# Towards a quieter neonatal intensive care unit: evaluating and visualizing soundscapes to raise awareness on sound-producing events

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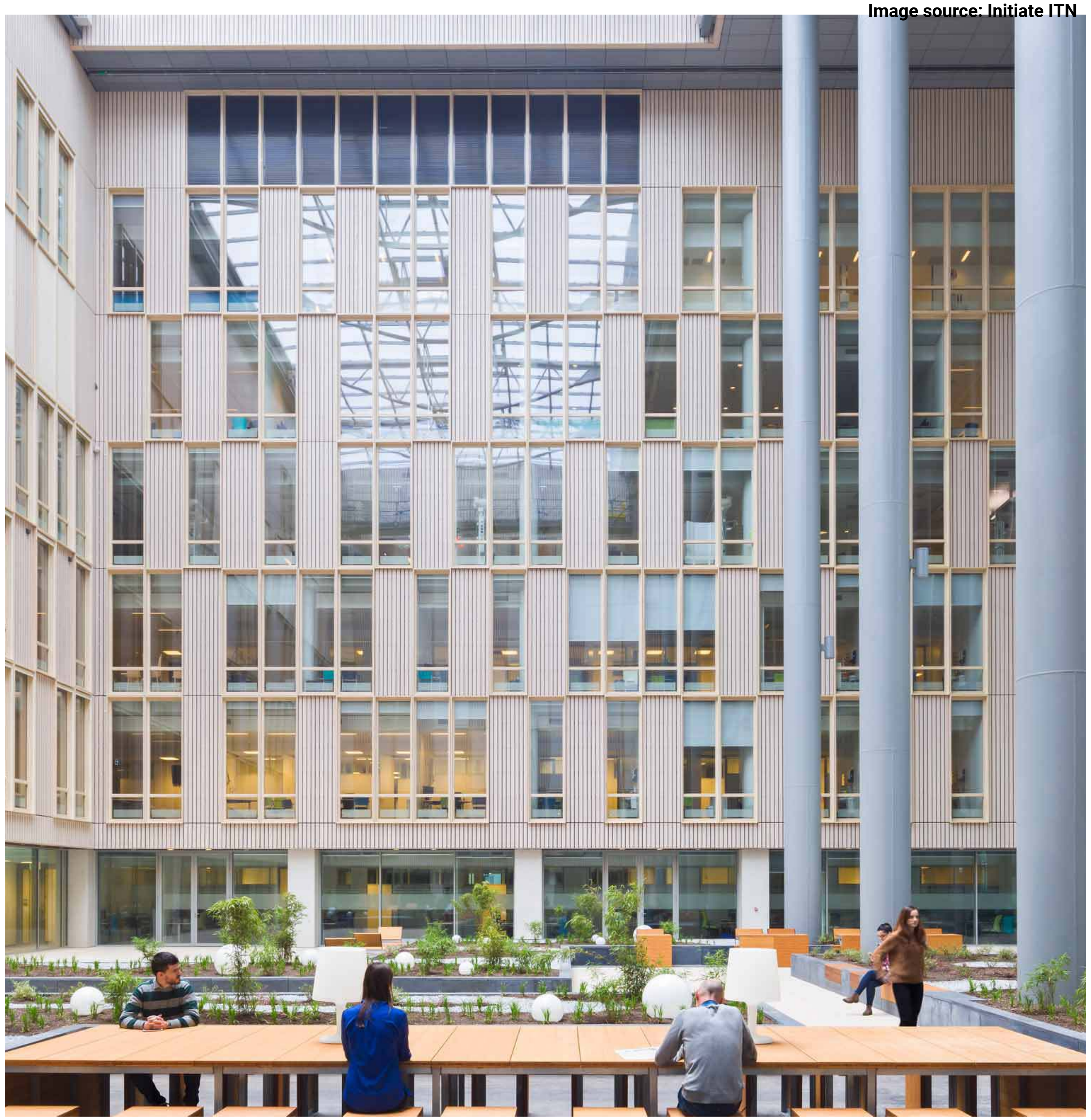
Núria Viñas Vila

**Image source: EGM architecten**

Image source: Initiate ITN



# Executive summary

A soundscape is the acoustic environment that is constantly surrounding us. Soundscapes in the neonatal intensive care unit (NICU) might adversely affect neonates, their families, and healthcare providers. In this unit, the number of alarms and nuisance is very high, and studies show that it negatively affects both the well-being of patients and the performance of healthcare professionals (Bliefnick, Ryherd, Jackson, & 2019). Additionally, elevated sound levels in the NICU may contribute to undesirable physiologic and behavioral effects in infants. Hearing impairment, heart rate, blood pressure, oxygen saturation, respiratory rate, and sleep were all deteriously affected (Zimmerman & Lahav, 2013).

Sound studies within NICUs have only focused on short-term outcomes such as monitoring sound levels in decibels (dB) and reporting the results, with no further implication. Current market solutions give only feedback on high dB levels, limiting medical professionals' complete understanding of the cacophonous environment. Additionally, they rely on counting sound in dB, