mentioned above.

The recordings were randomly selected among a large number of recordings (630 recordings in the refurbished and 393 in the reference room) for all time periods.

First a list has been made with all the available recordings sorted by date and time period. Eleven recordings for day time and 12 recordings for night time have been selected for random dates for both rooms. In total, 23 recordings (23 hours) have been used and evaluated. The number of the recordings from each room is presented in Table 4.1.

Day time		
Refer. room	6 recordings	11 recordings
Referb. room	5 recordings	
Night time		
Refer. room	7 recordings	12 recordings
Referb. room	5 recordings	

Table 4.1.: Number of selected recording for reference and refurbished room for day and night time.

4.1.2. Listening process

The reproduction of the recordings has been done through Audacity Software version 2.0.5. During the listening process the noises/sounds were identified and noted under the spectrogram in label tracks (Fig 4.1) forming a table for each recording with the sounds and their exact starting and ending points.

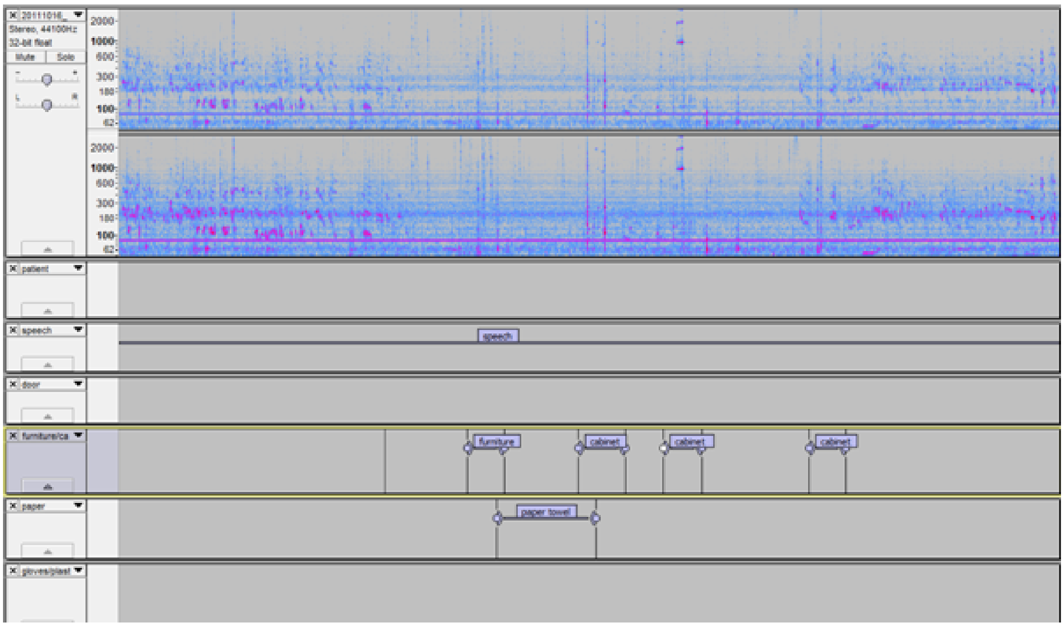

Figure 4.1.: Reproduction of the recordings through Audacity. Identification of the sources and durations.

4.1.3. Definition of the durations

From these tables we can calculate the exact duration of each sound over the 1 hour recording i.e. sound from furniture occurred in total 5 min over 60 min of the recording. The exact duration of each sound is defined as the time during which the sound is audible.

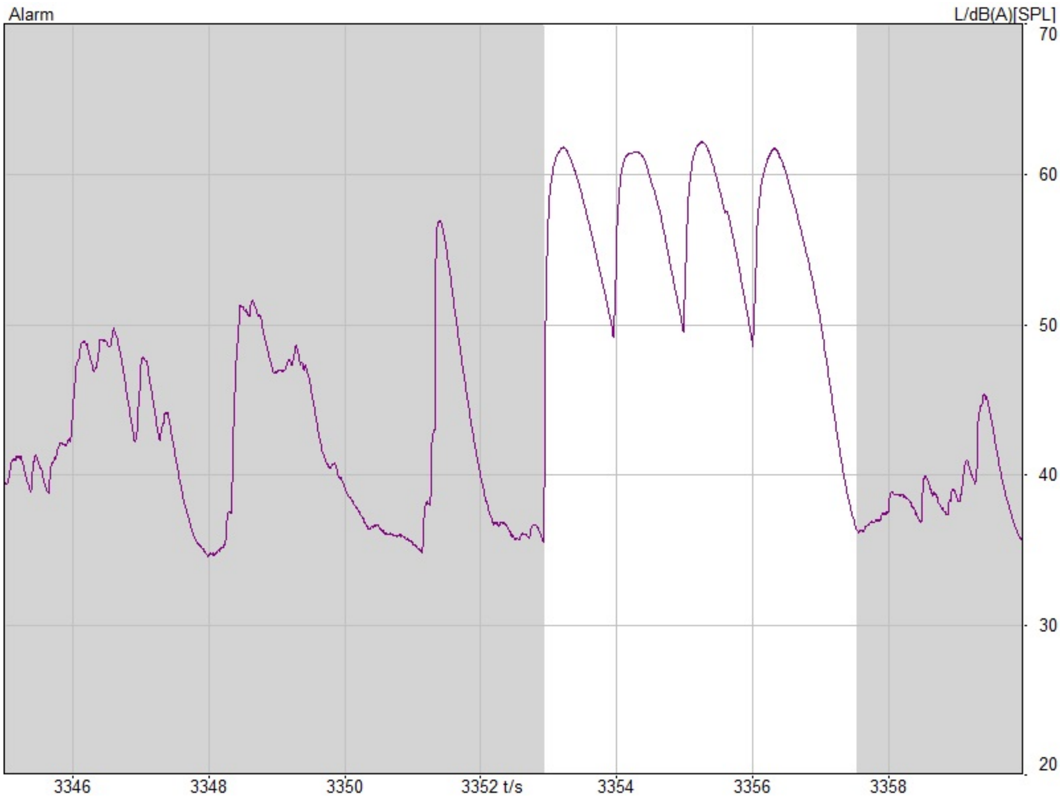

Figure 4.2.: Definition of the duration of a continuous sound. Example of a bleeping sound. The figure shows the A-weighted SPL with time weighting Fast.

For continuous sounds i.e. bleeping sounds, dragging and squeaking sounds etc. the duration is defined by the time that the sound is audible including fade out, if present. An example of a continuous sound is presented in Fig 4.2.

For impulsive sounds, Fig 4.3, the duration is also defined in the same way. The reverberation is also included when present.

4.1.4. Sound sources processing

After collecting all the sounds from all the recordings, the average, minimum and maximum durations were obtained together with the standard deviation. The minimum and maximum values show us the range of the duration of each sound and the standard deviation the amount of variation from the average.

Minimum and maximum durations are coming from the sum of the milliseconds or seconds that the sound occurs in every recording, i.e. the cabinet noise occurs in 11 of the 11 recordings that have been used as samples with minimum sum 0.22 min and maximum 4.61 min.

Tables with all noise sources and durations are presented in the Appendix.

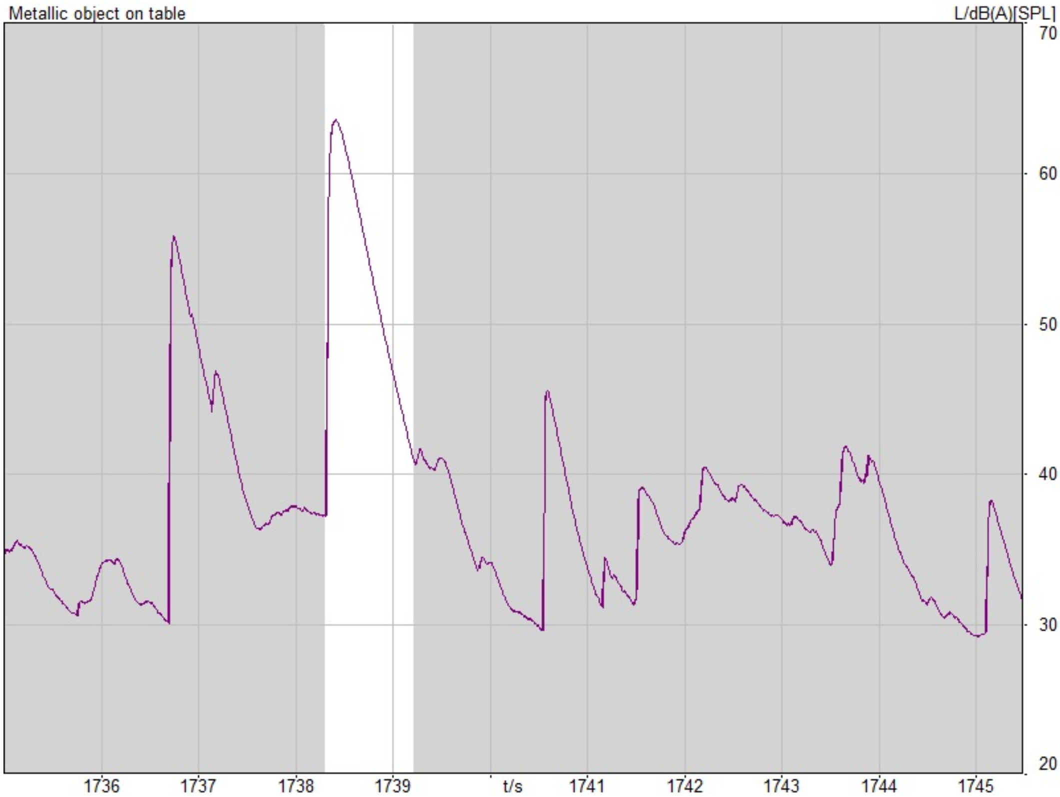

Figure 4.3.: Definition of the duration of an impact sound. Example of a metallic object hitting a table. The figure shows the A-weighted SPL with time weighting Fast.

4.2. Data Analysis

4.2.1. Statistical Analysis

A t-test has been performed in order to determine if there is a significant difference between the two rooms under study. This analysis is appropriate for comparing the means of two groups in order to assess if the compared groups are statistically different. A comparison of the means of the constructed variables has been done between the reference and the refurbished room and also separately for day and night. The sound events were grouped in three groups. The group "room equipment"includes noises from cabinets, furniture, rolling carts and doors, the group "medical equipment"includes bleeping and alarm sounds and "staff activity"includes the speech, objects hit on a table , plastic packaging, steps, apron and other noises from human activity. The test has been performed for the comparison between the number of events between the reference and the refurbished room and the comparison between the durations of the noises for both rooms. Both tests have been performed separately for day and night. The results can be found in Tables 4.2 and 4.3.

In simple terms, from Tables 4.2 and 4.3 looking at the averages of the ratio between reference room (1) and refurbished room (2), relative to the spread of the data of the rooms (confidence

Day time			
Variable	**Class**	**Mean**	**Confidence limits (95%)**
Room equipment	Ratio (1/2)	1.41	(0.60,3.30)
Medical Equipment	Ratio (1/2)	0.75	(0.16,3.55)
Staff activity	Ratio (1/2)	0.81	(0.26,2.49)
Night time			
Variable	**Class**	**Mean**	**Confidence limits (95%)**
Room equipment	Ratio (1/2)	2.26	(0.22,23.50)
Medical Equipment	Ratio (1/2)	0.93	(0.14,6.21)
Staff activity	Ratio (1/2)	1.04	(0.13,8.14)

Table 4.2.: T-test between the reference (1) and the refurbished (2) room in terms of number of events for day and night.

Day time			
Variable	**Class**	**Mean**	**Confidence limits (95%)**
Room equipment	Ratio (1/2)	1.06	(0.41,2.70)
Medical Equipment	Ratio (1/2)	0.27	(0.02,4.69)
Staff activity	Ratio (1/2)	0.93	(0.13,6.45)
Night time			
Variable	**Class**	**Mean**	**Confidence limits (95%)**
Room equipment	Ratio (1/2)	2.53	(0.07,92.71)
Medical Equipment	Ratio (1/2)	0.74	(0.03,18.63)
Staff activity	Ratio (1/2)	0.48	(0.01,35.48)

Table 4.3.: T-test between the reference (1) and the refurbished (2) room in terms of durations of events for day and night.

limits: lower and upper limits of the ratio between means), we cannot conclude that there is a difference with respect to the number or the duration of events during day and night between the reference and the refurbished room.

The confidence limits are an interval estimate of the ratio of the means. The narrower the interval the more precise is our estimate. The 95% in the tables is a confidence coefficient, associated with the method of calculation and shows that the true mean is contained within the interval with probability of 95% [2].

With the bootstrap technique the Confidence Intervals (CI) plot in Fig 4.4 is obtained.

The samples used for the analysis are random, as mentioned. With the bootstrap technique the data from both rooms, which are based on samples from an approximating distribution, are estimated. In Fig 4.4, one can see that there are no significant differences on the durations of the events between the rooms with only exception the equipment, which refers to the bleeping

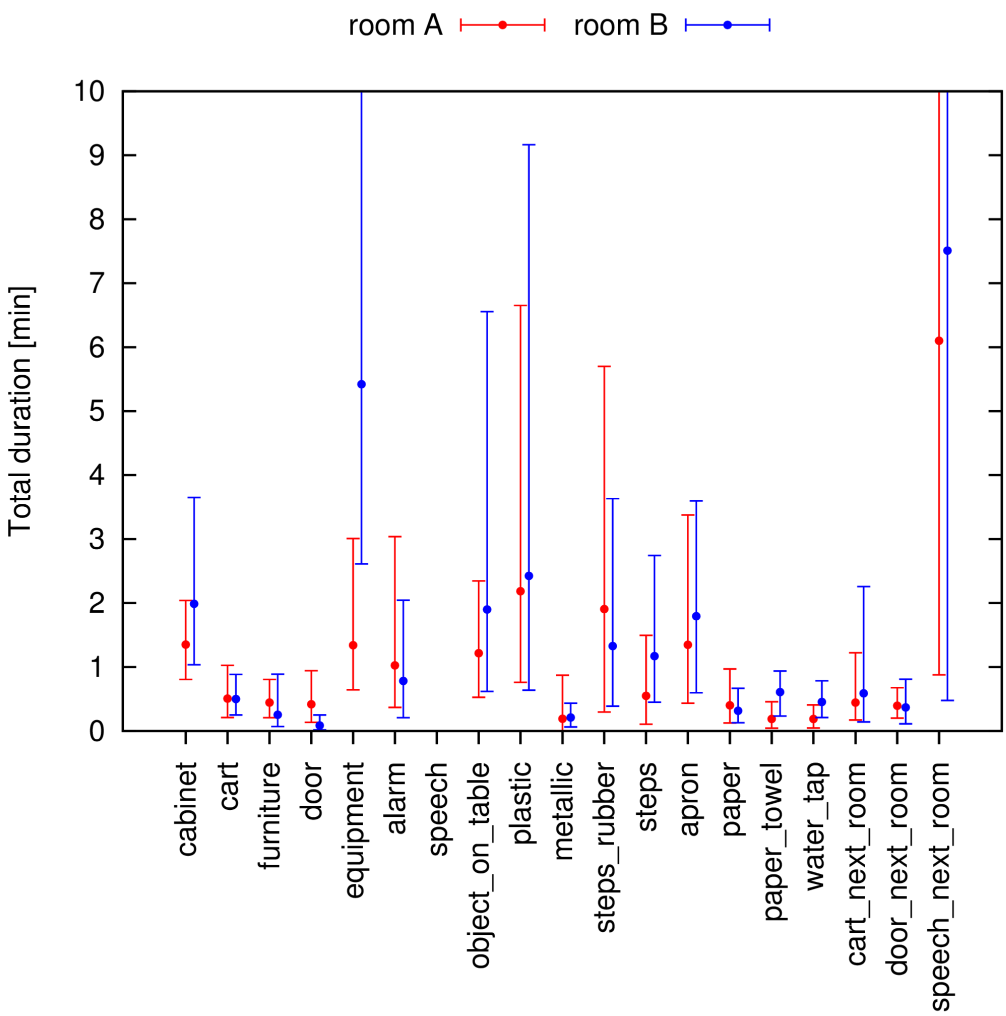

Figure 4.4.: Bootstrap plot of the comparison between the durations of events in both rooms. Reference room is room A (left line) and refurbished room is room B (right line).

medical equipment. The spread of the durations of "equipment"and "speech next room"go up to 45 minutes but this plot is used because the data are more legible.

Since there are no significant differences between the rooms regarding the number of events or the durations, the sound environment of the ICU is described without taking into consideration the different rooms but for day and night time with all the noise sources grouped by time period.

4.2.2. Description of the sound sources

Different noise sources produce different kinds of noise with different properties, such as loudness, frequency of the sound, adaptation to the noise level and also to what extent the noise is predictable and/or avoidable [44]. The adaptation to the noise (sensory adaptation) occurs when sensory processing becomes less sensitive to stimuli [36].

The noise sources that are active in a hospital environment can be categorized in those from medical equipment, alarms and those from human activity such as staff and visitor's activity, daily patient care. Identifying the source of noise is subjective since sometimes it is very difficult to identify where the sound comes from or also to define the exact duration of each sound. The sounds that have been identified in the recordings are analysed in the following section. The sounds are divided in categories according to Table 4.4.

Day time		**Night time**	
Noise from inside the patient's room	**Noise from outside the patient's room**	**Noise from inside the patient's room**	**Noise from outside the patient's room**
Room equipment	Room equipment	Room equipment	Room equipment
Medical equipment	Medical equipment	Medical equipment	Medical equipment
Equipment manually operated	Staff activity during patient care	Equipment manually operated	Staff activity during patient care
Staff activity during patient care	Other devices	Staff activity during patient care	-
Patient noise	-	Patient noise	-
Other devices	-	Other devices	-

Table 4.4.: List of noise sources that come from inside and outside the patient's room during day and night time.

From Table 4.4, one can clearly see that the noise sources during day and night time are the same. What differs is the incidence with which they occur. Some of the noise sources are analysed below separately for day and night. Tables with all the noise sources, the durations and number of events, are presented analytically in the Appendix.

4.2.3. Day time noise sources

Room equipment

With the description "room equipment"the sounds coming from furniture, cabinets, doors, rolling carts and metallic rolling carts inside and outside the room are described. Chairs or tables that are dragged on the floor, slamming doors and cabinet's doors or drawers, noise from the wheels of the carts and rattling sound from the objects on them as they roll, are the most frequently occurring and identifiable noises.

These noises are often loud impact noises that last for milliseconds but are loud enough to disturb a patient that is sleeping or trying to sleep. For the noise sources from inside the room, noise from the cabinet door or drawer occurs in every recording.

The second most frequently occurring sound is the one that comes from the rolling cart, and this is maybe because the daytime recordings have been performed at 12:00 which is lunch or patient care time. Also sounds from furniture and slamming doors occur a lot that is probably also because of the time period of the recordings which involves visiting hours.

The order of occurrence for the noise that comes from outside the room is different. The most frequent sound is the one from the rolling carts which seems reasonable if one takes into consideration that rolling carts go around the corridor passing by close to the room. Slamming doors come second and noise from furniture and cabinets are not that identifiable because the sound is reduced through walls and closed doors.

Medical equipment

Another noise source from inside the patient's room is the sound that comes from medical equipment. There are two kinds of sounds, the high frequency bleeping sounds that often correspond to alarms or monitoring equipment and the sounds that come from other parts of the equipment like portable equipment with motor sounds, computer fans or respirators with a constant pump-like sound. This noise source is a little bit controversial because on one hand these devises are located mostly next to the patient's bed and can be identifiable even in neighbouring rooms, but on the other hand these are essential for the patient's treatment and recovery.

The most frequently occurring sound inside the room is the bleeping sound from monitoring equipment and the low frequency constant sound from the respiratory machine. Due to the random selection of the recordings, we cannot really say if this is a representative situation, but we can say that the alarm sound occurred in almost half of the recordings. Other mechanical sounds were also observed from the moving parts of the equipment or the computer fan. These sounds are of low frequency and often constant but can still be considered as annoying, especially in quiet periods and if the equipment is located close to the patient.

Although the medical equipment sounds that coming from neighbouring rooms are lower in level than the ones from inside the room, they were easily identifiable especially in silent moments.

Apart from the medical equipment used for the treatment and recovery of the patients, there is other equipment that is used during the patient care. This includes the bed elevators, oxygen mask and other mobile equipment that is manually operated by the staff. In half of the recordings, noises from the equipment preparation occurred, like typing in keyboards, assembling equipment parts etc. These noises might not be of high level but come from activity that occurs next to the patient and also occurs at any time (day or night time).

Because of the nature of the sounds, since they come mostly from mobile equipment, special modifications on the machinery of the equipment need to be done in order to reduce noise to acceptable levels [25]. It is not a matter of staff's behaviour so there will be no improvement even if the staff is trained. One positive thing is that these noises are not of high level and frequency.

Patient noise

With this term, we refer to the noise that comes from the patient such as snoring, coughing, exclamations of pain and speech. This noise source is reported only as a fact/addition to the overall sound environment and cannot be changed or avoided.

Other devices/noises

In almost half of the recordings, noises from mobile phones from inside the room have been identified. These ringing tones sounds are of high frequency, continuous sounds, often with an increasing sound level over time. It is very easy to avoid this kind of noises since all the modern devices have the option to reduce or even mute the level of the ringing tones, which is an action that may be imposed to staff and visitors. Moreover, in one of the recordings there was a TV sound which indicates the presence of entertaining devices in the room. Of course for a single bed room and with the right volume level that would not be a problem but it might be a problem since the rooms under study are two-bed rooms.

While listening to the recordings, there was a sound that caught my attention. It was a short, low level, like a small spring sound which was repeated every 1 minute and was more noticeable in quiet periods in the room. The mystery was solved and the sound was detected. It was the wall clock located in the room. The minute hand produces a tremolo sound every time it moves. Of course it is not easily noticeable especially if there is high activity in the room but it can be annoying in quiet periods for a patient that is trying to sleep.

In this category, the noises that come from outside the room are a bell and a crying baby both occurring in only one recording and can be considered random events giving, however, more information about the total sound environment during a typical day in the ICU.

Staff activity

The activity in the patient's room during the day is higher, especially during the patient care or visiting hours either by the staff or visitors (i.e. family). Different kinds of sounds of different level and frequency have been identified in the recordings. Speech, steps, objects on table etc. are some of the most common sounds. Below an analytical description of each noise source is given.

Human speech is the most frequently appearing noise during day time, unsurprisingly, since the time period of the recording of the files is around lunch or visiting times (by both doctors and visitors). During the listening process the nature of the conversations were not recorded. The average of 42 minutes over the 60 minutes that human speech occurred indicates the presence of people in the room during the whole recording time. Conversations between the staff are crucial and important for the patient's treatment but can cause distress to those who need a quiet environment to recuperate [37]. One solution to this problem would be training the personnel about the recommended voice levels and restricting the discussions to the bare essentials. Also recommendations should be given to visitors about the proper behaviour during visiting hours.

Another common noise source in the recordings is the staff activity while taking care of the patient. Objects that hit on the table were the highest in terms of sound pressure level, especially when the objects were metallic. In addition to the high sound level some of these impact sounds occur often and are high frequency sounds. Noteworthy is that these noises often originate right next to the patient.

Other noise sources that occur due to the personnel activity while taking care of the patients are noises from the use of plastic packaging and containers, use of paper covers and cleaning paper, rubber gloves and also noises from using the water tap and the sink in the room while washing hands, objects or while opening and closing the tap.

Also some other noises have been detected but because of the difficulty in identifying them they have been called generally "patient care"noises and are reported in order to give a more complete information about the sound environment in the room.

Another noise source that has been detected in most of the recordings is the sound that comes from steps and shoes. Normal steps or the short, of high frequency, squeak sound that comes from rubber shoes on plastic floors have been identified and located inside the room with high peaks especially in quiet periods.

A noise that was identified in more than half of the recordings was the one that comes from the apron that the personnel uses while taking care of the patients to avoid infection. These aprons are kept folded outside of the room and are put on by shaking them to unfold. The sound coming from this shaking is very short but loud. The reason that I refer to this sound separately is because I noticed that the procedure described above is happening next to the patient but can also be annoying to the patient in the neighbouring bed.

Regarding the noise sources outside the room due to staff activity, speech from people in the corridor or neighbouring rooms is detected in almost half of the recordings. Also because of the time period that the recording has been done (around lunch time for staff and patients) a lot of noise coming from kitchen, including plates and silverware noise, has been detected.

4.2.4. Night time noise sources

Room equipment

The activity in an ICU never stops regardless of the time period. It is unknown when a patient needs to be treated. Noises coming from the use of the room equipment such as cabinets, drawers and furniture have been detected also during night. Rolling carts, slamming cabinet's doors and furniture drawn on the floor along with slamming doors in some cases are the most frequent noises.

For outside the room, the most frequent noise sources during the night are the opening and closing of doors, cabinet's slamming door and rolling carts in the corridor.

Medical equipment

As mentioned, the events in an ICU are random and unpredictable meaning that sounds from medical equipment especially alarms or monitoring equipment can occur any time during day and night. From the recordings high activity from medical equipment was observed especially bleeping sounds and alarms. This equipment is crucial and important for the patient's treatment so this kind of sound cannot be completely avoided.

Other devices

In the case of night time the repeated tremolo sound of the clock that mentioned before, is even more noticeable because of the silence that prevails during the night. Also noise from entertaining devices such as radio and TV were detected and located both inside and outside of the room.

4.3. Conclusions

From an overall view of the noise sources that are located inside and outside the patient's room and focusing only on the comparison between day and night time since there is no significant difference between the two rooms, the conclusions below arise.

As mentioned before, the number and nature of the events in the ICU is random and unpredictable. There are noises that are connected to these random events such as the medical equipment sounds and alarms and other noises that are more connected to the human activity (staff, visitors and patients). Some of these noises are predictable and avoidable but other noises must be treated in a different way.

Most noise sources are more frequent and with longer duration during the day, as expected since the day time recordings have been done during the rush hour of the ICU.

While trying to qualitatively describe the sound sources in a specific area, the duration of the sound is also important together with the frequency of occurrence. For example, the maximum duration of the slamming cabinet's door sound is 6.55 minutes since it is a short impact sound but occurs in most of the recordings regardless the time period. On the other hand, the sound that comes from the rolling carts, for example, is more continuous, rattling sound that can have also long duration. In Chapter 5, a more qualitative investigation of the sounds is presented, analysing the characteristics of the sounds.

The noise environment of a hospital is a very complex environment consisting of equipment and human activity. It is very hard to try to characterize such an environment because it is an alternating environment. The best thing one can do is to try to identify the predictable and unpredictable sounds and give the best and most suitable solution for each case in order to achieve a more healthy and pleasant sound environment for patients, personnel and visitors.

Concluding, the most frequent and longer in duration noise sources are the ones connected to human activity while generally loud and sudden noises occur often from many different noise sources.

5. Perceptual Characteristics in the ICU

5.1. Noise impact on patients

The hospitalization experience can be stressful for patients. Being in a hospital environment can lead to emotional overload that has to do with the different kinds of events happening during day and night [46]. A study conducted by Busch – Vishniac et al. in 2005 [15] has revealed that noise plays significant part on both psychological and physiological condition of the patients.

A noisy environment can cause stress, anger, confusion and distraction. Loud noises in hospitals are also linked to sleep disturbances [14]. Other negative physiological effects of noise on patients such as cardiovascular response, extended hospital stay and increased dosages of pain medication have been documented in previous research [40].

In Chapter 4 the noise sources in the ICU environment have been identified through a number of recordings. From the noise sources tables (see Appendix), one can see that the most frequent noises are unwanted or unnecessary sounds coming from staff and visitors activity during visiting or care taking hours. Most of the sounds are sudden impact sounds coming from furniture, slamming doors or objects hitting the surface of a table etc. Previous research revealed that these sudden, loud noises can decrease oxygen saturation, increase blood pressure, increase heart and respirator rate [31].

These psychological and physiological impacts are more connected to the level of a sound (loudness) and the time period that occur. A sound can be considered as "noise"if makes people feel uncomfortable, annoying or alarming and it depends on much more than the level of the sound [14].

In order to describe the sound environment in the ICU from a qualitative view, fundamental psychoacoustic metrics have been used. These metrics have been developed through subjective evaluations trying to stimulate the sound processing of the human hearing system [27]. The psychoacoustic measures are used to characterize the sound quality by quantifying the attributes of an individual sound that combine to give the overall impression of sound quality [45].

5.2. Psychoacoustic metrics

The calculated metrics are Loudness, Specific Loudness, Sharpness, Roughness, Fluctuation Strength and Tonality. A short description of the psychoacoustic metrics is presenting below. All the descriptions have been taken from the book "Psychoacoustics – Facts and Models"by Hugo Fastl and Eberhard Zwicker [19].

5.2.1. Loudness

Loudness level measure is used to characterize the loudness sensation of any sound according to a critical – band rate, the Bark, which was introduced in the twenties by the researcher Barkhausen. The unit for loudness level is phon and it is the sound pressure level of a 1 kHz tone in a plane wave and frontal incident that is as loud as the sound. For any pure sound it is possible to measure the loudness level using the so called equal-loudness contours (Fig 5.1).

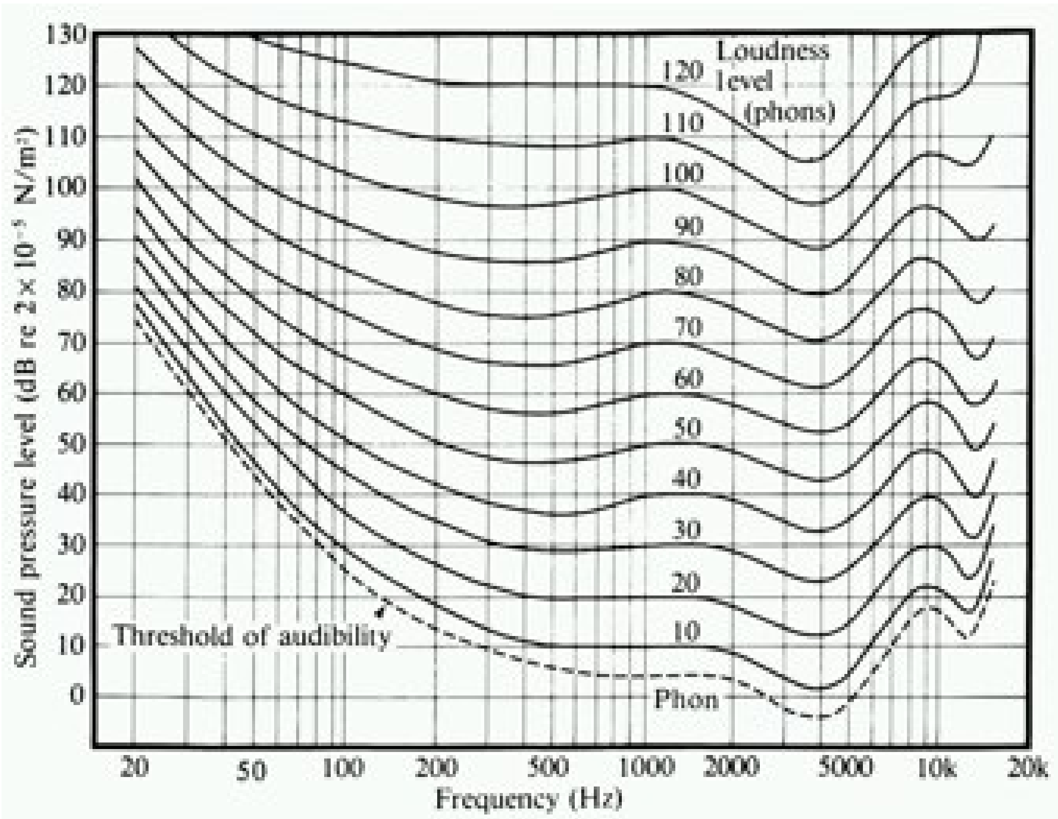

Figure 5.1.: Equal – loudness – contour according to ISO 226 standard. Picture accessed from [26] (November 2014).

As one can see in Fig 5.1, all the curves have to go through the sound pressure level at 1 kHz where the dB and phon coincide, according to the definition. For example, 40 phons contour goes through 40 dB at 1 kHz. The dashed line shows the threshold in quiet that, as one can see, the limit of loudness sensation does not correspond to 0 dB but to 3 dB (3 phons) at 1 kHz.

In order to measure the sensation that corresponds most closely to the actual intensity of a sound, a more subjective and linear scale is used called sone. The reference of loudness sensation (1 sone) is the level of 40 dB (40 phons) at 1 kHz. Table 5.1 shows the relation between phon and sone.

Phon **(Loudness level, non-linear scale)**	**Sone** **(Loudness sensation, linear scale)**
40	1
50	2
60	4
70	8
80	16
90	32
100	64

Table 5.1.: Relation between sones and phons. Table accessed from [5] (November 2014)

From Table 5.1 one can see that increasing the level by 10 dB doubles the loudness and decreasing it by 10 dB cuts in half the sensation of loudness.

Furthermore, because of the frequency sensitivity of the human ear, two sounds of equal intensity does not mean that they will have the same loudness, i.e. an 80 dB tone at 200 Hz is not as loud as at 3 kHz. Loudness is frequency dependent which can be also seen in the equal – loudness contours.

For the calculations that have been performed in this study, the sone scale has been used for loudness as a function of time because of the time – varying characteristics of the sounds. Another metric relative to loudness that has been calculated is the Specific Loudness (loudness per critical band) which is basically loudness as a function of frequency. It is a model of loudness that has been developed using Steven's power law that says that a relative change in loudness is proportional to a relative change in sound pressure. This loudness model that is developed by Zwicker (1956) is based on the excitation pattern. The excitation pattern represents how the excitation distributes in the cochlea. Zwicker's model transforms the excitation pattern to specific loudness pattern and taking the overall loudness by calculating the area under the specific loudness [35].

The critical band that is referred above, is a psychoacoustic term introduced by Harvey Fletcher, giving, basically, the frequency resolution of the ear. A test tone is been masked by another tone or noise when they are less than a critical bandwidth apart. In this case, it is hard to separate the two sounds and the summation of loudness becomes complex. When a tone is masked by another we mean that the perception or detection of this tone is affected by the presence of another tone or noise.

5.2.2. Sharpness

The sensation of sharpness can be also related to the "density"of sound. Sharpness is generally linked to the spectral characteristics of the sound with higher values of sharpness occur in high frequency signals. The unit used for sharpness is acum. A narrow- band noise, one critical-band wide at 1 kHz (center frequency) and of a 60 dB level, produces 1 acum of sharpness.

A more general description of sharpness could be that it is a metric that can give the "color"of a tone. It can show for example how aggressive or powerful the sound from a product or equipment can be. It is one of the most important psychoacoustic quantities to describe the quality of a sound.

5.2.3. Roughness

Another important psychoacoustic quantity used in this project is roughness. It is the sensation of fluctuation that is produced by temporal variations of the sound reaching a maximum for 70 Hz modulation frequencies. Changing the modulation frequency from low to high gives a sensation of fluctuation for three perceptual stages. The first stage is at very low modulation frequencies (with maximum at 4 Hz) where it gives the perception of changes in loudness. This sensation decreases when we increase the rate of fluctuation and at about 15 Hz modulation frequency the sensation of roughness is perceived reaching a maximum value at about 70 Hz. As the fluctuation amplitude is further increased, the sensation of roughness diminishes until disappears [42]. Generally, roughness is the perception of fast modulations.

Roughness is defined by the unit asper. A tone at 1 kHz, of 60 dB with a 100% amplitude modulation at 70 Hz defines the roughness of 1 asper. A broader description would also be that roughness gives us the information of how "rough"a sound is perceived [10].

5.2.4. Fluctuation strength

The fluctuation strength is a psychoacoustic metric similar to roughness. Is the perception of slow modulations (beating) which reaches a maximum at modulation frequencies at about 4 Hz. At around 20 Hz of modulation frequencies, the transition between fluctuation strength and roughness is placed.

A 1 kHz tone of 60 dB and 100% amplitude modulated at about 4 Hz gives 1 vacil of fluctuation strength. Generally this metric can give the information of how "strong"or "weak"a sound is perceived.

5.2.5. Tonality

The tonal components of a sound are determined by tonality. A non-tonal sound is a noise-like non-periodic sound and masks a tonal sound more easily than vice versa. The unit for tonality is tu and 1 tu is given by a reference tone at 1 kHz at 60 dB. The information given by tonality does not depend on critical bands or loudness so tonality is a psychoacoustic metric that has to be judged subjectively.

Trying to give a general description about tonality, one can say that can be used to give the magnitude of tonal content of a sound (number of pure tones in the noise spectrum) [3].

5.2.6. Just Noticeable Differences (JND)

The just noticeable differences are the minimum changes in psychoacoustic metrics that can be identifiable by humans [27]. In previous research there is not a lot of information about these minimum values. A previous research by You and Jeon on refrigerator noise [47] yielded these differences for the psychoacoustic metrics under study. Table 5.2 has been taken from Timothy Yuan Ting Hsu dissertation [27].

Psychoacoustic metrics	**JND**
Loudness	0.5 sones
Sharpness	0.08 acums
Roughness	0.012 aspers
Fluctuation strength	0.004 vacils

Table 5.2.: Just Noticeable Differences for Psychoacoustic metrics. Table accessed from [27] (September 2014).

5.3. Method

The samples have been selected from the wave files and several objective psychoacoustic measures have been calculated through HEAD Acoustics Artemis Software version 11.0.200 (calculation method ISO 532 B [9] for Loudness over time, Specific Loudness and Sharpness over time).

Most of the sounds that have been identified in the recordings are impulsive sounds with short duration. The amplitudes of the sounds are either stable or increasing with time in duration or/and loudness. Depending on the type and character of the sounds, descriptions such as “squeaking sound”, “dragging sound”, “bleeping sound”or “rattle sound”have been used. As mentioned in Chapter 4, according to the type of the sound, the noises in the room can be divided in three general categories. Those coming from medical equipment and cannot be avoidable, those coming from the staff's activity during taking care of the patients which can be partially avoidable and those that may come also from people's activity in the room or the spaces close to the room and can be completely avoidable such as unnecessary speech or slamming doors, dragging furniture etc.

Of all the noises that are presented in Chapter 4, some are perceived as more annoying than others. For example, the slamming door or the objects hitting on the table are noises that occur frequently and are loud enough to be perceived as annoying.

In the following analysis, the most frequent unwanted or unnecessary sounds are presented trying to gain some information for their perceptual characteristics. Since there were no listening tests performed it is hard to make conclusions about the perceived annoyance or any other subjective quality. It is, though, interesting to present and compare these metrics as a contribution to the overall characterization of the sound scape.

The purpose of the first part of the analysis is to present the perceptual characteristics of some of the most frequent noises occur in the room. All the sounds have been collected from the reference room because it was easier to get more representative samples. All the figures of the sounds under test are presented in the Appendix.

The second part of the analysis includes a comparison between the rooms to see if the acoustic treatment changed or/and improved the characteristics of the noises. Samples of the same sounds have been collected from the recordings in both rooms and are presented in Chapter 6.

5.4. Analysis of the perceptual characteristics

5.4.1. Room equipment

In this category the commonest noises are the slamming doors, furniture that hit and are dragged on the floor, rolling carts and cabinet doors (open-close and squeaking sound from the hinges). In Fig 5.2 the sounds from furniture and the cabinet door are presented since they were the most frequent and longer in duration in this category and occur right next to the patients.

Furniture

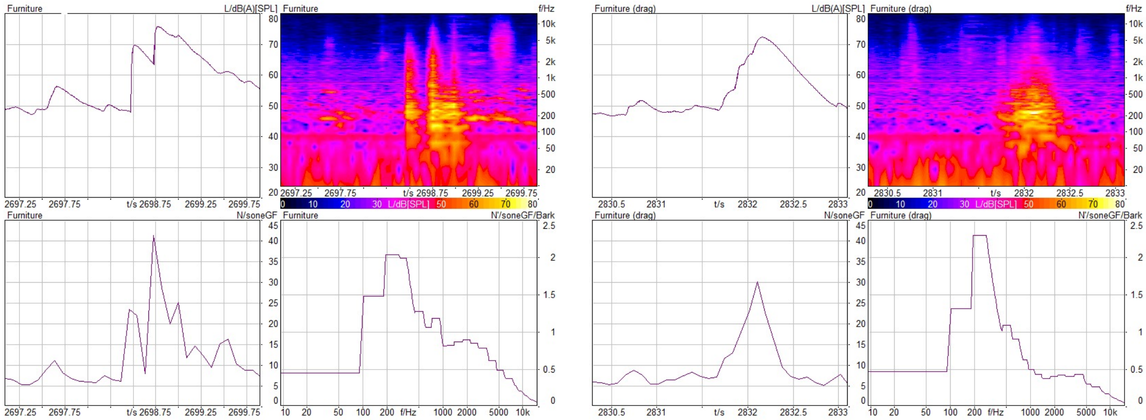

Figure 5.2.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of sound of a furniture that hits on the floor (left) and furniture that is dragged on the floor (right).

As one can see in Fig 5.2 the two sounds, both produced by furniture (probably chair), are of almost the same level. The sound from the furniture that hits on the floor is presented by the two big peaks and the dragging sound is the big peak in the right graph. By looking at the loudness time history, the sound in the first case has a maximum loudness of 41 sones whereas in the second case the maximum loudness is much less reaching 30 sones. That is probably because the perceived loudness is frequency dependent and it is considered as the summation of loudness contributions of different frequency channels [39]. The furniture that hits on the floor generates a noise with high overtones and even though both are around 75 dB the perceived loudness is different. Looking at the specific loudness graph, which is basically the loudness over bandwidth, is almost the same for both cases over the bandwidth of interest. The overall loudness in sones is calculated from the area under the specific loudness. The curved slopes that protrude above the rest of the pattern (on the high frequency side of bands) represent the masking effect. Most of the sounds are impulsive and a single specific loudness graph could only complete the overall picture of the sound and not sufficiently describe the sound [20]. The total loudness for the furniture hit on the floor is 13 sones (the specific loudness is 20 sones) while the dragging furniture has a total loudness of approximately 10 sones (the specific loudness is 15 sones). (see Table 5.3)

Generally the values for loudness in both cases are very high since values from 1 to 4 sones represent a typical conversation in 1m and 5 to 15 sones a passing car in 10 m [27].

Fig 5.3 shows other psychoacoustic metrics for the furniture sounds such as sharpness, tonality, roughness and fluctuation strength.

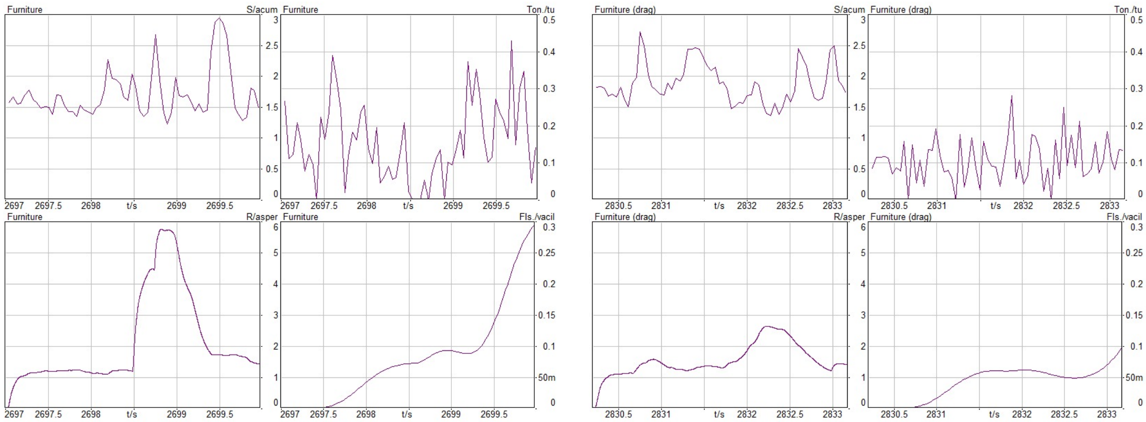

Figure 5.3.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of sound of a furniture that hits on the floor (left) and furniture that is dragged on the floor (right).

The first sound (furniture that hits on the floor) has a little bit higher sharpness, as expected, since it is a sound with higher frequency components but looking at the roughness the difference is much bigger. The first sound is perceived much rougher than the other but knowing that a sound over 0.10 asper is considered rough [27] then both sounds are considered to be rough. From the fluctuation strength graph, one can conclude that for both sounds the temporal variations of low frequency are low which is preferable for noises of this kind in order not to increase the annoyance. Higher values for fluctuation strength are preferable for certain sounds, like speech [27]. Since both sounds are considered impact sounds with no tonal components, the graph of tonality can only complete the overall picture showing that the sounds under test are non-periodic, noise-like sounds.

Cabinet

In Fig 5.4 the sound from the cabinet door while open and closes together with the stick-slip sound produced by the hinges, are presented.

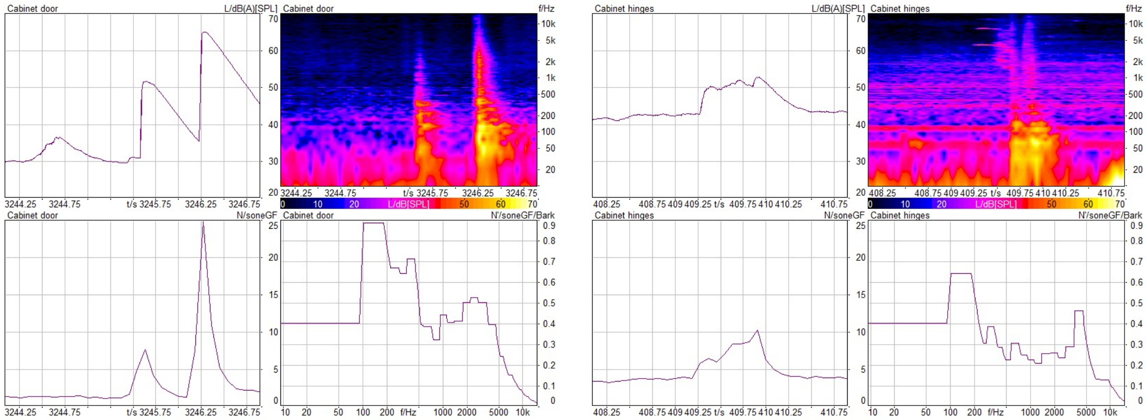

Figure 5.4.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of an impact cabinet door sound (left) and stick-slip sound generated by the hinges (right).

Since the impact sound of the cabinet door is much louder than the stick-slip sound of the hinges, the perceived loudness in the first case is much higher as expected. The impact sound is approximately 10 dB higher than the stick-slip sound, which doubles the perceived loudness (see Table 5.1) . Of course the stick-slip sound has still high loudness (maximum 10 sones) since as mentioned 5 to 10 sones is the perceived loudness of a passing car in 10 m. From the specific loudness graph, one can see that the loudness over critical band in the impact cabinet door sound is much higher. The stick-slip sound though has higher energy in much higher frequencies (5 kHz) were the human hearing is more sensitive as one can see from the dip at 5 kHz in Fig 5.1. As mentioned, the psychoacoustic metrics are also connected to the duration of the sound meaning that in some cases the information given probably does not represent the specific sound but the overall sound in the room.

In Fig 5.5, the other psychoacoustic metrics for these sounds are presented.

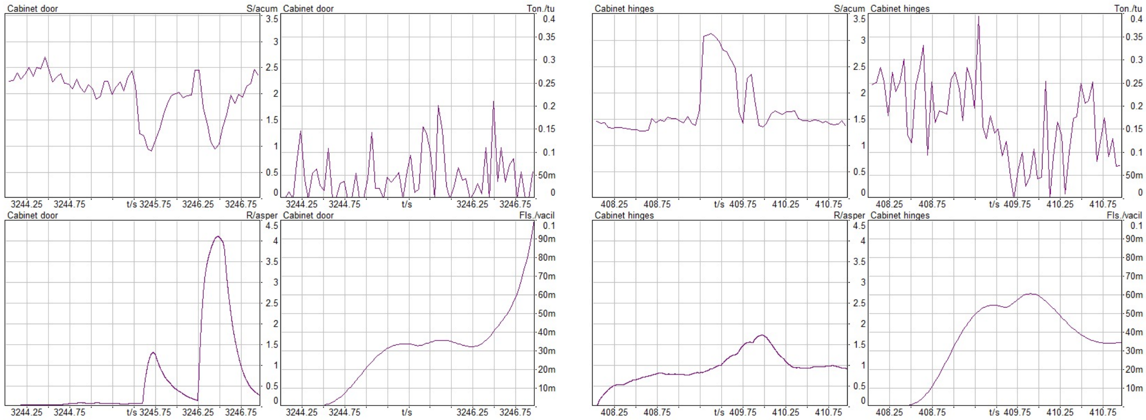

Figure 5.5.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of an impact cabinet door sound (left) and stick-slip sound generated by the hinges (right).

The stick-slip sound appears to be sharper since it is a sound with higher frequency components. On the other hand, the impact door sound is perceived much rougher and with lower fluctuation strength which can give us the information of how different these two noises are, even if they produced by the same object. Also looking the tonality one can see that the stick-slip sound has more tonal components than the impact sound.

From the comparison above, one can see how much different sounds can be produced by the same object. We must not forget that these two sounds follow each other since in order to open and close the door the stick-slip sound from the hinges is difficult to avoid. A sharp but lower in level sound is followed by a rough and loud impact sound.

5.4.2. Staff activity during patient care

In this category, the most common noise source was speech by staff and visitors occurring in all the recordings. The second most frequent noise is the one produced by objects hitting on a table while taking care of the patients or setting the equipment. The next most frequent sounds that caught my attention while listening to the recordings are the squeaking sound produced by rubber shoes and the sound from the apron that the staff wears. These sounds are presented in Fig 5.6, 5.7 and 5.8.

Object on table

The sound consists of an impact sound (big peak starts at 1715.25 sec) when the object hits on the table and a second peak that shows the rattle sound generated from the object while rolls on the table. The overall picture of the sound (Fig 5.6) is that it is of high level of 58 dB, high perceived loudness (12.5 sones for the first peak and 8 sones for the second maximum loudness over time) and high frequency components. Even though the second part of the noise is lower in level the excitation at around 4 kHz (higher sensitivity of human ear) is very high.

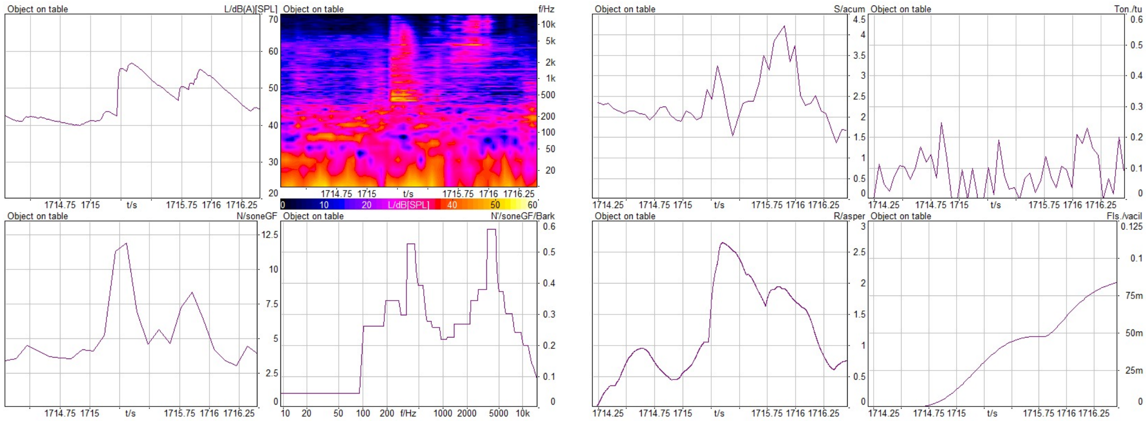

Figure 5.6.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) (left) and Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) (right) of an object hitting on table sound.

It is a noise-like sound with high maximum roughness (more than 2.5 asper) and some high peaks in sharpness because of the high frequency content especially for the rolling sound (maximum 4.5 acum). It can be considered that the first sound is rougher and the second is sharper. The maximum sharpness is 4.5 acum which is almost the sharpness of a flute [27] but roughness above 0.10 asper is high as mentioned before. That means that a rough loud sound is followed by a sharper but lower in level sound. The high peaks in all metrics are much higher than the just noticeable differences (JND) that shows that the perceptible changes occur often and from noises of different kind.

Apron

While the staff is taking care of the patient, noise from the nylon apron was audible all the time. The sample that is presented in Fig 5.7 is from a characteristic shaking movement that the personnel does in order to unfold the apron and it is illustrated by the two peaks. It is an impact sound, really loud and right next to the patient.

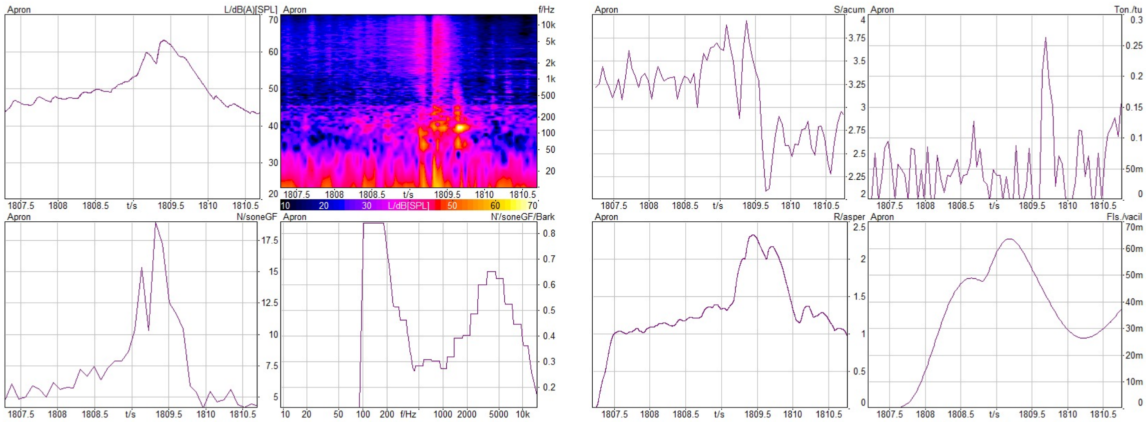

Figure 5.7.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) (left) and Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) (right) of apron sound.

With a maximum loudness of almost 18 sones and high energy in high frequencies it is a sound that cannot be unnoticed. The peak in loudness goes from 7.5 to 18 sones in less than 1 sec and the total loudness is 10.3 sones. Sharpness has a big peak in 4 acum with 2 acum variations which is 25 times the JND for sharpness and roughness is 2.4 asper. It is a very sudden noise that was detected in more than half of the recordings both day and night time and that is followed by the continuous sound of nylon because of the movement of the person who wears it.

Rubber shoes

The squeaking sound produced by rubber shoes has been chosen to be presented for two reasons. First because it is one of the most frequent and longer in duration sounds and second because, in my opinion, it is one of the most avoidable sounds. The sound is presented in Fig 5.8.

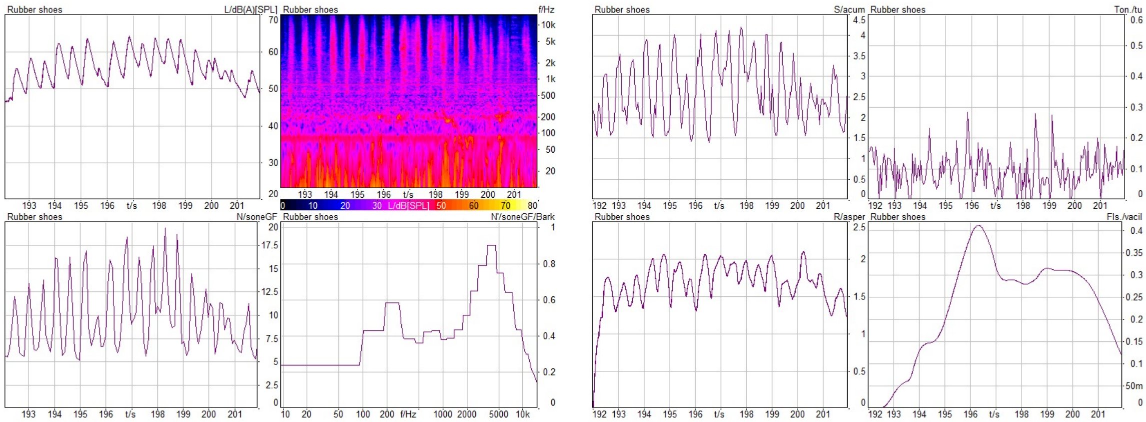

Figure 5.8.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) (left) and Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) (right) of squeaking sound from rubber shoes on a plastic floor.

This squeaking sound with sound levels that exceed 60 dB and maximum loudness reaching almost 20 sones, with maximum variations in loudness 10 sones (20 times the JND for loudness) has frequency components up to 5 kHz. The sharpness has maximum 4.2 acum and roughness exceeds 2 asper. It is a sound that consists of a number of impulses, which means sudden, short-term sound events that vary in level and loudness. The temporal variations of low frequency are higher than the other sounds presented above making the sound to be perceived as slow amplitude modulation sound.

5.4.3. Alarms and monitoring equipment

Medical equipment sounds are the most frequent sounds identified in the recordings. They can be divided in two categories, the alarms that are usually short in duration since the staff turns it off as soon as possible and the bleeping sounds from monitoring equipment that are audible during longer time periods than the alarms.

Bleeping sounds

Many different kinds of bleeping sounds have been identified in the recordings. Some of these are produced by monitoring equipment occurring throughout the duration of the recordings and some others are some kind of notification sounds informing the end of a procedure or a measurement and occur occasionally etc. Another difference between the bleeping sounds, except the frequency of occurrence or the purpose, is in tonality. The sounds from the monitoring equipment are mostly of constant sound level, consisting from one single tone that is repeated. The notification sounds are mostly louder and usually consist of two or three closely spaced tones that vary fast, like a small melodic pattern. In the analysis below these sounds are called "melodic bleeping sounds"and "rhythmic bleeping sounds". For the psychoacoustic analysis, one bleeping sound of each case has been chosen in order to see if there is a difference between a single tone and a two-tone sound. The sounds are presented in Fig 5.9.

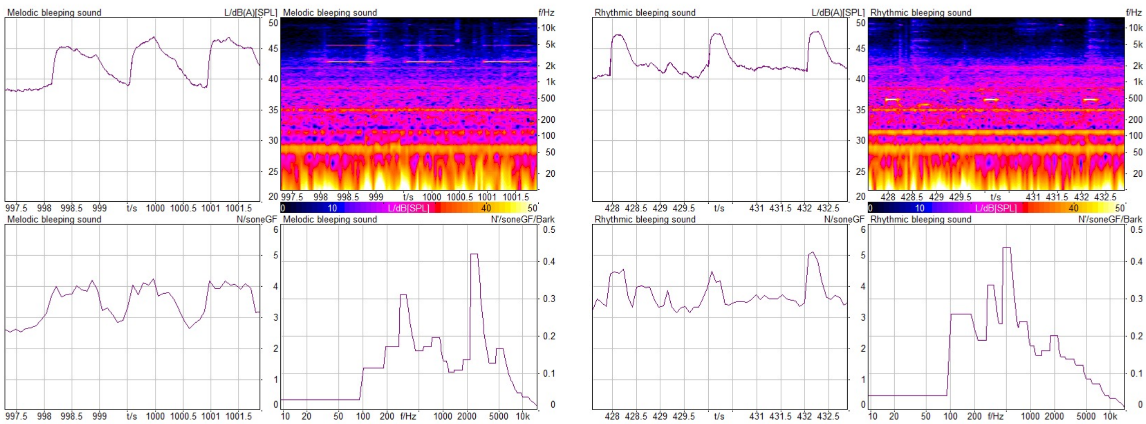

Figure 5.9.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of melodic bleeping sound (left) and rhythmic bleeping sound (right).

Both sounds have been collected from the same recording and also the same channel which means that these sounds come from the equipment of the same patient. The first sound (melodic) is probably a notification sound that indicates the end of a procedure or a measurement and occurs occasionally during the recorded time and lasts for at least a couple of minutes. The rhythmic sound comes from monitoring equipment and occurs throughout the whole recorded time. The graphs show the two sounds separately. From both spectrograms, one can see that there is a lot of noise in the room which is probably coming from the ventilation and other equipment that is active at the same time.

The sound levels are almost the same with small differences of 1-2 dB. Even though the melodic sound is of higher frequency, both sounds are perceived almost equally loud and this can also be seen in the equal loudness contour. It is noticeable though that the second tone of the melodic sound occurs at approximately 3 kHz, the most sensitive for the human ear area (2-5 kHz) that it is also showed in the equal-loudness contour with a dip at this range (see Fig 5.1). The rhythmic sound is at 500 Hz. The specific loudness is almost the same but over different critical bands.

The sharpness of the melodic sound is a little bit higher (Fig 5.10), as expected, since the sound is of higher frequency and also the presence of low frequency noise together with the rhythmic sound lowers the spectral center of gravity in the second case. Since there is a lot of fan noise in the room, probably the roughness and fluctuation strength graphs do not represent the sounds but the overall noise in the room. From the tonality graph, one can see that there are tonal components together with noise.

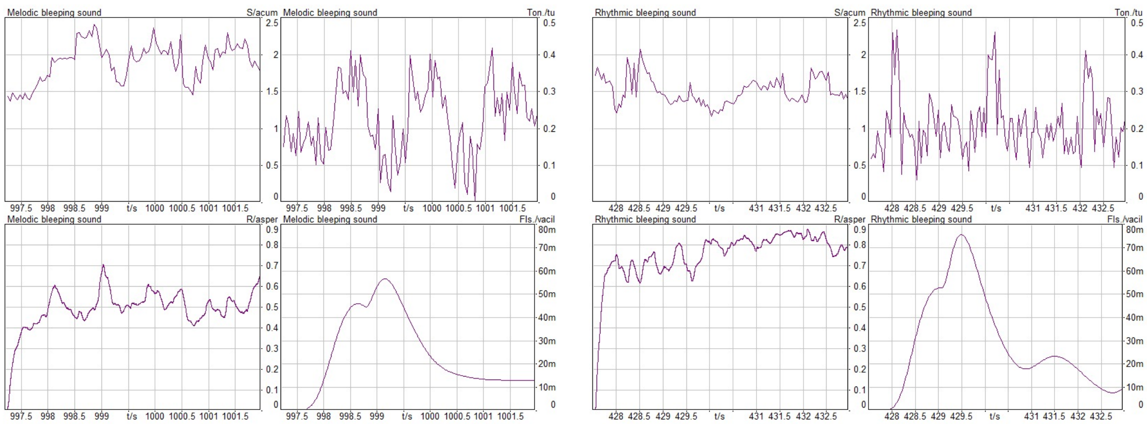

Figure 5.10.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation Strength vs Time (Fls) of melodic bleeping sound (left) and rhythmic bleeping sound (right).

Comparing a single-tone with a two-tone sound, from the psychoacoustic point of view, there are no significant differences in theses examples that attribute to the tonal difference. Further investigation needs to be done with more samples and different tones.

Another rhythmic bleeping sound is presented in Fig 5.11.

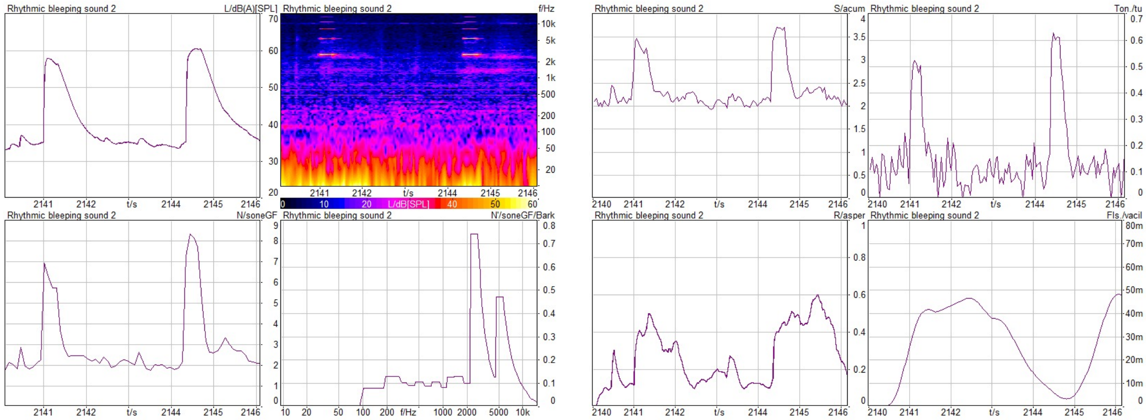

Figure 5.11.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) (left) and Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation Strength vs Time (Fls) (right) of rhythmic bleeping sound.

This sound has been collected from another recording during night time. As one can see, the sound level exceeds 60 dB and the maximum loudness is more than 8 sones. The sound is showed by the two big peaks in the graph. Each tone lasts for about 1 sec and they occur every 3 sec approximately. The maximum loudness increases at the second tone but since the sounds occur every 3 sec and the reverberation time at this frequency is 30 ms this cannot be attributed to room acoustics but could probably be because of the microphone or the speaker. It is a sound of high frequency that can be characterized as sharp rather than rough, with tonal components. It should be pointed that the background noise in the room is now much lower than in previous cases so sharpness is expected to be higher. The sound was identified in many recordings and with long duration and it is produced, probably, by monitoring equipment since the staff did not turn it off.

Alarms

Clinical alarms are among the sounds that are not avoidable since they enhance safety and also give important information regarding the patient's condition or even warnings of equipment failure. Two different types of alarm signals are the most frequent in the recordings, the alarm from the ventilator and the bradycardia monitoring alarm (Fig 5.12).

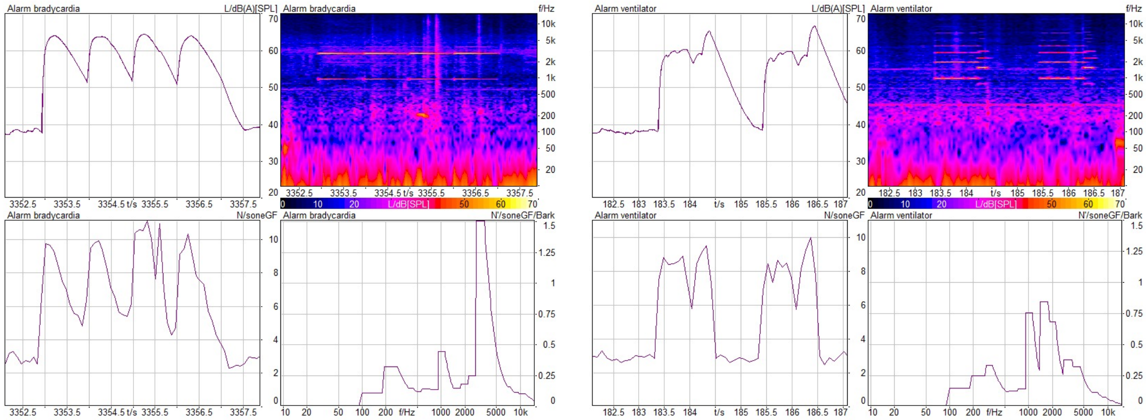

Figure 5.12.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of bradycardia alarm (left) and ventilator alarm (right).

Even though it is obvious from the graphs that the sound levels of the alarms are high (both are above 60 dB), we cannot be sure that this is the typical level since it is possible that someone has adjusted the level. But if we accept these levels and concentrate on the loudness graphs both alarms have high values of perceived loudness with a little bit higher for the bradycardia alarm. Of course this sound is of higher frequency and also is repeated faster making the sound to be perceived as almost constant because of the reverberation time that it is 30 ms at frequencies above 1 kHz. This is obvious also in the spectrogram where the sound is showed with a constant line at approximately 3 kHz. Also the specific loudness over critical band is very high and for this sensitive, for the ear, area.

The bradycardia alarm is a sharper sound because of the higher energy at higher frequencies (Fig 5.13). Both alarms have almost the same roughness. The big peak in the roughness graph for the bradycardia alarm is due to another activity that occurs at the same time and not the alarm. There is a difference in fluctuation strength with the bradycardia alarm having a more stable curve and the ventilator alarm having a dip between two peaks. This might be due to the character of the sounds since the first consists of one single tone that is repeated fast (giving the perception of an almost continuous tone) in contrast to the ventilator alarm that consists of two tones that form a motive which is repeated slower and the big dip is because of the pause between repetitions.

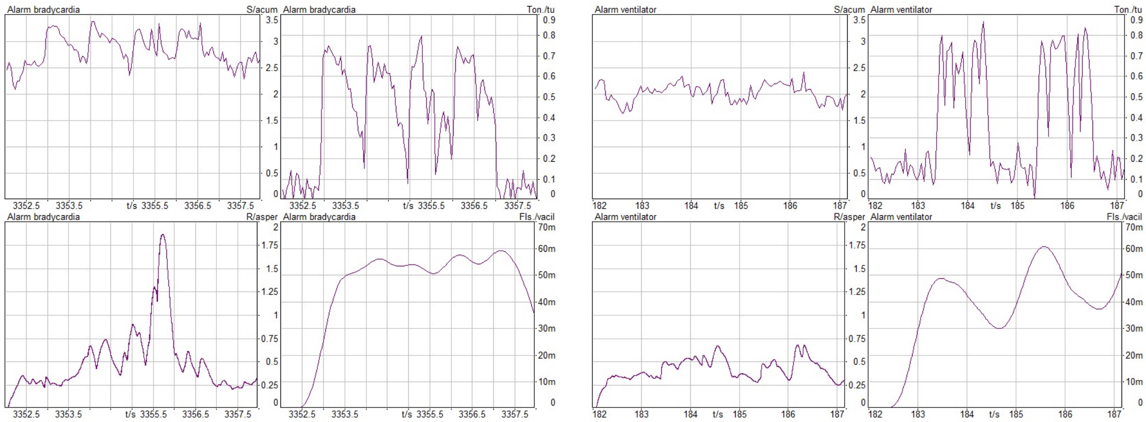

Figure 5.13.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation Strength vs Time (Fls) of bradycardia alarm (left) and ventilator alarm (right).

5.4.4. Total values

Tables 5.3 and 5.4 show the values for each metric and each sound, calculated with HEAD acoustics Artemis software.

Source	**SPL (dBA)**	**Loudness (sone)**	**Spec.Loud. (sone)**	**Sharpness (acum)**	**Tonal. (tu)**	**Roughness (asper)**	**Fluct.Strength (vacil)**
Apron	54.0	7.36	10.3	3.12	0.05	1.30	0.033
Cabinet door	53.4	3.27	9.79	1.99	0.05	0.68	0.023
Cabinet hinge	46.8	4.83	6.51	1.69	0.17	0.93	0.033
Furniture	66.7	13.0	20.9	1.74	0.15	2.26	0.068
Furniture drag	62.5	9.43	14.9	1.88	0.11	1.54	0.041
Rubber shoes	57.4	9.71	12.0	2.62	0.09	1.67	0.228
Obj on table	49.6	5.24	7.0	2.39	0.09	1.20	0.034

Table 5.3.: Psychoacoustic metrics for human activity sounds.

Source	SPL (dBA)	Loudness (sone)	Spec.Loud. (sone)	Sharpness (acum)	Tonal. (tu)	Roughness (asper)	Fluct.Strength (vacil)
Melodic	43.3	3.47	3.72	1.90	0.23	0.49	0.023
Rhythmic 1	43.3	3.73	3.98	1.51	0.21	0.75	0.028
Rhythmic 2	50.6	2.91	4.55	2.33	0.15	0.27	0.026
Alarm cardia	59.4	6.17	7.87	2.83	0.38	0.49	0.044
Alarm vent	57.7	5.15	7.63	2.03	0.35	0.41	0.036

Table 5.4.: Psychoacoustic metrics for medical equipment sounds.

As one can see in Table 5.3, the sounds that are connected to human activity are of high level and loudness. The furniture sound (both hit and dragged) is the louder sound while the apron and the rubber shoes are perceived sharper.

From Table 5.4 for the medical equipment it is noticeable that all the sounds that come from monitoring equipment (three bleeping sounds) are of the same level and perceived equally loud with the overall loudness in the limits of a normal conversation in a room (1-4 sones). On the other hand, the alarm sounds are higher by 14-16 dB from the bleeping sounds with double the overall loudness, as expected. The volume of the alarms are higher since they are warning sounds indicating urgency and loudness appears to be one of the stronger cues for urgency [24].

An overview of both tables leads to the conclusion that the sounds that are connected to human activity contribute to the increase of noise much more than the medical equipment sounds. Sounds from furniture, cabinets, aprons etc. are perceived louder and rougher with higher values for fluctuation strength and less tonal components.

5.5. Conclusions

Analysing the perceptual characteristics of some of the sounds, one can see the complexity of the soundscape in the ICU room. Different noises from various sound sources varying in levels and frequency. If we take a general look at the sounds presented in the analysis, a general conclusion could be that the perceived loudness, regardless the kind of the sound, is very high. With maximum values from 10 to 40 sones, the noise in the room exceeds the loudness of a passing car in 10 m.

The presence of low frequencies probably reduces the high frequency energy in the room decreasing some of the sharper noises. Probably this is why the values for sharpness are not as high, reaching a value of 5 acum which is the typical sharpness of a flute, as mentioned. On the other hand, the sounds are considered rough since 0.10 asper is a limit above which a sound is considered rough. This probably implies that the rates of temporal amplitude variations are high in the room and also taking into consideration the relatively low fluctuation strength values, the overall character of the noise in the room is of high frequency modulations [27]. Finally, looking at the tonality graphs, all the sounds have some tonal components but the majority of the sounds are non-periodic, noise-like sounds.

Alarm and bleeping sounds are very frequent and the most expected sounds in an ICU environment. By looking the values for the psychoacoustic metrics of the alarms, the bleeping sounds and the other sounds that have been analysed before there are no big differences in sharpness, roughness or fluctuation strength. The higher values in sharpness are dominated by the tonal sounds of alarms and bleeping sounds that contribute to high frequency energy (sharp and tonal). Generally, we can conclude that even there are sounds in the room with very high frequencies, the sound sources do not highlight a sharp character of the sound [27] and this could also be, as mentioned, due to the presence of very low frequency noise coming from building or medical equipment and changing the frequency distribution. Moreover, the sound sources that increase significantly the levels in the room are sounds connected to human activity (loud and rough). A previous research of Västfjäll (2012) [43] showed that valence is associated with perceived loudness, roughness and naturalness while sharpness and tonality are related to activation.

6. Comparison of the perceptual characteristics between the rooms

In Chapter 5, the perceptual characteristics of the commonest sounds in the room have been analysed giving us an overall picture of the sounds. Since one of the rooms is acoustically treated, the next step for the analysis is to compare the two rooms from the psychoacoustic point of view. The perceptual characteristics of the sounds in both rooms are compared to see if the acoustical treatment affects these metrics.

6.1. Background noise

The acoustical treatment in one of the rooms has been done in order to achieve quiet conditions in the ICU environment. Low background noise is an essential condition for the achievement of the best possible outcome when designing a room [22].

Before the psychoacoustic analysis, the background noise in both rooms for day and night is presented to get an overall picture of the sound environment when no activities occur. Quiet periods of about 15 sec have been collected for both rooms.

According to the World Health Organization the average background noise in hospitals should not exceed 30 dBA, with peaks during the night time lower than 40 dBA. From Fig 6.1, one can see that the background noise is a little bit higher than the recommended during day time especially in the reference room. While listening to these two samples, one can immediately hear the difference of the frequency distribution in the rooms. The spectral analysis for both rooms is presented in Fig 6.2.

The refurbished room has higher levels in low frequencies, below 100 Hz, with a big peak at around 80 Hz. This is due to the HVAC which is obviously much lower in the reference room. In the reference room higher levels occur at frequencies between 150 Hz and 4 kHz. It is possible that the microphone in the refurbished room to be closer to the air grill or the velocity airflow from the HVAC in the reference room is higher. The background noise can influence people's perception for the acoustic quality of the room. The personnel rated the sound in the reference room as more hissing [38] and this is obvious in Fig 6.2.

During the night time the levels of the background noise in the rooms are presented in Fig 6.3.

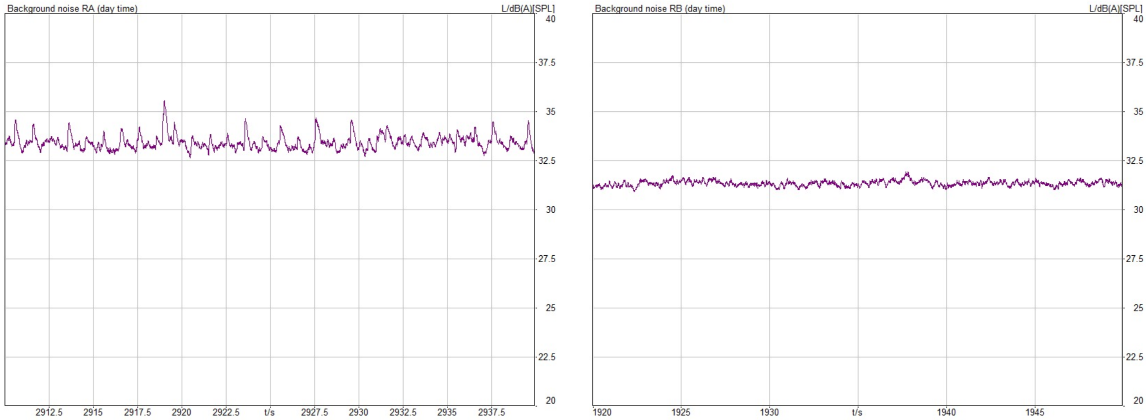

Figure 6.1.: Background noise in the reference room (left) and the refurbished room (right) during day time. The figure shows the A-weighted SPL (Y-axis) with time weighting Fast (X-axis).

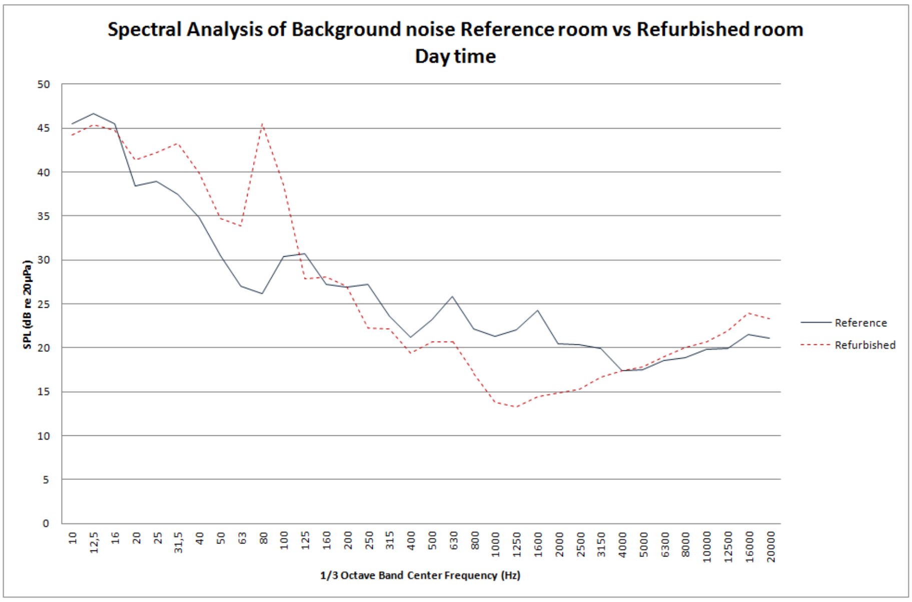

Figure 6.2.: Background noise spectra in one-third octave bands during day time for reference (blue solid line) room and refurbished room (red dashed line).

The background noise in the refurbished room is much lower comparing to reference room, but also comparing to the day time levels. The levels in the room follow the recommended by WHO. But this is not the case in the reference room. The levels are still a little bit higher than the recommended with no differences comparing to day time levels in the same room.

The peaks that are shown in reference room are because of a clock on the wall of the room. The spectral analysis for night time is presented in Fig 6.4.

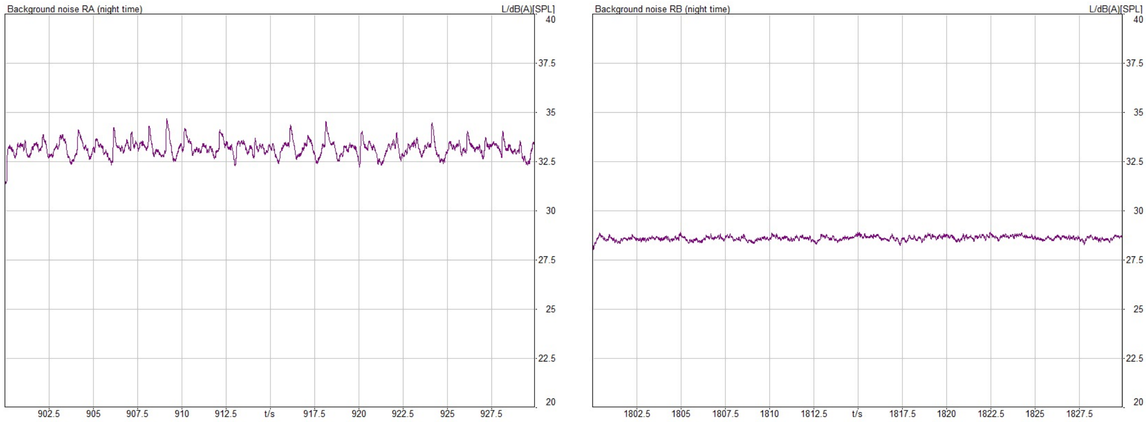

Figure 6.3.: Background noise in the reference room (left) and the refurbished room (right) during night time. The figure shows the A-weighted SPL (Y-axis) with time weighting Fast (X-axis).

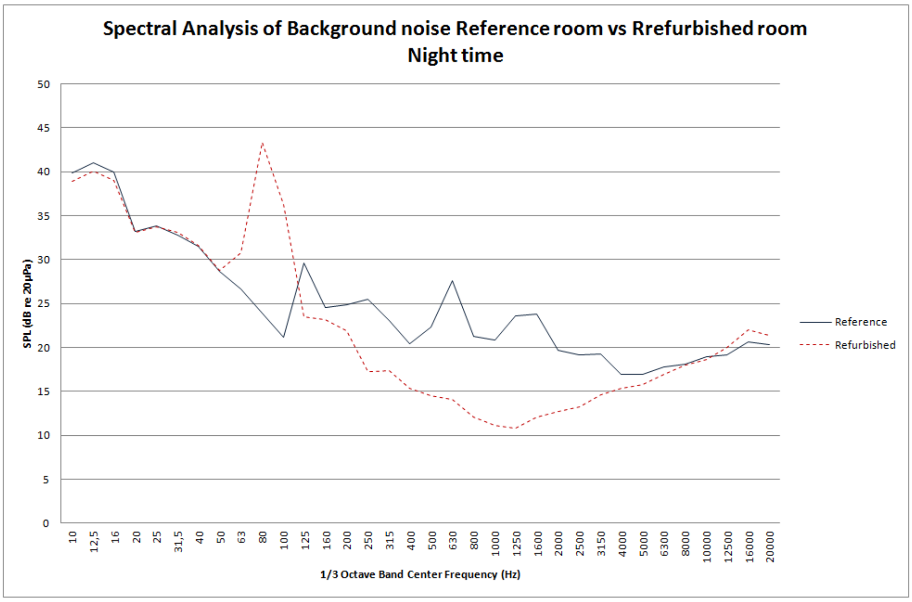

Figure 6.4.: Background noise spectra in one-third octave bands during night time for reference room (blue solid line)and refurbished room (red dashed line).

The curves follow the same shape as in day time but in lower levels (little bit lower for reference room, much lower for refurbished room). Higher energy in low frequencies occurs in the refurbished room while higher frequency energy occurs in reference room. The difference between the rooms at frequencies between 100 and 4 kHz is bigger reaching almost 13 dB at around 1 kHz.

Finally, an improvement of the background noise in the refurbished room can be seen in figures above.

6.2. Comparison of the perceptual characteristics

Some of the noises that have been identified as the most frequent and annoying have been chosen for the purpose of this comparison. It is difficult to collect similar samples for both rooms especially because lots of activities occur at the same time. Even if in some samples was impossible to isolate the sound under test from the noise, using this analysis we might come to some useful conclusions about the effectiveness or not of the acoustical treatment.

6.2.1. Staff activity during patient care

Plastic packaging

One of the sounds that occur in most of the recordings of this category is the plastic disposable packaging. The sound is very sudden and of high frequency. Two samples of this noise from both rooms have been collected and are presented in Fig 6.5.

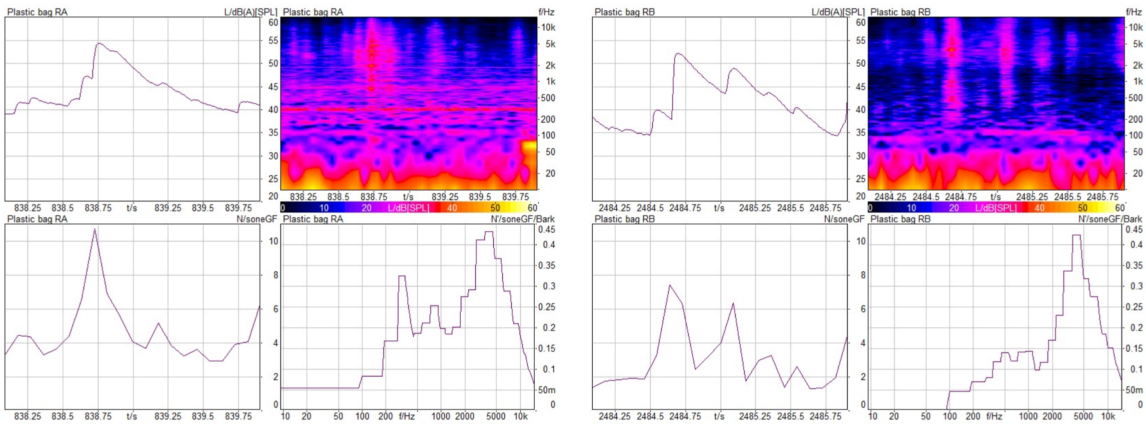

Figure 6.5.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of sound of a plastic package in the reference room (left) and plastic package in the refurbished room (right).

The two sounds, which occur during the opening of the plastic packaging, are of the same frequency and almost the same timbre. The only difference is that in the refurbished room the opening of the packaging is done in two steps while in the reference room the bag opens at once and that is showed by the peaks in levels and loudness. In the reference room the sound is showed with the peak at 838.75 sec and in the refurbished room the sound is showed with the two peaks between 2484.5 sec and 2485.25 sec. The maximum loudness in the refurbished room is less than in reference room by approximately 3 sones, which is expected since the second noise is higher. Moreover, in the reference room there is noise at around 400 Hz that probably comes from fan equipment that is active at that moment and it is clearly audible in the sample. However, it can be observed that in the refurbished room the two-step noise varies from 2 to 7.5 sones (first peak) and then again drops to 2 and goes up to more than 6 sones in 0.5 sec. On the other hand, in the reference room the loudness has only one peak from 4 to more than 10 sones. According to the JND for loudness (0.5 sones), in both rooms, perceptible changes of 8 to 12 times the JND value occur.

Other psychoacoustic metrics have been calculated and presented in the Fig 6.6.

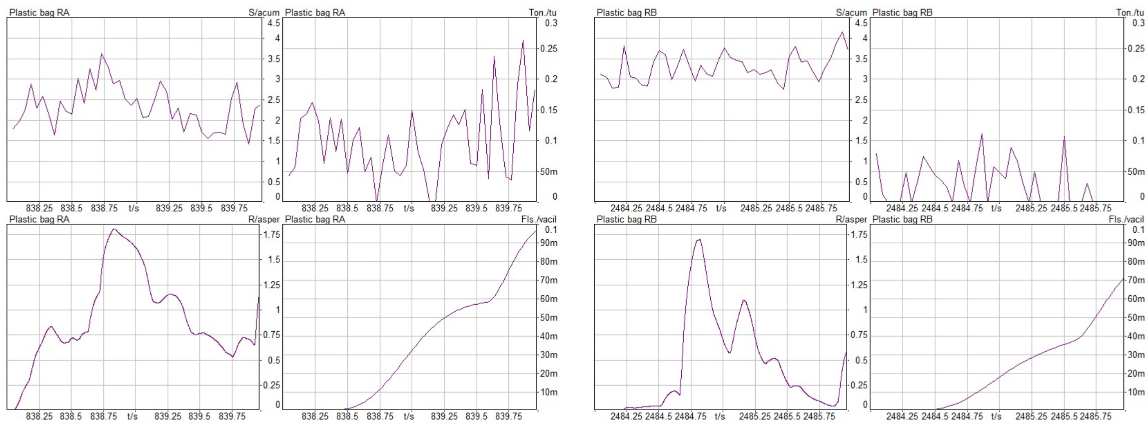

Figure 6.6.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of sound of a plastic package in the reference room (left) and plastic package in the refurbished room (right).

Both sounds have the same sharpness at around 3.5 acum. One would expect probably higher values for sharpness since both samples have high energy in high frequencies. From the analysis of the background noise we got the information than in both rooms the presence of low frequencies is significant which could be a reason for lower values for sharpness than the expected.

Tonality is also low which confirms the noise-like character of the sounds. We cannot be sure if the values for roughness and fluctuation strength are representative for the sounds because of the noise in the rooms and also the short duration of the sounds. However, one can conclude that the sound is sharper than rough and the fluctuation strength is very low as should be in a noise-like sound but no significant differences in these metrics are observed between the two rooms.

Metallic object on table

While taking care of the patient, the staff uses a side table with a metallic surface to place the equipment. Most of the tools are metallic objects and this metal to metal contact produces a high frequency impact sound. Two examples of this sound have been collected from the rooms and presented in Fig 6.7.

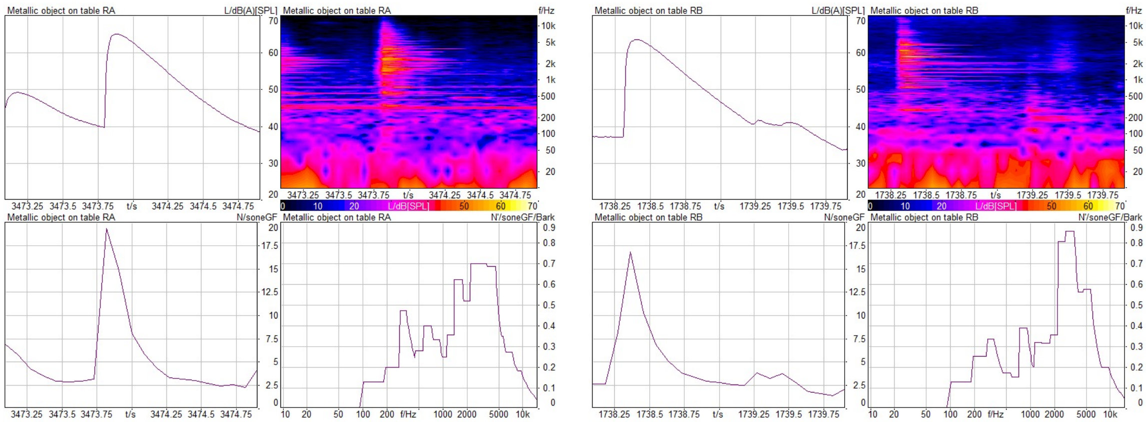

Figure 6.7.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of a metallic object hit on a table in the reference room (left) and metallic object hit on a table in the refurbished room (right).

Both sounds are illustrated in the graphs by high peaks. Based on the fact that the two noises are coming from random events having little information for the objects used, only the overall picture of the sounds will be discussed. It is noticeable that in both cases the levels are about 65 dB at approximately 3 to 4 kHz with maximum loudness 18 and 20 sones with the lower values in the refurbished room.

From Fig 6.8, one can see that the sharpness in the refurbished room is slightly higher than in reference room in contrast to roughness that is lower. Both sounds have tonal components with higher values in the refurbished room and the fluctuation strength is very low. The noise levels in the reference room are again noticeable.

Since the only information given about the sound is that is generated from a metallic object hitting on a table but no information about the type of the objects, these small differences cannot be attributed with certainty to the rooms.

From the analysis of these random noises no significant differences, attribute to the rooms,

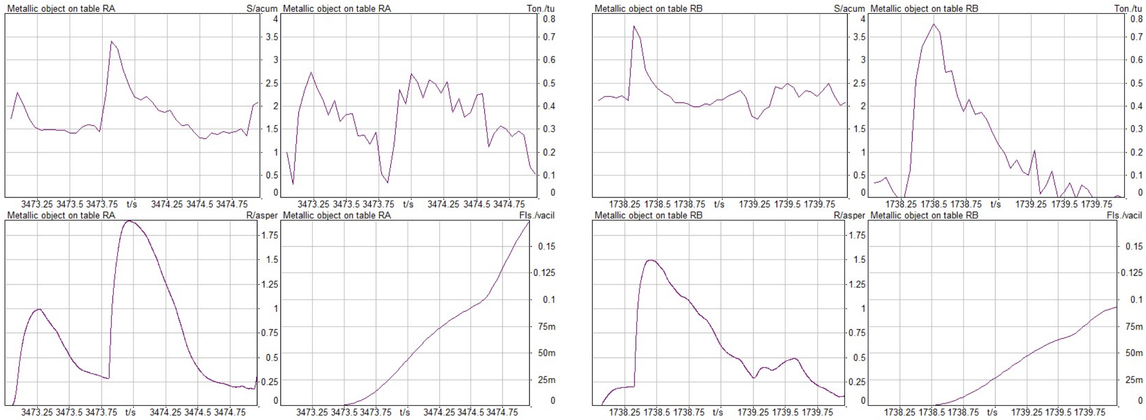

Figure 6.8.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of a metallic object hit on a table in the reference room (left) and metallic object hit on a table in the refurbished room (right).

occur. The number of the samples is very small but, as mentioned, it is very difficult to find similar sounds from the recordings.

6.2.2. Medical equipment

Bleeping sounds from monitoring equipment

Since the equipment used in both rooms is the same, two kinds of bleeping sounds have been collected and compared. The same sounds have been collected from both rooms.

The first bleeping sound is a rhythmic sound at around 500 Hz that is showed in Fig 6.9 by the peaks.

As one can see in Fig 6.9, the levels in the refurbished room are higher by almost 5 dB leading to higher loudness. The difference in maximum loudness though, is less than 1 sone which is lower than expected. In the reference room there is a lot of noise with high energy in frequencies between 80 and 300 Hz because of equipment that was active at that moment and might act as masking noise to the bleeping sound. The perception of loudness for both rooms is at almost the same level and this could be because at 450-500 Hz for levels 48-53 dB the sounds are perceived almost as equally loud according to the equal loudness contours.

Observing the peaks in the loudness graphs, one can see that in the reference room the loudness increases on the second bleeping tone while in the refurbished room decreases and this might be due to the absorption added in the refurbished room. The overall effect on loudness within a room is a combination of the direct and the reflected sound and it is determined by the absorption, leading to the possible conclusion that in the refurbished room the reflected

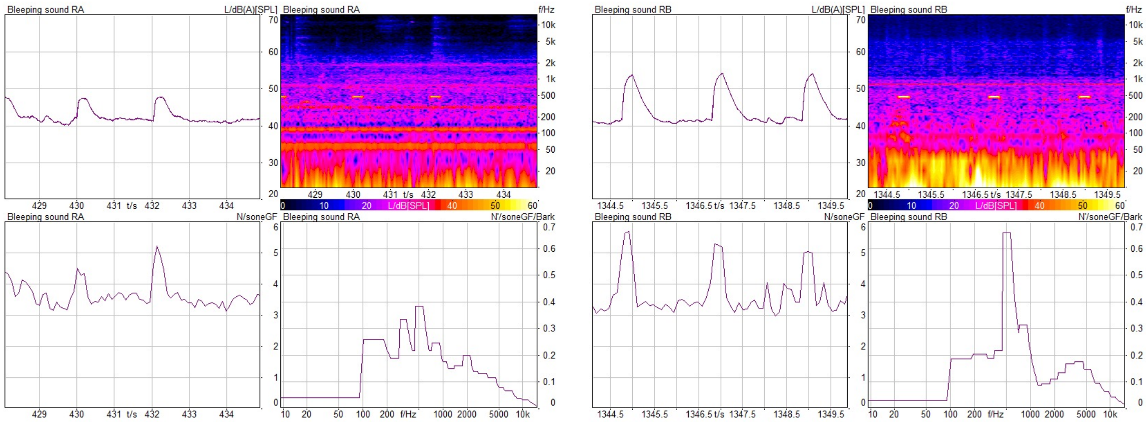

Figure 6.9.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of a bleeping sound in the reference room (left) and a bleeping sound in the refurbished room (right).

sound loses more energy than the reflected sound in the reference room [23]. The differences are small but not smaller than the JND. Furthermore, the difference in the reverberation time between the rooms at 500 Hz is 100 msec (see Chapter 2).

The tonal components in the refurbished room are more distinct making the sound perceived shaper while in the reference room the environment is noisier (Fig 6.10). In both rooms the fluctuation strength is low with higher values in the refurbished room but as mentioned the duration of the sounds is not enough for a sufficient analysis.

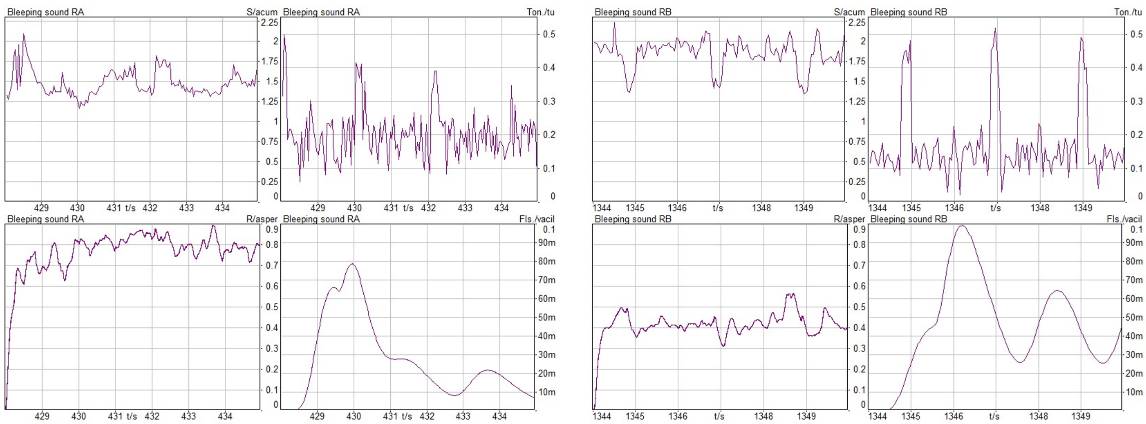

Figure 6.10.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of a bleeping sound in the reference room (left) and a bleeping sound in the refurbished room (right).

Another type of bleeping sound has been collected and compared in order to gain more information about the contribution of the rooms on the perceptual characteristics (Fig 6.11)

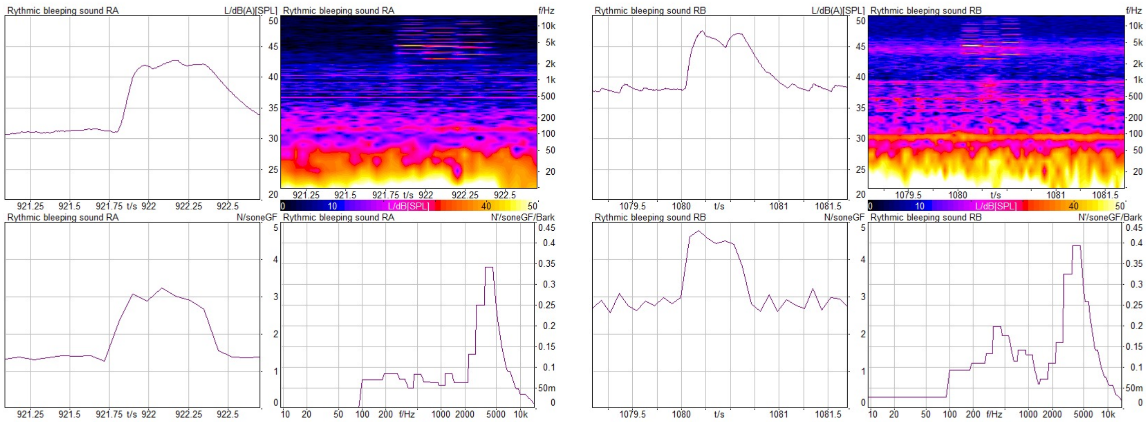

Figure 6.11.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of a bleeping sound in the reference room (left) and a bleeping sound in the refurbished room (right).

In this case the sound in the refurbished room is higher in level than in the reference room. But looking at the spectrogram of the refurbished room, one can see high energy noise at around 100 Hz and a noisier environment. This might means that the level of the equipment in the room has been adjusted in order to be more audible and distinctive. The values for the loudness are lower in the reference room as expected since the level difference between the two sounds is about 5 dB.

A closer observation of the loudness curves shows the same behaviour as in the previous bleeping sound. The loudness in the reference room increases while in the refurbished room decreases and as explained before, this might be due to the absorption effect on loudness. It is more obvious though for the other bleeping sound at 500 Hz.

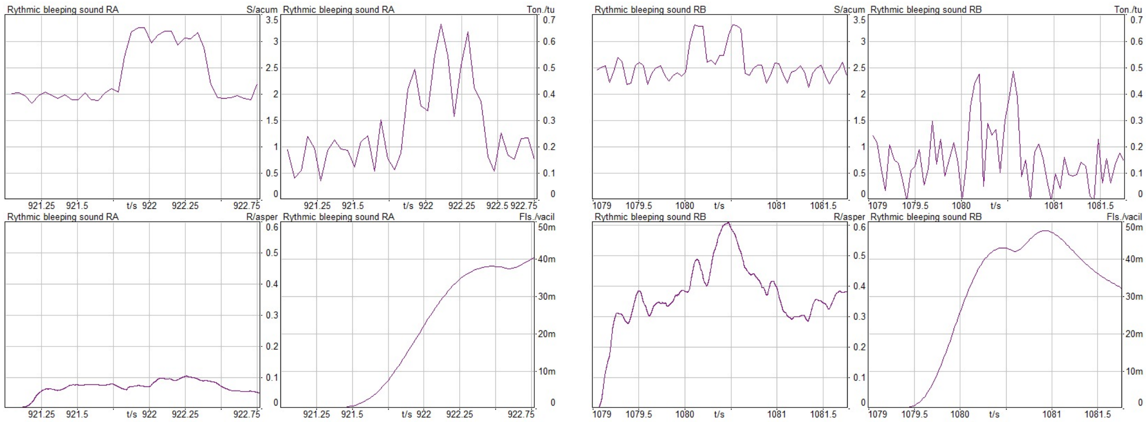

Figure 6.12.: Sharpness vs Time (S), Roughness vs Time (R), Tonality vs Time (Ton) and Fluctuation strength vs Time (Fls) of a bleeping sound in the reference room (left) and a bleeping sound in the refurbished room (right).

Since the environment in the refurbished room is noisier, the tonal components in the reference room are higher. However, both sounds are perceived equally sharp with higher variations in the refurbished room as one can see in Fig 6.12. Roughness, on the other hand, is much higher in the refurbished room but could be affected by the presence of the noisy equipment that is active.

Alarm

The next sound to be analysed is an alarm sound that was identified in both rooms and in many recordings.

The reason for selecting this sample to be presented is because as one can see in Fig 6.13, the levels in the reference room are more than 15 dB higher. The difference is too big to be considered as an attribute of the room. Most possible scenario is that the staff lowered the volume of the equipment which can be considered as a positive consequence since that could be a possible solution for high levels in the room produced by medical equipment. The noise in the refurbished room is low enough for the alarm to be audible even at much lower volume. On the other hand, there is a lot of noise in the reference room that comes from other equipment and makes this adjustment impossible.

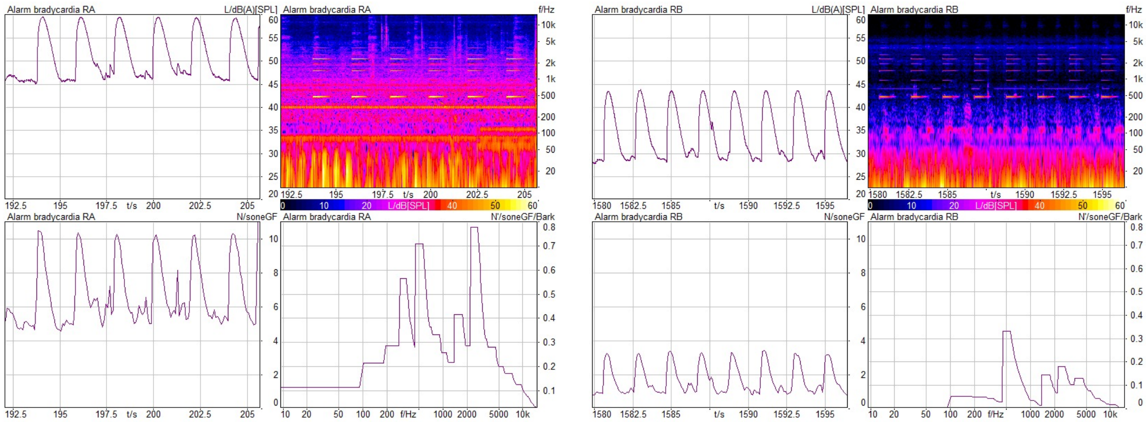

Figure 6.13.: LAF (up left), Spectrogram (up right), Loudness Time History (down left) and Specific Loudness (down right) of alarm sound in the reference room (left) and alarm sound in the refurbished room (right).

Since no information is given for the patients and the equipment used in these two recordings, this example is given just to show that in quiet periods this adjustment of the volume could be possible and effective without affecting the performance of the staff or jeopardize patients' safety. Moreover, this adjustment could be attributed to the visual improvement of the environment in the room that influences the staff to move and talk more quietly [38].

6.2.3. Total values

The values for the presented examples are summarized in Tables 6.1 and 6.2. The values have been calculated through HEAD acoustics Artemis.

Plastic packaging (4 kHz)		
Psychoacoustic metric	**Reference room**	**Refurbished room**
LAeq (dBA)	46.5	44.2
Loudness (sone)	4.62	2.98
Spec. Loudness (sone)	5.77	4.22
Sharpness (acum)	2.34	3.31
Roughness (asper)	0.91	0.43
Fluct. Strength (vacil)	0.033	0.012
Tonality (tu)	0.09	0.03
Metallic object on table (3 kHz)		
Psychoacoustic metric	**Reference room**	**Refurbished room**
LAeq (dBA)	55.8	54.4
Loudness (sone)	5.17	4.35
Spec. Loudness (sone)	9.18	8.48
Sharpness (acum)	1.79	2.26
Roughness (asper)	0.74	0.57
Fluct. Strength (vacil)	0.053	0.033
Tonality (tu)	0.35	0.21

Table 6.1.: Psychoacoustic metrics for plastic package and metallic obj sounds.

Bleeping sound 1 (500 Hz)		
Psychoacoustic metric	**Reference room**	**Refurbished room**
LAeq (dBA)	43.1	46.7
Loudness (sone)	3.65	3.68
Spec. Loudness (sone)	3.84	4.19
Sharpness (acum)	1.49	1.85
Roughness (asper)	0.76	0.41
Fluct. Strength (vacil)	0.027	0.044
Tonality (tu)	0.20	0.17
Bleeping sound 2 (4 kHz)		
Psychoacoustic metric	**Reference room**	**Refurbished room**
LAeq (dBA)	37.9	41.9
Loudness (sone)	1.93	3.21
Spec. Loudness (sone)	2.47	3.62
Sharpness (acum)	2.35	2.55
Roughness (asper)	0.07	0.37
Fluct. Strength (vacil)	0.018	0.028
Tonality (tu)	0.27	0.16

Table 6.2.: Psychoacoustic metrics for two bleeping sounds in reference and refurbished room.

From the tables of the psychoacoustic values one can conclude that all the compared sounds are perceived rougher in the reference room and sharper in the refurbished. The differences in loudness are probably because of the differences in volume control settings.

6.3. Conclusions

The number of the sample is very small for the rooms to efficiently be compared but an overall picture of the rooms and the sounds is given. Small differences in LAeq give small differences in loudness as expected. For the example of the bleeping sound at 500 Hz, even though the level in the refurbished room is higher by 3.5 dB, the difference in overall perceived loudness is less than 0.5 sones which is the just noticeable difference for loudness showing that both sounds are perceived equally loud. This is not the case for the bleeping sound at 4 kHz that the LAeq is higher in the refurbished room and so is the overall loudness. Furthermore, for the medical equipment examples the peaks in loudness over time decrease in the refurbished room while increase in the reference room and this could be due to the absorption added in the refurbished room and the reflected sound loses more energy. This is more obvious for the first bleeping sound (at 500 Hz).

The sharpness, on the other hand, is higher in the refurbished room in almost all the samples and the sounds have more tonal components while the roughness is higher in the reference room. In all the examples the presence of noise in the reference room is noticeable.

Finally, from the comparison of an alarm sound (see Fig 6.13), because of the big difference in the sound levels, one can lead to the conclusion that the volume in the refurbished room has been adjusted (lowered) which could be either because of the quieter environment in the room that makes the alarm audible or the acoustic and visual treatment affects positively the staff making them act in a different way.

However, due to the different noise sources and background noise it is not sure if we can rely on this comparison.

7. Discussion

The main noise sources in ICU are the equipment/machinery and the staff/visitors along with the activities. A major cause for the increase of the sound levels in the room/corridors is the hard surfaces and reflective materials that are usually used in hospitals to avoid infections and to be able to clean them easily. All these hard, sound-reflecting, surfaces help the sound to propagate into the room and the corridors to echo and overlap. In the ICU the number of visitors and staff around the patients changes during day and night and the more serious the condition of the patient is the more people are around and eventually results in a noisier environment.

7.1. Room acoustics evaluation

One of the rooms is acoustically treated by adding a suspended plaster ceiling of 20 mm absorbent layer and a thicker layer in the corners for extra bass absorption. The room acoustics measurements that have been performed in the refurbished and the reference room showed that the strength in the refurbished room is lower by 2 dB at lower frequencies (125-400 Hz), higher by 1 dB at frequencies between 500 Hz and 1.5 kHz and lower by 1 dB at 2-4 kHz. The reverberation time in the refurbished room is significantly decreased basically at lower frequencies while clarity of speech is improved for the whole frequency range with greater improvement at frequencies below 1 kHz, which provides a good acoustic environment and a high level of speech intelligibility.

Clearly the refurbished room is acoustically improved, compared to the reference room, in terms of reverberation time and speech intelligibility. Since the sound levels are equally high in both rooms according to the measurements that have been performed after the refurbishment, further treatment to improve even more the sound strength especially for frequencies between 500 Hz and 1.5 kHz needs to be done.

In addition to the acoustical treatment, the room was renovated with changes in colouration, furnishings and lighting, improving the image of the room aiming for a more comfortable environment for patients and staff. A preliminary study about the effect of the interventions (visually and acoustically) on the personnel done by Persson Waye and Ryherd (2013), showed that the refurbished room was rated as more quiet and less noisy and hissing with better light and aesthetics while ergonomic and available work space were rated as worst in the refurbished room (the new equipment is taking more space). That shows that the personnel perceived the sound quieter in the refurbished room but didn't approve the arrangement of the equipment as practical. But since the sound environment in the refurbished room is perceived as improved by the personnel this might lead to the assumption that the interventions may influence the staff make them behave and talk in a quieter way in the room (since the clarity of speech intelligibility is also improved) [38].

7.2. Levels distribution

The A- weighted equivalent levels as well as the maximum, minimum and the C-weighted peak levels were measured during day and night from microphones that have been placed above each patient's bed. Five pairs of patients (one patient of each room for each pair) with similar severity of illness have been randomly chosen in order to compare the measured levels and the levels distribution along with "quiet"periods over 24h.

The results showed that all the levels in both rooms are high with A-weighted maximum levels between 45 and 75 dB and the C-weighted peak levels from 65 to 85 dB. From the figures of the statistical distribution, one can see that these values occur for almost the whole day with very high peaks during the night.

The calculations of the "quiet", restorative times led to an expected finding. The levels in the reference room are higher and the quiet periods in terms of occurrence and duration are shorter than in the refurbished room especially for the case of LAFmax and LCpeak. The main activity, which is indicated by the LAeq levels, is the same in both rooms with the reference rooms having less but longer periods and the refurbished room more but shorter periods during day time (the opposite applies for the night time). Since the number of periods and the mean length (at least during day time) are higher in the reference room that means that we have more high peaks and maximum A-weighted levels (sudden noises) followed by "quiet"periods. In a research conducted by Biley (1993) [14] is indicated that sudden noise of 30 dB above the background noise has more startling and stress-producing effect on patients than a continuous background noise. This could be considered as an advantage for the refurbished room without being able to attribute it with certainty to the acoustical treatment. The different distribution of the levels in the refurbished room could be probably connected to different behaviour of the staff as mentioned in the previous paragraph and also in Chapter 3. Additionally, the levels in the refurbished room are still much higher than the recommended that indicates that further improvement is needed. Moreover, from the overall results, one can see that the maximum lengths of silent periods are not long enough to help the patient to have calmer sleep patterns.

7.3. Noise source identification

The wave files that have been recorded for two hours per day (one during day time and one during night time) have been used in order to identify the noise sources that occur in and outside the rooms. After performing a t-test to the randomly chosen recordings and with the help of a confidence intervals plot using bootstrap technique, the results showed that there is no significant difference between the rooms with regards to number of events and duration. From the analysed data nothing confirms that the different noises are related to the different rooms and for this reason the source identification has been done based on the comparison between day and night time events.

The sound sources are the same for day and night time and can be divided into two general categories, the sounds that are generated from medical equipment and alarms and the sounds that are connected to staff and visitors activity.

Medical equipment sounds are the most frequent and unpredictable. The duration varies depending whether it is monitoring equipment or an alarm. The sound that is generated from medical equipment is not avoidable since enhance safety and give important information regarding patient's condition. A solution to improve this situation is to adjust the volume in a level that is effective without affecting the performance of the personnel or jeopardize patient's safety.

For noises that are connected to human activity such as slamming doors, furniture, apron, steps etc. the way to deal with them is only a matter of training the staff and informing the visitors. Changing the behaviour of the people in the room such as the way they open and close the cabinets or leave objects on the table and by lowering the voice level keeping the conversations short, would improve the sound environment in the room a lot and would give the patients better access to "quiet"restorative periods. Of course there are some cases that are hard to deal with such as the case mentioned about the noise from objects on the tables. Since in the hospitals all the surfaces are hard for hygiene reasons and when the patient is in need it is hard for the personnel to think at the same time to be more careful while placing objects on the side table, a possible solution could be a disposable absorbent material on the table surface which will be discarded after the treatment. Finally, small low-cost alterations such as fixing the squeaking hinges or place chairs with wheels could have a noticeable effect on the sound levels in the room.

For the use of entertaining device in and outside the room the solution of adjusted volume has already been given. Additional solution would be the prohibition of the use of these devices during quiet hours or in case of the presence of another patient in the room. Another simple solution for the rattling noise coming from the rolling carts would be the same as the one given for the tables with the disposable absorptive material. Further investigation must be done for a more effective solution such as changing the wheels or improving the connection between the wheels and the body of the cart.

7.4. Perceptual Characteristics

With the previous analysis useful information has been gathered about the levels in the rooms, how they are distributed and which are the noise sources that attribute to that.

According to Biley (1993) a noisy environment causes stress, anger, confusion and distraction. These psychological and physiological impacts are more connected to the level of a sound (loudness) and the time period that occur.

In order to analyse the noise sources from a psychoacoustic point of view, important psychoacoustic metrics such as loudness, specific loudness, sharpness, roughness, fluctuation strength and tonality have been calculated through HEAD acoustics Artemis software. Samples of the most common sounds have been gathered from both human activity and medical equipment. The number of the samples is small but still leads to interesting conclusions for the overall picture of the sound environment in the room.

Most of the sounds are loud, impact, sudden sounds, with high frequency components coming from noise sources located most of the times next to the patients. For example a noise from furniture that hit on the floor reaches maximum loudness 40 sones with overtones up to 2 kHz while the furniture that is dragged has maximum loudness approximately 30 sones because of the lower frequency components of the sound. Loudness is frequency dependent and this can be showed also in another example for a noise source that produces two different kinds of sounds. The slamming cabinet door is one of the sounds that have been identified in most of the recordings. But except the slamming sound there is another sound emitted from the hinges. This switch from one sound to the other occurs frequently and right next to patient's bed with a loud and rough sound to be followed by sharp more tonal sound.

According to the analysis of the sound sources in the rooms the medical equipment noises occur in all of the recordings. But from the analysis of the perceptual characteristics and comparing the medical equipment noises with the human activity noises, one can see that the maximum perceived loudness is much higher in the human activity sounds. The overall loudness for the bleeping sounds is around 4 sones while the human activity sounds have overall loudness that varies between 10 and 20 sones indicating that the human activity sounds attribute more to the noisy environment in the room. Further investigation needs to be done in order to determine if these high loudness levels are perceived louder if someone tries to sleep or is awake. Also the variations of loudness are big enough and since the just noticeable difference for loudness is 0.5 sone, for the majority of the time during day and night, perceptible loudness changes occur from different directions and noise sources.

All the samples used in this analysis have values for sharpness that reach a maximum of 5 acum which is a typical value for the sharpness of a flute. The higher values of sharpness are dominated by alarms and impact loud sounds. The presence of low frequency noise in the room generated from HVAC and increases the background noise, is probably the reason why the sharpness for some of the sounds is not as high as expected.

On the other hand, sounds with roughness above 0.10 asper can be considered as rough and all the examples presented have higher roughness. The fluctuation strength is relatively low which is good for noise-like sounds. Since most of the sounds are impulsive sounds of short duration we cannot rely on roughness and fluctuation strength to get a real picture of the sounds' character. Maybe it is more important to look at the variations of loudness, roughness, sharpness and fluctuation strength over time comparing to the JND. From the analysed examples and knowing that the sounds in the rooms are sudden and unpredictable, one can see that all the psychoacoustic metrics vary all the time between low and high values. If we take for example the ventilator alarm we will see that the peaks and dips in all psychoacoustic graphs are much higher than the JND making, in this way, the patient able to perceive these changes.

Lotta Johansson's research showed that patients experience the ICU sounds subjectively and different which is connected to their previous experience of hospitalization and background with the general conclusion that the patients feel vulnerable and powerless [29].

In concluding, most of the noises that are connected to human activity are loud and rough while the medical equipment sounds are perceived more sharp and tonal. A previous research showed that activation increases with sharpness and tonality while valence was associated with perceived loudness and roughness [43].

7.5. Comparison of the perceptual characteristics

Since one of the purposes of this study is also to compare the two rooms and identify if the acoustical treatment is effective or not, a comparison between the two rooms in terms of the perceptual characteristics has been done. Sounds from human activity and medical equipment have been gathered from both rooms trying to choose sounds as similar as possible with respect to sound level, duration and timbre. In order to make the comparison easy, the averages of the psychoacoustic metrics have been obtained.

No significant differences occur for loudness between the two rooms. It is noticeable though that for the repeated bleeping sounds the peaks in loudness decrease in the refurbished room while increase in the reference room. This is more obvious for the bleeping sound that occurs at 500 Hz. This could probably be the effect of the added absorption on loudness. From the room acoustics measurements we also obtained lower reverberation time at 500 Hz by 100 ms.

Comparing the sounds in both rooms in terms of the sharpness, the average values are not high as mentioned. Higher values occur in the refurbished room since in the reference room high level noise around 300 Hz occurs in almost all the samples. In short terms, both rooms have typical sound sources (e.g. ventilation) that do not accentuate sharpness.

The average roughness is higher in the reference room while the fluctuation strength is higher in the refurbished room, but still in low values. This might indicate that the varying nature of the sounds in both rooms is of higher frequency amplitude modulations.

7.6. Conclusions

From my personal experience while listening to the recordings, there is an obvious audible difference of the noise in the rooms. In the reference rooms recordings the noise between 100-300 Hz was audible almost all the time while in the refurbished room the higher energy noise occurs under 100 Hz. From the samples used for the analysis there is a big improvement in the background noise which is also obvious in the background noise figures in Chapter 6.

In summary, the acoustical treatment improved the characteristics of the room but since the levels are still much higher than the recommended further improvement needs to be done. Also personnel and visitor should be aware about the needs for quieter environment in the ICU. Changing both the characteristics of the room and the human behaviour the results will be optimum.

7.7. Future work

- In order to have a complete picture of the ICU environment, my suggestion is to listen, evaluate and compare as many as possible from the available recordings. It is a procedure that requires lot of time but could give more accurate results.
- Also more detailed and subjective analysis for the perceptual characteristics in the rooms by analysing higher number of recordings and performing listening tests would be valuable.
- A similar, to this thesis, research could be done after the training of the personnel to investigate if the situation is improved or not.
- Further research must be done in order to evaluate the psychological and physiological impacts on patients, staff and visitors of the visual treatment of the room with questionnaire and ask for people's suggestions.

References

[1] Diracdelta.co.uk. http://www.diracdelta.co.uk/science/source/a/w/aweighting/source.html. Accessed: 2014-11-15.

[2] Engineering statistics handbook. http://http://www.itl.nist.gov/div898/handbook/index.htm. Accessed: 2014-11-15.

[3] Head acousrics-artemis suite. http://www.head-acoustics.de/eng/nvh_artemis_suite.htm. Accessed: 2014-10-01.

[4] Hearforever. http://www.hearforever.org/tools\discretionary{-}{}{}to\discretionary{-}{}{}learn/sound\discretionary{-}{}{}source\discretionary{-}{}{}a\discretionary{-}{}{}and\discretionary{-}{}{}c\discretionary{-}{}{}weighted\discretionary{-}{}{}noise\discretionary{-}{}{}measurements. Accessed: 2014-11-15.

[5] Hyperphysics. http://hyperphysics.phy-astr.gsu.edu/hbase/sound/phon.html. Accessed: 2014-10-15.

[6] Sound and vibration basics statistical noise levels. http://www.gracey.co.uk/basics/statistics-b1.htm. Accessed: 2014-07-15.

[7] ISO 10052:2004. *Acoustics– Field measurements of airborne and impact sound insulation and of service equipment sound– Survey method*. 2004.

[8] ISO 3382:2003. *Acoustics–Measurement of the reverberation time of rooms with reference to other acoustical parameters.* International organization of standardization, 2003.

[9] ISO 523:2012. *Acoustics– Method for calculating loudness level*. 2012.

[10] Ernesto Accolti and Federico Miyara. Fluctuation strength of mixed fluctuating sound sources. *Mecánica Computacional*, 28:9–22, 2009.

[11] Neriman Akansel and Şenay Kaymakçi. Effects of intensive care unit noise on patients: a study on coronary artery bypass graft surgery patients. *Journal of clinical nursing*, 17(12):1581–1590, 2008.

[12] Elizabeth Bailey and Stephen Timmons. Noise levels in picu: an evaluative study. *Paediatric nursing*, 17(10):22–26, 2005.

[13] Birgitta Berglund, Thomas Lindvall, Dietrich H Schwela, et al. Guidelines for community noise. In *Guidelines for community noise*. OMS, 1999.

[14] Francis C Biley. Effects of noise in hospitals. *British journal of nursing (Mark Allen Publishing)*, 3(3):110–113, 1993.

[15] Ilene J Busch-Vishniac, James E West, Colin Barnhill, Tyrone Hunter, Douglas Orellana, and Ram Chivukula. Noise levels in johns hopkins hospital. *The Journal of the Acoustical Society of America*, 118(6):3629–3645, 2005.

[16] Ceilings and Interior Systems Construction Association (CISCA). Acoustics in health care environments. Technical report, 2010.

[17] Martin Christensen. Noise levels in a general intensive care unit: a descriptive study. *Nursing in critical care*, 12(4):188–197, 2007.

[18] Frank Fahy and John Walker. *Fundamentals of noise and vibration*. CRC Press, 1998.

[19] Hugo Fastl and Eberhard Zwicker. *Psychoacoustics-Facts and Models*. 2006.

[20] Richard J Fridrich. Percentile frequency method and zwicker loudness. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 2002, pages 411–416. Institute of Noise Control Engineering, 2002.

[21] Ecophon Group. *Healthy sound environments for patients and staff*. 2011.

[22] Interface group. Just the facts acoustics. Technical report, 2011.

[23] MBI group. Room acoustics. Technical report, 1992.

[24] Ellen C Haas and John G Casali. Perceived urgency of and response time to multi-tone and frequency-modulated warning signals in broadband noise. *Ergonomics*, 38(11):2313–2326, 1995.

[25] Colin H Hansen and David A Bies. *Engineering noise control*. Spon, 1995.

[26] J R Hassall and K Zaveri. *Acoustic Noise Measurements*. 1988.

[27] Timothy Yuan-Ting Hsu. *Relating acoustics and human outcome measures in hospitals*. 2012.

[28] Jerald R Hyde and Henrik Möller. Sound strength in small halls. *Proceedings of the Institute of Acoustics, St. Albans, UK*, 2006.

[29] Lotta Johansson. Being critically ill and surrounded by sound and noise. patient experiences, staff awareness and future challenges. 2014.

[30] Lotta Johansson, Ingegerd Bergbom, Kerstin Persson Waye, Erica Ryherd, and Berit Lindahl. The sound environment in an icu patient room—a content analysis of sound levels

and patient experiences. *Intensive and Critical Care Nursing*, 28(5):269–279, 2012.

[31] Anjali Joseph and Roger Ulrich. Sound control for improved outcomes in healthcare settings. *Concord, CA: Center for Health Design*, 2007.

[32] Mendel Kleiner. *Audio technology & acoustics*. Chalmers University of Technology, 2005.

[33] Nancy Lawson, Kim Thompson, Gabrielle Saunders, Jaya Saiz, Jeannette Richardson, Deborah Brown, Naomi Ince, Marc Caldwell, and Diana Pope. Sound intensity and noise evaluation in a critical care unit. *American Journal of Critical Care*, 19(6):e88–e98, 2010.

[34] Jean-Roger Le Gall, Philippe Loirat, Annick Alperovitch, Paul Glaser, Claude Granthil, Daniel Mathieu, Philippe Mercier, Remi Thomas, and Daniel Villers. A simplified acute physiology score for icu patients. *Critical care medicine*, 12(11):975–977, 1984.

[35] Brian C. J. Moore. Development and current status of the ”cambridge” loudness models. *SAGE*, 2014.

[36] Jeffrey Nevid. *Psychology: Concepts and applications*. Cengage Learning, 2012.

[37] Florence Nightingale. *Notes on nursing: What it is, and what it is not*. Lippincott Williams & Wilkins, 1992.

[38] Kerstin Persson Waye and Erica Reyherd. Achieving a healthy sound environment in hospitals. In *INTER-NOISE and NOISE-CON Congress and Conference Proceedings*, volume 247, pages 6452–6459. Institute of Noise Control Engineering, 2013.

[39] Thomas D Rossing. *Springer handbook of acoustics*. Springer, 2007.

[40] Erica E Ryherd, Kerstin Persson Waye, and Linda Ljungkvist. Characterizing noise and perceived work environment in a neurological intensive care unit. *The Journal of the Acoustical Society of America*, 123(2):747–756, 2008.

[41] C Tsiou, D Eftymiatos, E Theodossopoulou, P Notis, and K Kiriakou. Noise sources and levels in the evgenidion hospital intensive care unit. *Intensive care medicine*, 24(8):845–847, 1998.

[42] Pantelis N Vassilakis and Roger A Kendall. Psychoacoustic and cognitive aspects of auditory roughness: definitions, models, and applications. In *IS&T/SPIE Electronic Imaging*, pages 75270O–75270O. International Society for Optics and Photonics, 2010.

[43] Daniel Västfjäll. Emotional reactions to sounds without meaning. *Psychology*, 3:606, 2012.

[44] Cassandra H Wiese. Investigation of patient perception of hospital noise and sound level measurements: Before, during, and after renovations of a hospital wing. 2010.

[45] Andrew M Willemsen and Mohan D Rao. Characterization of sound quality of impulsive

sounds using loudness based metric.

[46] Jenifer Wilson-Barnett. Interventions to alleviate patients' stress: a review. *Journal of psychosomatic research*, 28(1):63–72, 1984.

[47] Jin You and Jin Yong Jeon. Just noticeable differences in sound quality metrics for refrigerator noise. *Noise Control Engineering Journal*, 56(6):414–424, 2008.

A. Sound Level distribution over time

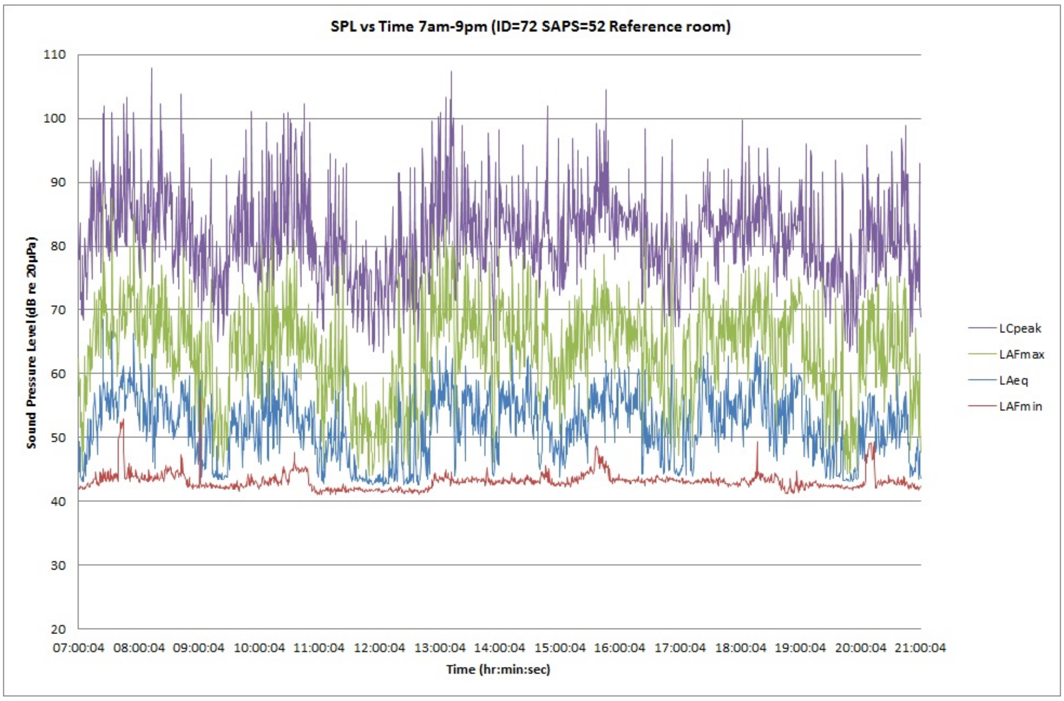

Figure A.1.: Pair 1: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during day time.

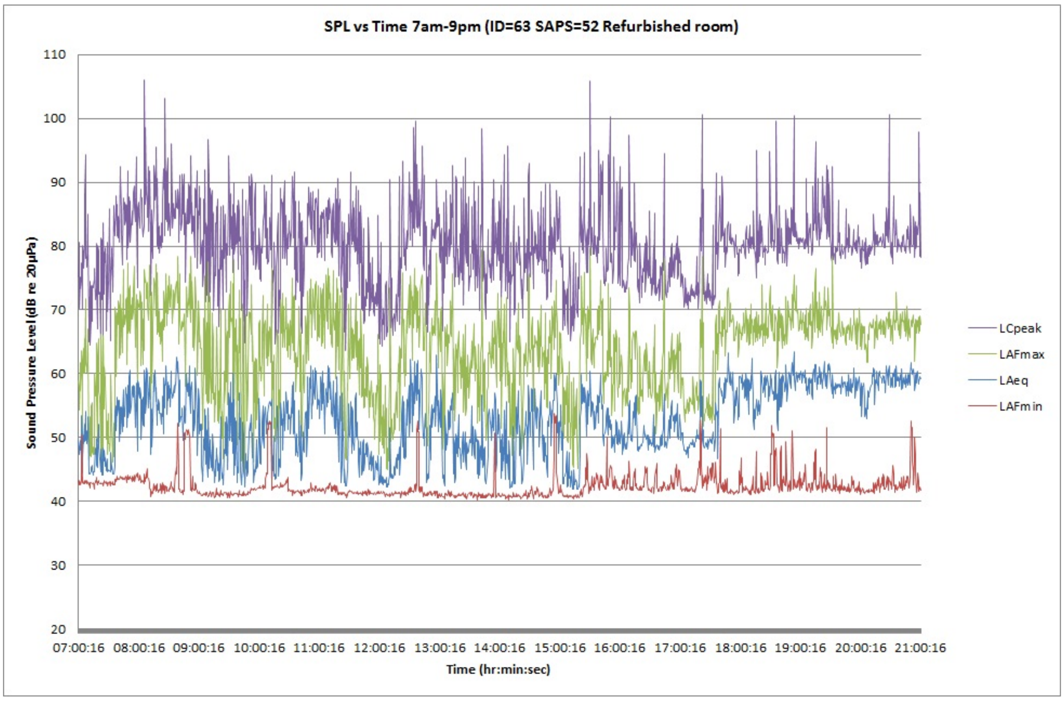

Figure A.2.: Pair 1: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during day time.

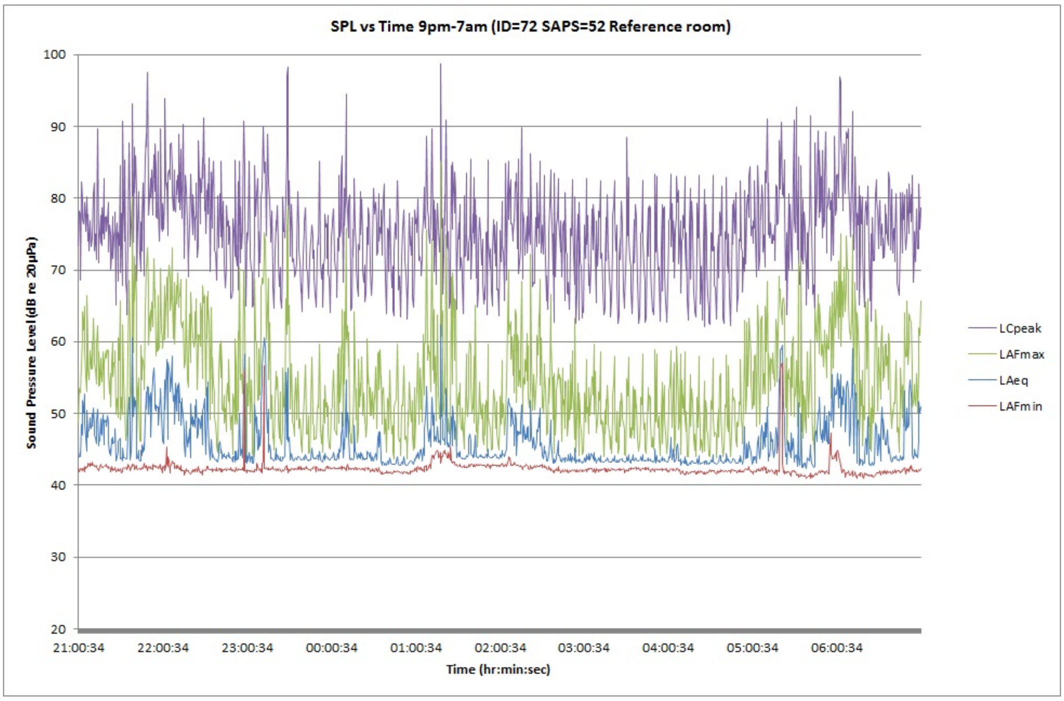

Figure A.3.: Pair 1: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during night time.

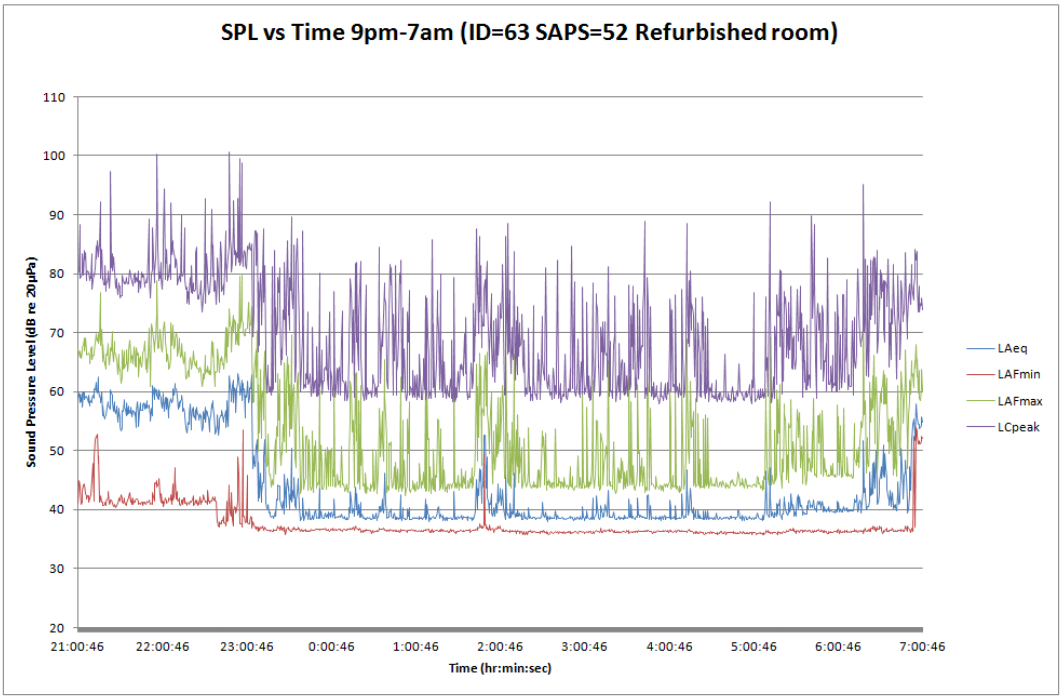

Figure A.4.: Pair 1: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during night time.

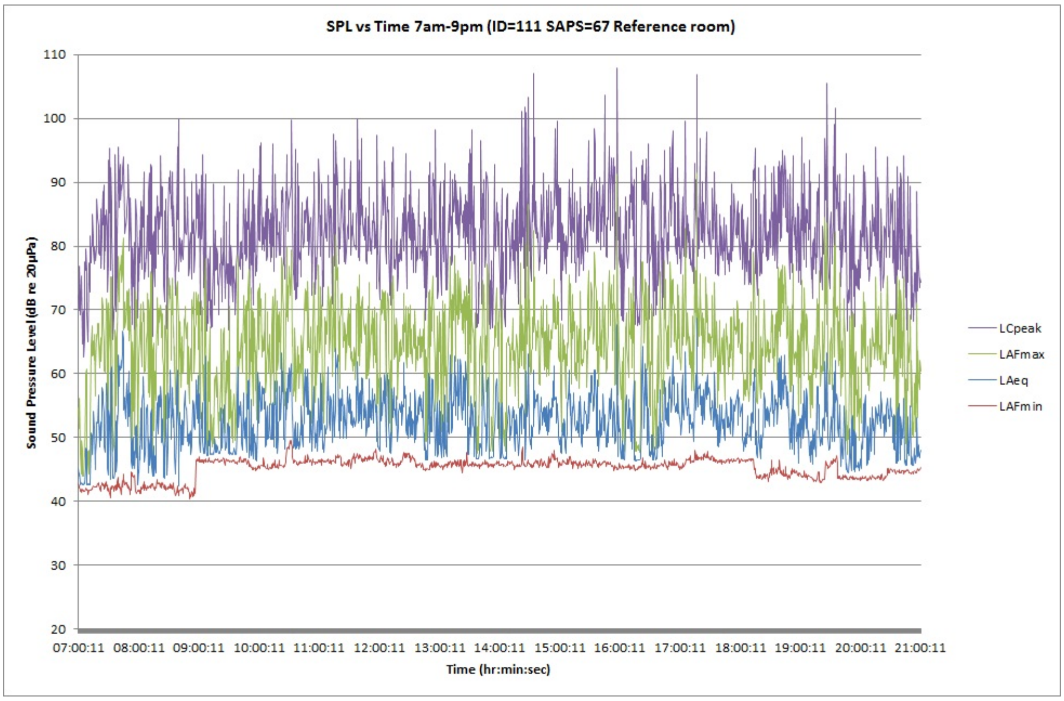

Figure A.5.: Pair 2: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during day time.

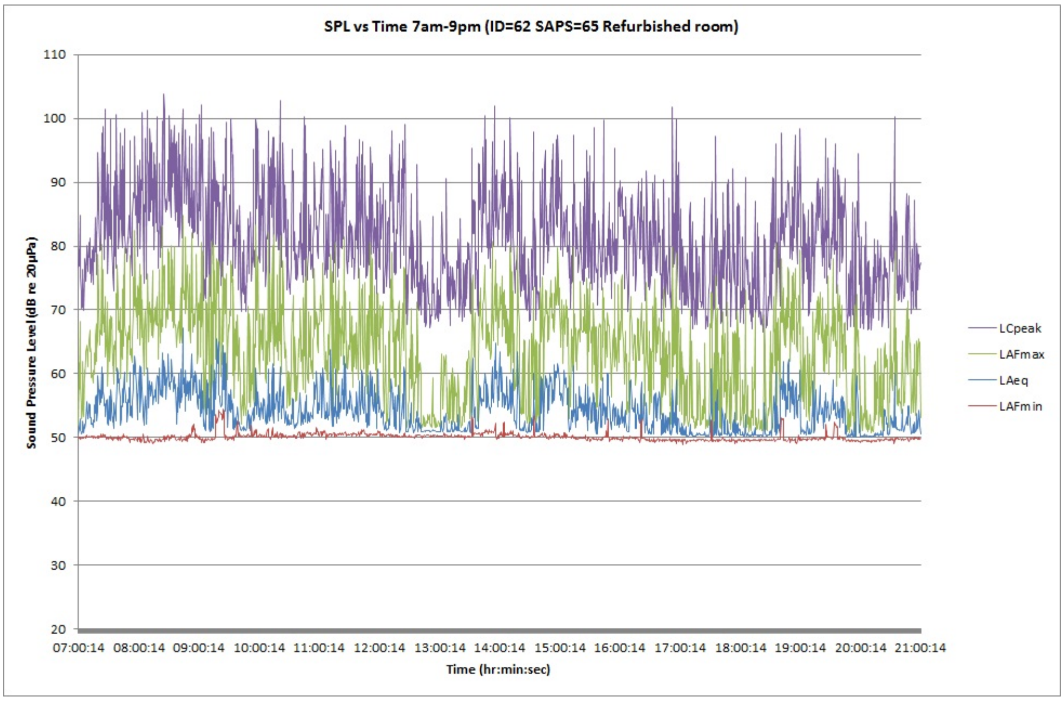

Figure A.6.: Pair 2: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during day time.

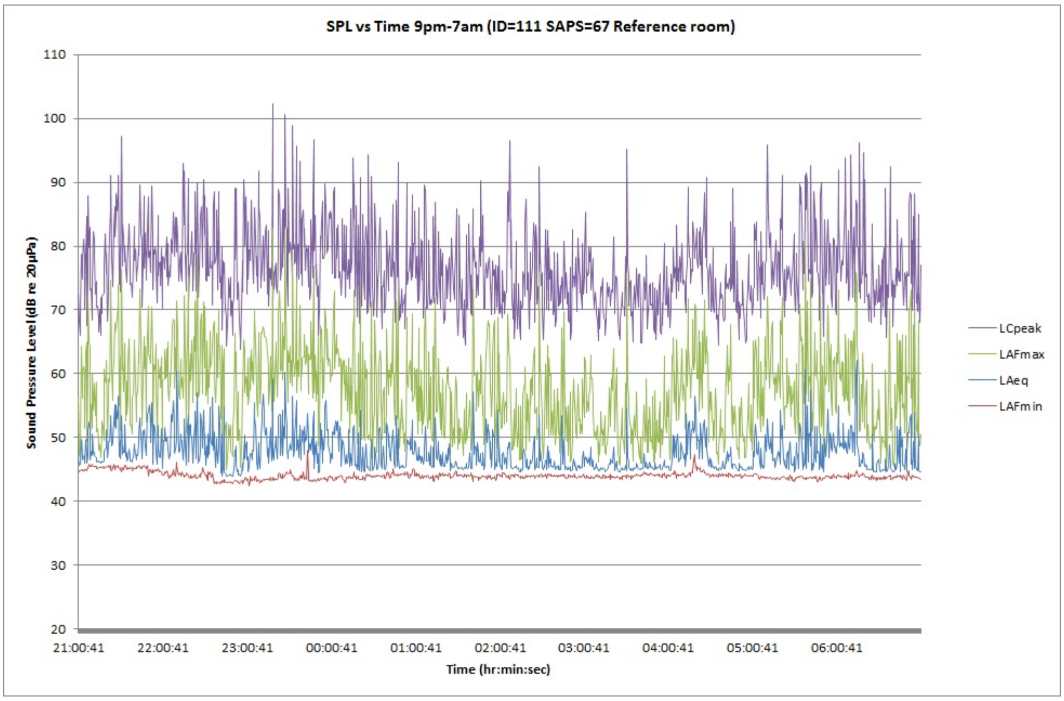

Figure A.7.: Pair 2: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during night time.

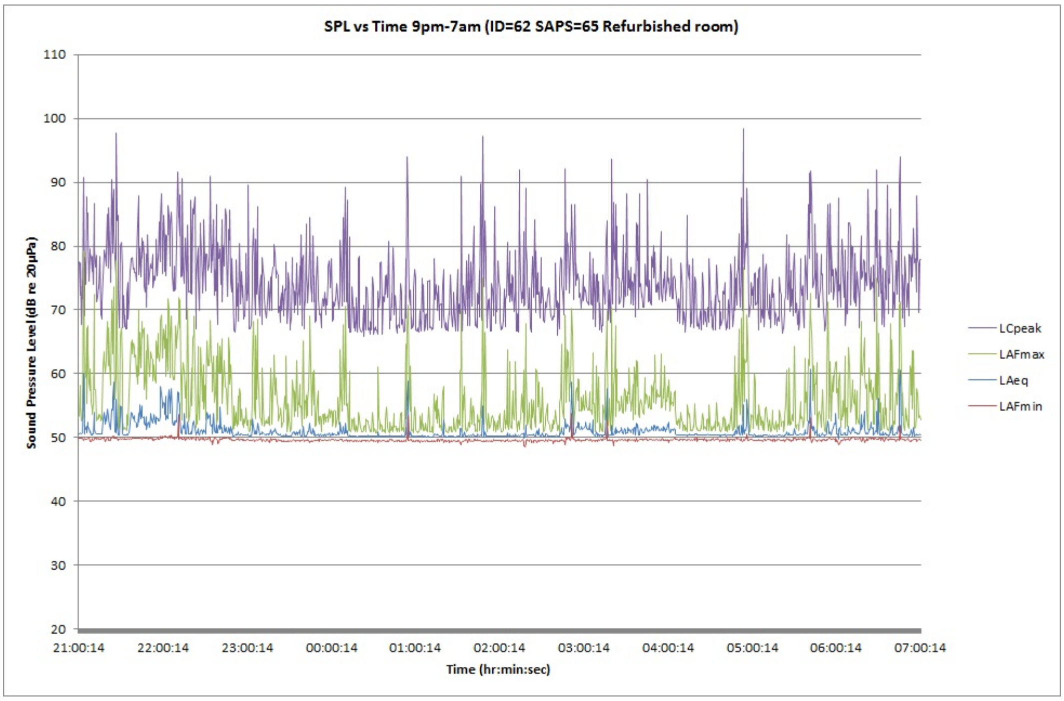

Figure A.8.: Pair 2: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during night time.

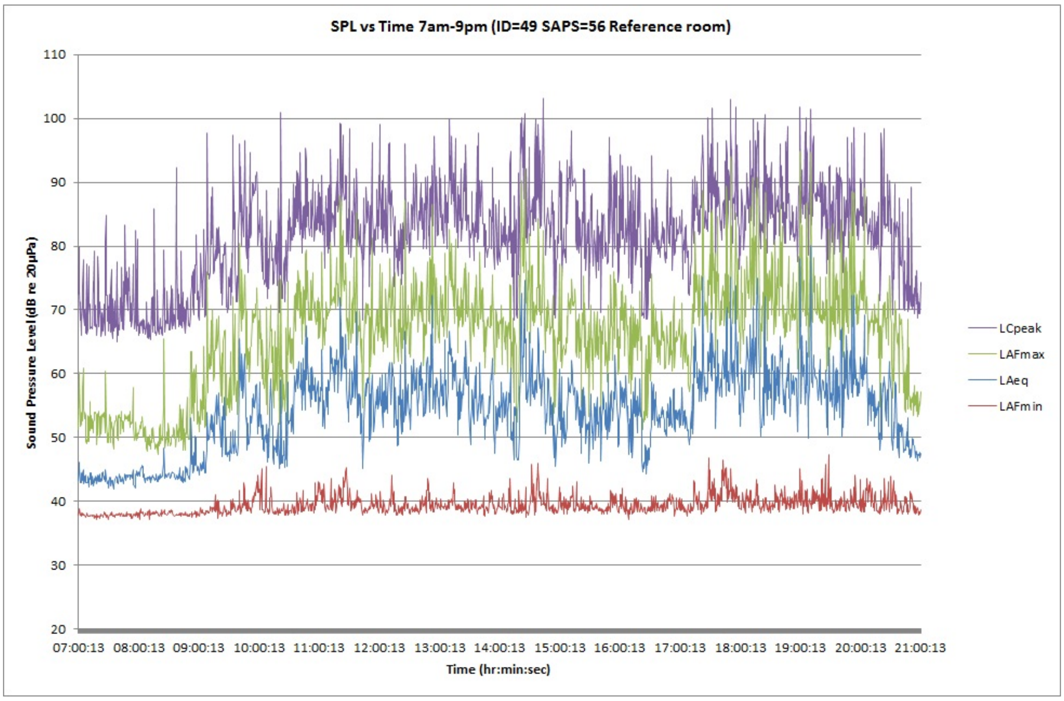

Figure A.9.: Pair 3: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during day time.

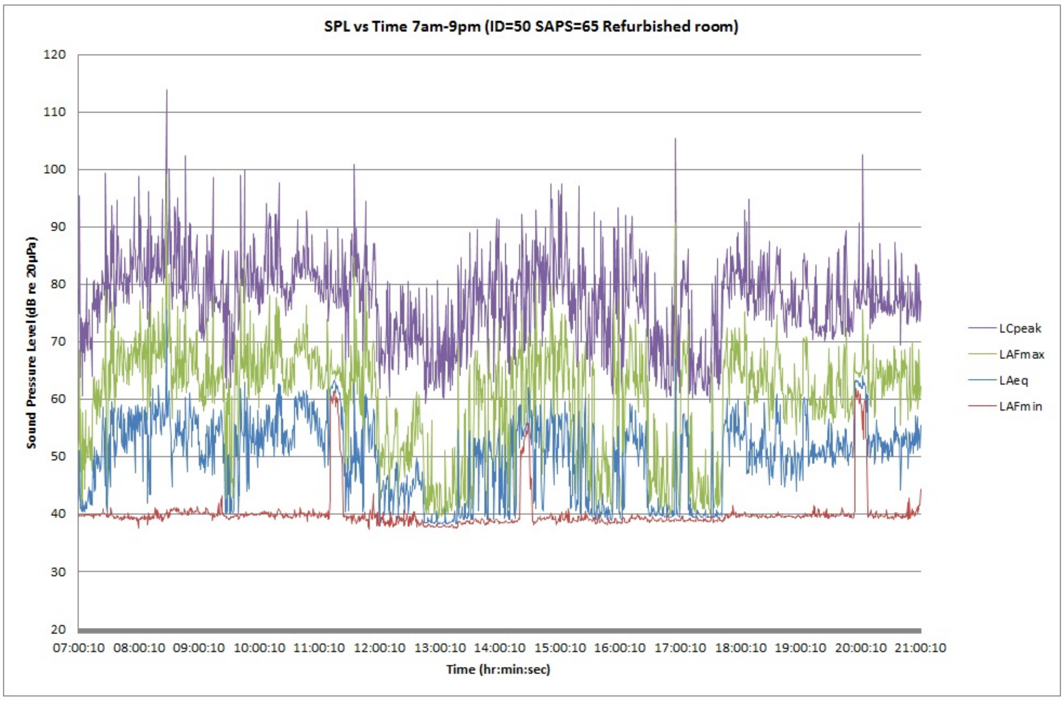

Figure A.10.: Pair 3: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during day time.

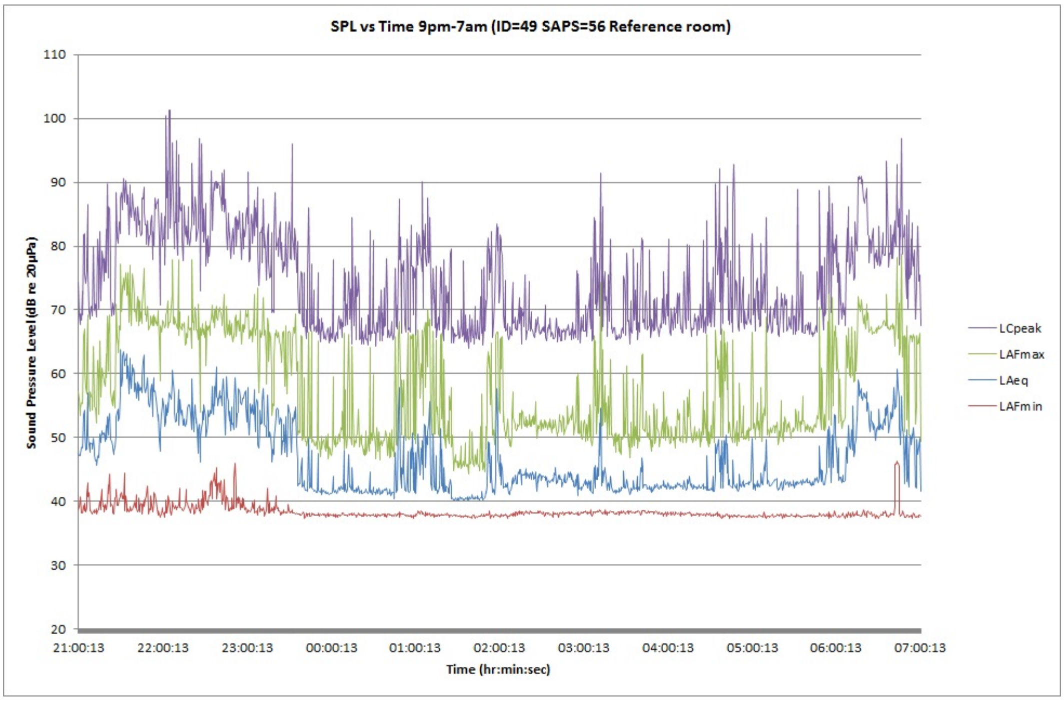

Figure A.11.: Pair 3: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during night time.

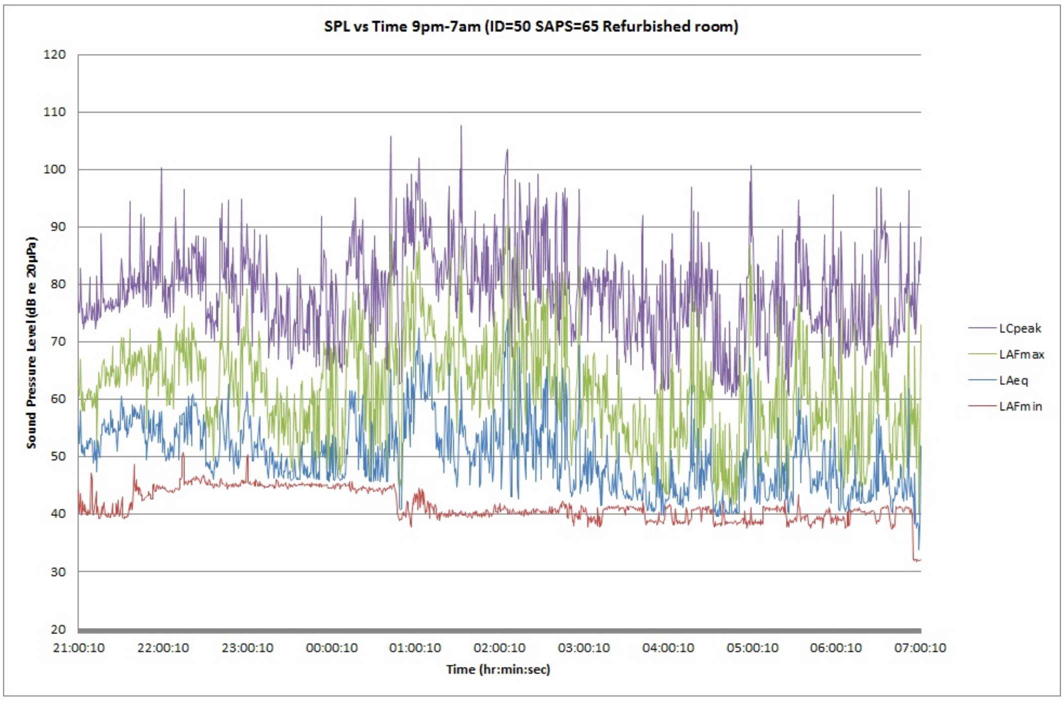

Figure A.12.: Pair 3: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during night time.

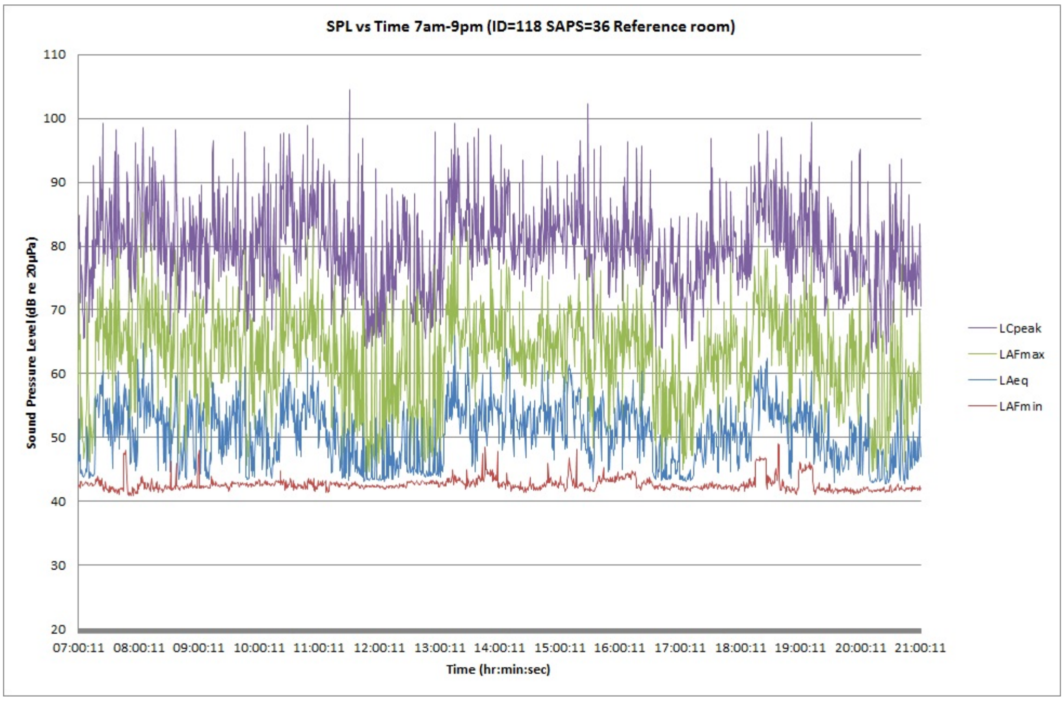

Figure A.13.: Pair 4: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during day time.

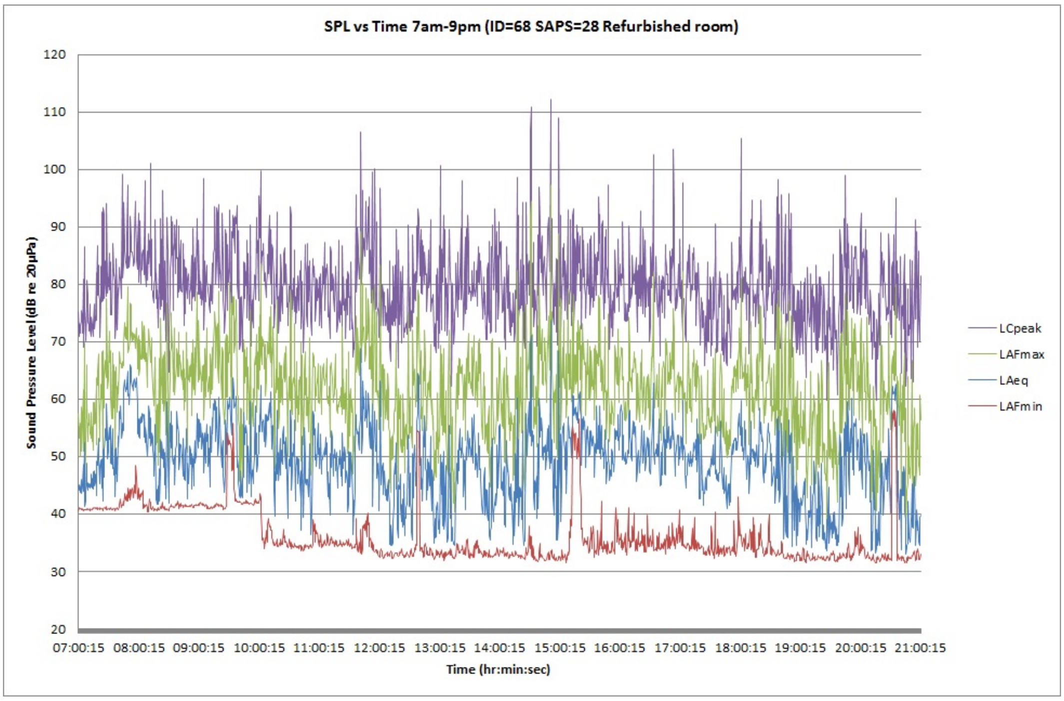

Figure A.14.: Pair 4: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during day time.

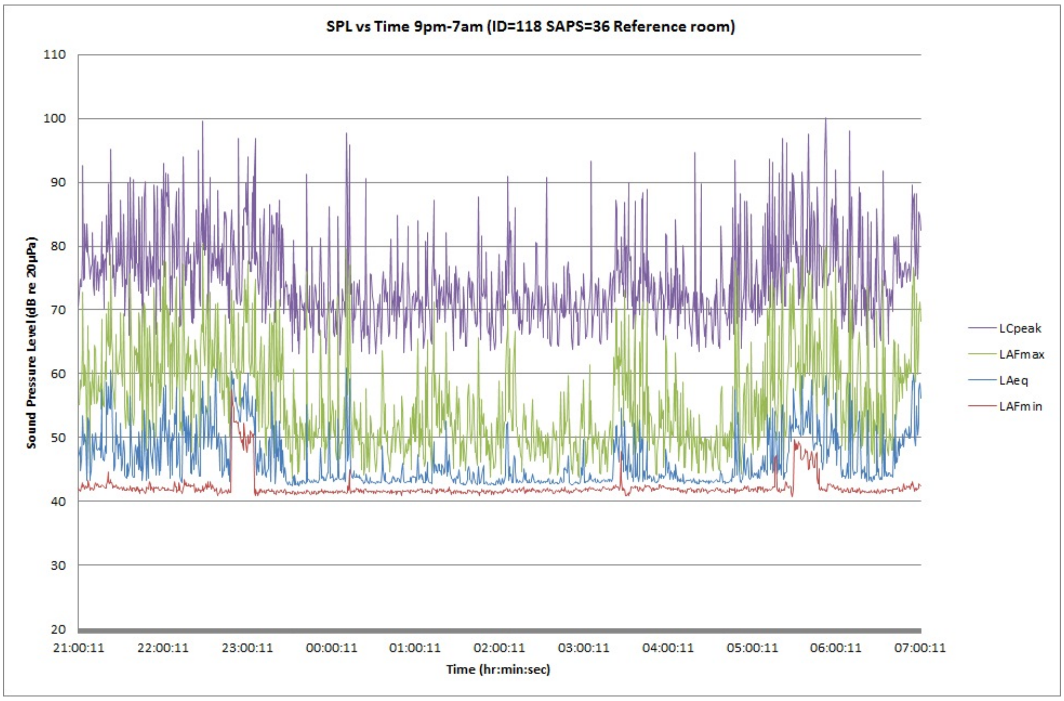

Figure A.15.: Pair 4: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for reference room during night time.

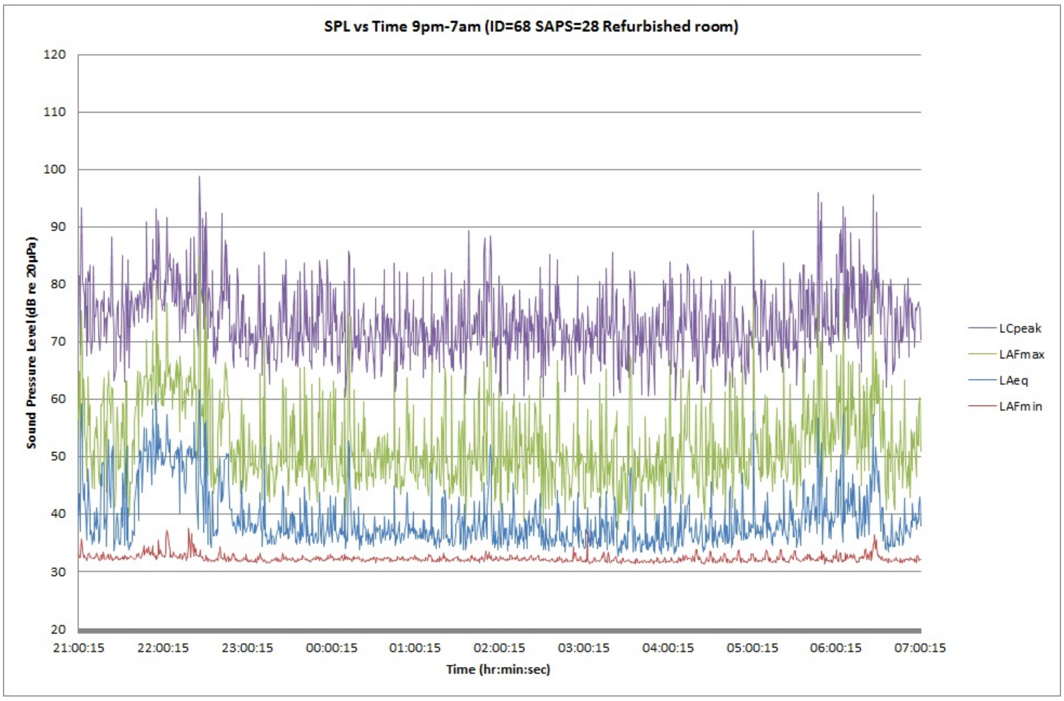

Figure A.16.: Pair 4: A-weighted equivalent, maximum and minimum, C-weighted peak over time (with 30 sec intervals) for refurbished room during night time.

B. Noise Source Identification

Noise sources per day and night time for both rooms (comparison between day and night)

Day time

Noise from inside patient's room

Room Equipment					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Cabinet	11	1.97	1.31	0.22	4.61
Rolling cart	10	0.64	0.53	0.14	1.63
Furniture	8	0.76	0.60	0.14	1.78
Door	7	0.78	0.77	0.11	2.44

Table B.1.: Noise sources from room equipment inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Medical Equipment					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Bleeping	10	9.10	12.48	0.32	38.83
Respirator	5	44.54	22.02	3.59	60.00
Alarm	5	2.33	1.78	0.40	5.34
Equipment(fan)	3	9.98	9.88	0.90	23.72
Equipment(pump)	1	60	-	-	-

Table B.2.: Noise sources from medical equipment inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Equipment manually operated					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Equipment preparation	6	1.82	1.48	0.56	4.59
Equipment(motor)	5	4.37	7.48	0.15	19.32
Bed elevator	2	1.38	0.75	0.63	2.13
Oxygen mask	2	8.24	1.43	6.81	9.67

Table B.3.: Noise sources from equipment manually operated inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Staff activity during patient care					
Noise source	**Number of rec/11 rec**	**Mean time (min)**	**SD**	**Min(min)**	**Max(min)**
Speech	11	41.56	22.23	0.28	60.00
Object on table	10	2.67	3.31	0.72	12.18
Plastic package	9	3.08	4.63	0.36	15.51
Steps rubber	8	2.23	4.12	0.15	13.05
Steps	8	1.46	1.14	0.34	3.64
Apron	7	3.22	2.64	0.28	7.82
Paper	7	0.95	0.64	0.25	2.23
Paper towel	7	0.95	0.64	0.27	5.03
Water tap	7	0.65	0.37	0.30	1.36
Metallic obj on table	6	0.73	0.72	0.10	2.24
Patient care	5	7.93	5.38	1.72	16.64
Plastic glove	2	0.23	0.15	0.08	0.38
Spoon on plastic plate	1	1.62	-	-	-
Zip	1	0.94	-	-	-
Velcro	1	1.07	-	-	-

Table B.4.: Noise sources from staff during patient care inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Patient noise					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Patient	5	24.99	28.60	0.65	60.00

Table B.5.: Noise sources from patient. Number of recordings in which the sound occurs over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Other devices					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Mobile phone	5	0.27	0.05	0.22	0.36
Clock	4	60.00	-	-	-
TV	1	7.80	-	-	-

Table B.6.: Noise sources from other devices inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Noise from outside patient's room

Room Equipment					
Noise source	**Number of rec/11 rec**	**Mean time (min)**	**SD**	**Min(min)**	**Max(min)**
Rolling cart	8	1.03	1.38	0.12	3.85
Door	7	0.81	0.50	0.20	1.51
Furniture	4	1.12	1.06	0.20	2.90
Cabinet	3	2.13	1.12	1.33	3.71
Metallic rolling cart	1	0.13	-	-	-

Table B.7.: Noise sources from room equipment outside the patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Medical Equipment					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Bleeping	3	0.47	0.31	0.11	0.87
Alarm	2	0.54	0.30	0.24	0.83

Table B.8.: Noise sources from medical equipment outside the patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Staff activity during patient care					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Speech	5	28.62	25.95	0.57	60.00
Kitchen noise	3	20.31	28.06	0.12	60.00
Steps rubber	1	0.06	-	-	-

Table B.9.: Noise sources from staff during patient care outside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Other devices					
Noise source	**Number of rec/11 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Door bell	1	0.14	-	-	-
Crying baby	1	2.98	-	-	-

Table B.10.: Noise sources from other devices outside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Night time

Noise from inside patient's room

Room Equipment					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Cabinet	8	1.97	1.96	0.07	6.55
Rolling cart	7	0.77	0.81	0.04	2.57
Furniture	5	0.46	0.39	0.01	0.96
Door	4	0.22	0.22	0.04	0.58

Table B.11.: Noise sources from room equipment inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Medical Equipment					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Bleeping	10	1.92	2.22	0.12	6.61
Alarm	7	1.36	1.44	0.17	4.43
Respirator	5	48.07	23.86	0.35	60.00
Equipment(pump)	1	60.00	-	-	-
Equipment(fan)	1	2.07	-	-	-

Table B.12.: Noise sources from medical equipment inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Equipment manually operated					
Noise source	Number of rec/12 rec	Mean time(min)	SD	Min(min)	Max(min)
Equipment preparation	6	2.31	0.88	1.05	3.69
Equipment(motor)	3	0.76	0.14	0.57	0.91
Bed elevator	2	0.41	0.06	0.35	0.47
Equipment(fan)	1	0.17	-	-	-
Oxygen mask	1	2.22	-	-	-

Table B.13.: Noise sources from equipment manually operated inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Staff activity during patient care					
Noise source	Number of rec/12 rec	Mean time(min)	SD	Min(min)	Max(min)
Object on table	8	1.01	1.55	0.10	5.01
Speech	7	12.27	15.35	0.70	49.12
Plastic package	7	3.43	5.67	0.38	17.25
Steps	5	1.73	1.99	0.11	5.36
Steps rubber	4	5.04	3.57	1.43	9.14
Apron	4	3.22	2.58	0.63	6.31
Paper	4	0.42	0.26	0.11	0.71
Water tap	4	0.61	0.35	0.17	0.96
Paper towel	3	0.72	0.55	0.23	1.49
Patient care	2	11.67	10.49	1.18	22.16
Plastic glove	2	0.07	0.03	0.04	0.09
Metallic obj on table	1	0.17	-	-	-

Table B.14.: Noise sources from staff during patient care inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Patient noise					
Noise source	Number of rec/12 rec	Mean time(min)	SD	Min(min)	Max(min)
Patient	7	31.15	25.40	0.47	60.00

Table B.15.: Noise sources from patient. Number of recordings in which the sound occurs over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Other devices					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Clock	5	60.00	-	-	-
Radio	1	9.85	-	-	-
TV	1	60.00	-	-	-

Table B.16.: Noise sources from other devices inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Noise from outside patient's room

Room Equipment					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Furniture	7	0.25	0.14	0.10	0.47
Door	6	0.52	0.30	0.09	1.08
Cabinet	5	0.32	0.25	0.07	0.73
Rolling cart	5	0.69	0.36	0.09	1.07

Table B.17.: Noise sources from room equipment outside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Medical Equipment					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Bleeping	2	0.11	0.08	0.03	0.18
Alarm	2	0.39	0.07	0.32	0.45

Table B.18.: Noise sources from medical equipment outside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Staff activity during patient care					
Noise source	**Number of rec/12 rec**	**Mean time(min)**	**SD**	**Min(min)**	**Max(min)**
Speech	4	1.98	1.90	0.17	5.06
Kitchen noise	1	0.38	-	-	-

Table B.19.: Noise sources from staff during patient care inside patient's room. Number of recordings in which the sounds occur over the total number of the recordings. Average, minimum and maximum durations in minutes and Standard deviation.

Tables of the recordings for each room separately

Reference room

Noise from inside patient's room / Day time

Room Equipment									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Cabinet	1	10	17	9	8	9	9	1	17
Rolling cart	0	1	7	1	1	3	2.2	0	7
Furniture	0	3	2	9	0	16	5	0	16
Door	5	6	10	1	0	8	5	0	10

Table B.20.: Noise sources from room equipment inside patient's room in the reference room. Noise sources analytically per recording.

Medical Equipment									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Bleeping	8	18	6	5	7	0	7.3	0	18
Alarm	0	3	14	0	6	0	3.8	0	14

Table B.21.: Noise sources from medical equipment inside patient's room in the reference room. Noise sources analytically per recording.

Staff activity during patient care									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Speech	1	1	1	2	7	1	2.2	1	7
Object on table	0	3	6	11	6	5	5.2	0	11
Plastic package	0	5	11	0	2	18	6	0	18
Metallic obj on table	0	1	8	0	0	2	1.8	0	8
Steps rubber	0	0	1	27	2	1	5.2	0	27
Steps	1	1	1	0	0	25	4.7	0	25
Apron	1	6	1	0	0	0	1.3	0	6
Paper	0	3	3	0	0	11	2.8	0	11
Paper towel	0	2	0	1	2	3	1.3	0	3
Water tap	0	0	1	2	1	0	0.7	0	2

Table B.22.: Noise sources from staff activity inside patient's room in the reference room. Noise sources analytically per recording.

Other devices									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Mobile phone	0	0	2	0	0	0	0.3	0	2

Table B.23.: Noise sources from other devices inside patient's room in the reference room. Noise sources analytically per recording.

Noise from outside patient's room / Day time

Room Equipment									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Rolling cart	8	0	0	0	2	2	2	0	8
Door	9	0	0	0	1	7	2.8	0	9

Table B.24.: Noise sources from room equipment outside patient's room in the reference room. Noise sources analytically per recording.

Staff activity during patient care									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Mean**	**Min**	**Max**
Speech	15	0	0	0	0	1	2.7	0	15

Table B.25.: Noise sources from staff activity outside patient's room in the reference room. Noise sources analytically per recording.

Noise from inside patient's room / Night time

Room Equipment										
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Cabinet	1	16	7	8	1	8	0	6	0	16
Rolling cart	1	1	1	7	0	3	0	2	0	7
Furniture	1	0	2	4	0	4	0	2	0	4
Door	1	0	0	0	1	1	0	0	0	1

Table B.26.: Noise sources from room equipment inside patient's room in the reference room. Noise sources analytically per recording.

Medical Equipment										
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Bleeping	0	19	2	4	12	10	2	7	0	19
Alarm	0	3	4	7	0	3	0	2.4	0	7

Table B.27.: Noise sources from medical equipment inside patient's room in the reference room. Noise sources analytically per recording.

Staff activity during patient care										
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Speech	0	7	2	5	0	6	0	2.9	0	7
Object on table	0	1	1	5	1	3	0	1.6	0	5
Plastic package	0	4	2	4	0	2	0	1.7	0	4
Metallic obj on table	0	0	0	0	0	0	0	0	0	0
Steps rubber	0	13	4	0	0	0	0	2.4	0	13
Steps	1	0	0	5	2	0	0	1.1	0	5
Apron	0	0	0	2	0	1	0	0.4	0	2
Paper	0	2	0	2	0	0	0	0.6	0	2
Paper towel	0	0	0	1	0	0	0	0.1	0	1
Water tap	0	0	0	2	0	0	0	0.3	0	2

Table B.28.: Noise sources from staff activity inside patient's room in the reference room. Noise sources analytically per recording.

Other devices										
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Mobile phone	0	0	0	0	0	0	0	0	0	0

Table B.29.: Noise sources from other devices inside patient's room in the reference room. Noise sources analytically per recording.

Noise from outside patient's room / Night time

Room Equipment										
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Rolling cart	7	0	3	2	0	0	1	1.9	0	7
Door	0	0	5	2	3	2	8	2.9	0	8

Table B.30.: Noise sources from room equipment outside patient's room in the reference room. Noise sources analytically per recording.

Staff activity during patient care									
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Rec.6**	**Rec.7**	**Mean**	**Min**	**Max**
Speech	0	0	0	1	2	1	0	0.6	0	2

Table B.31.: Noise sources from staff activity outside patient's room in the reference room. Noise sources analytically per recording.

Refurbished room

Noise from inside patient's room / Day time

Room Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Cabinet	10	4	7	16	6	8.6	4	16
Rolling cart	2	1	4	1	3	2.2	1	4
Furniture	8	1	1	2	0	2.4	0	8
Door	0	0	0	1	1	0.4	0	1

Table B.32.: Noise sources from room equipment inside patient's room in the refurbished room. Noise sources analytically per recording.

Medical Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Bleeping	22	5	9	10	3	9.8	3	22
Alarm	2	0	7	0	0	1.8	0	7

Table B.33.: Noise sources from medical equipment inside patient's room in the refurbished room. Noise sources analytically per recording.

Staff activity during patient care								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Speech	4	11	5	1	2	4.6	1	11
Object on table	3	3	8	4	5	4.6	3	8
Plastic package	2	3	2	7	2	3	2	7
Metallic obj on table	0	1	2	3	0	1.2	0	3
Steps rubber	1	3	0	1	4	1.8	0	4
Steps	4	5	3	0	2	2.8	0	5
Apron	4	0	7	3	1	3	0	7
Paper	3	0	2	3	2	2	0	3
Paper towel	5	0	5	3	1	2.8	0	5
Water tap	5	0	2	3	1	2.2	0	5

Table B.34.: Noise sources from staff activity inside patient's room in the refurbished room. Noise sources analytically per recording.

Other devices								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Mobile phone	1	1	1	1	0	0.8	0	1

Table B.35.: Noise sources from other devices inside patient's room in the refurbished room. Noise sources analytically per recording.

Noise from outside patient's room / Day time

Room Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Rolling cart	2	1	1	1	9	2.8	1	9
Door	0	10	5	1	7	4.6	0	10

Table B.36.: Noise sources from room equipment outside patient's room in the refurbished room. Noise sources analytically per recording.

Staff activity during patient care								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Speech	0	1	0	1	8	2	0	8

Table B.37.: Noise sources from staff activity outside patient's room in the refurbished room. Noise sources analytically per recording.

Noise from inside patient's room / Night time

Room Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Cabinet	0	12	24	0	0	7.2	0	24
Rolling cart	0	2	1	0	0	0.6	0	2
Furniture	1	0	0	0	0	0.2	0	1
Door	0	0	2	0	0	0.4	0	2

Table B.38.: Noise sources from room equipment inside patient's room in the refurbished room. Noise sources analytically per recording.

Medical Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Bleeping	7	13	20	0	2	8.4	0	20
Alarm	0	3	14	0	1	3.6	0	14

Table B.39.: Noise sources from medical equipment inside patient's room in the refurbished room. Noise sources analytically per recording.

Staff activity during patient care								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Speech	0	6	5	0	4	3	0	6
Object on table	0	4	3	0	1	1.6	0	4
Plastic package	0	6	11	0	4	4	0	11
Metallic obj on table	0	0	1	0	0	0.2	0	1
Steps rubber	0	8	4	0	0	2.4	0	8
Steps	0	0	7	2	0	1.8	0	7
Apron	0	2	6	0	0	1.6	0	6
Paper	0	1	0	0	1	0.4	0	1
Paper towel	0	1	3	0	0	0.8	0	3
Water tap	0	3	2	0	1	1.2	0	3

Table B.40.: Noise sources from staff activity inside patient's room in the refurbished room. Noise sources analytically per recording.

Other devices								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Mobile phone	0	0	0	0	0	0	0	0

Table B.41.: Noise sources from other devices inside patient's room in the refurbished room. Noise sources analytically per recording.

Noise from outside patient's room / Night time

Room Equipment								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Rolling cart	0	0	0	5	0	1	0	5
Door	0	0	0	0	1	0.2	0	1

Table B.42.: Noise sources from room equipment outside patient's room in the refurbished room. Noise sources analytically per recording.

Staff activity during patient care								
Rec.	**Rec.1**	**Rec.2**	**Rec.3**	**Rec.4**	**Rec.5**	**Mean**	**Min**	**Max**
Speech	0	0	0	2	0	0.4	0	2

Table B.43.: Noise sources from staff activity outside patient's room in the refurbished room. Noise sources analytically per recording.

C. Perceptual characteristics

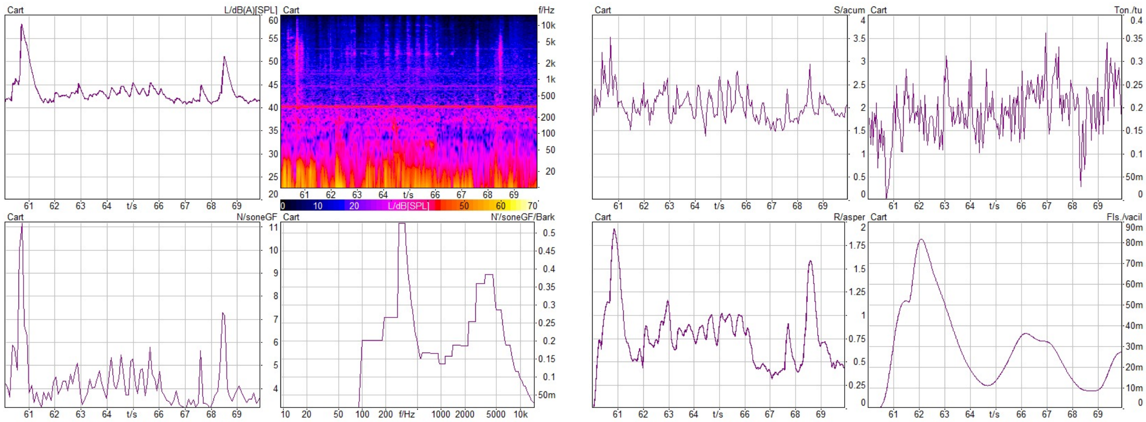

Figure C.1.: LAF, Spectrogram, Loudness Time History and Specific Loudness (left) and Sharpness vs Time, Roughness vs Time, Tonality vs Time and Fluctuation strength vs Time (right) of a rolling cart sound.

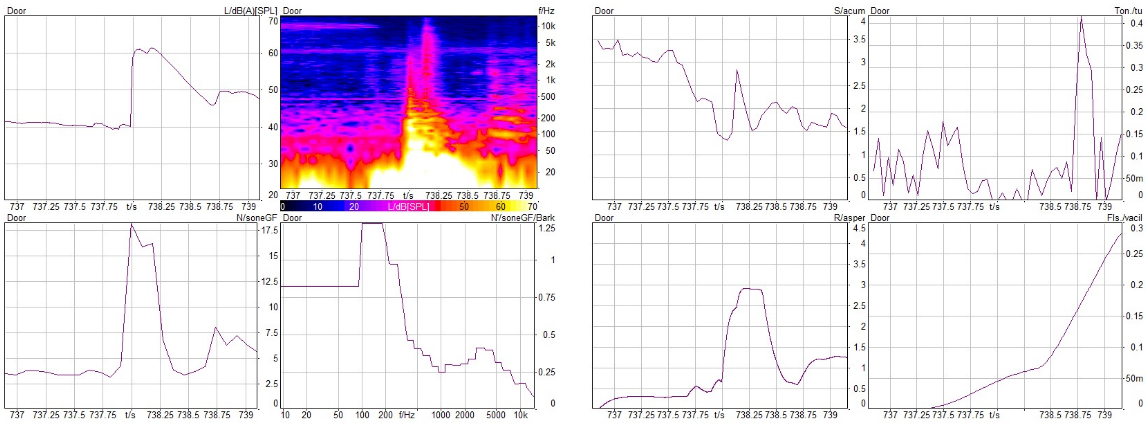

Figure C.2.: LAF, Spectrogram, Loudness Time History and Specific Loudness (left) and Sharpness vs Time, Roughness vs Time, Tonality vs Time and Fluctuation strength vs Time (right) of a slamming door sound.

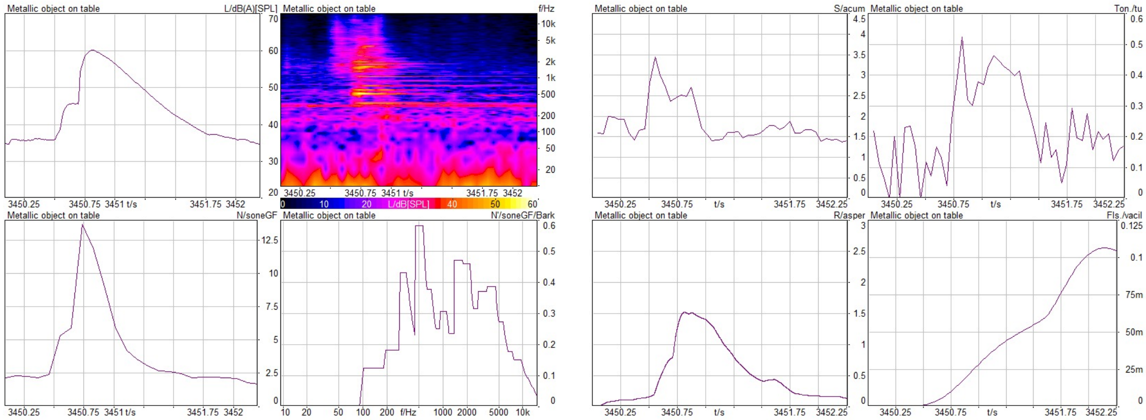

Figure C.3.: LAF, Spectrogram, Loudness Time History and Specific Loudness (left) and Sharpness vs Time, Roughness vs Time, Tonality vs Time and Fluctuation strength vs Time (right) of a metallic object hit on table sound.

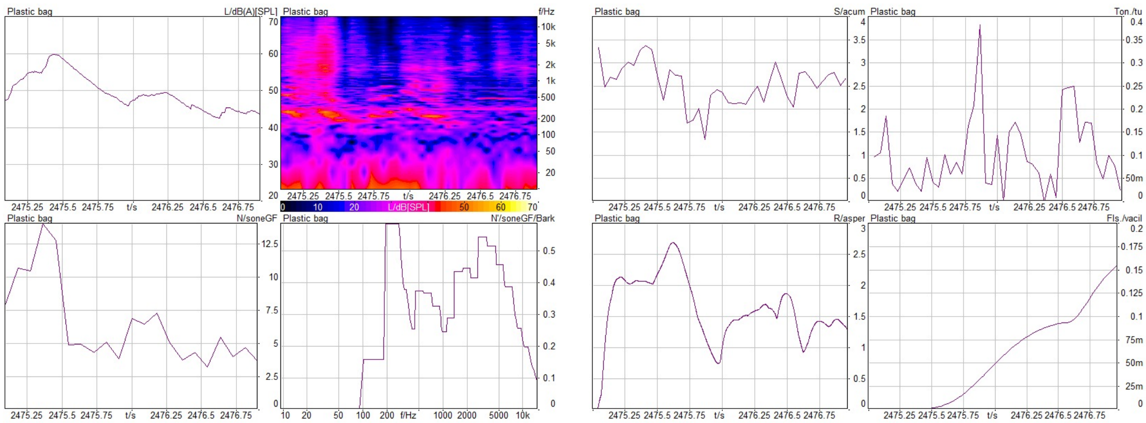

Figure C.4.: LAF, Spectrogram, Loudness Time History and Specific Loudness (left) and Sharpness vs Time, Roughness vs Time, Tonality vs Time and Fluctuation strength vs Time (right) of a plastic package sound.

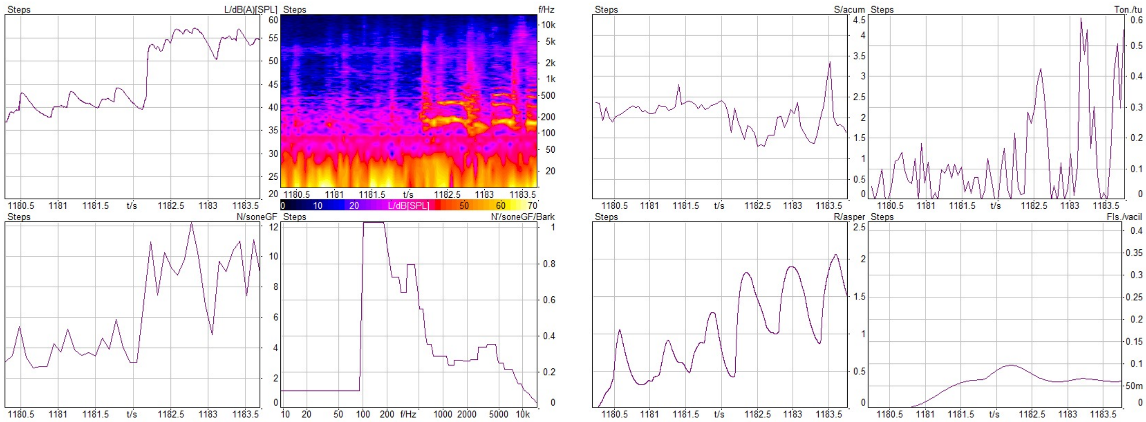

Figure C.5.: LAF, Spectrogram, Loudness Time History and Specific Loudness (left) and Sharpness vs Time, Roughness vs Time, Tonality vs Time and Fluctuation strength vs Time (right) of steps sound.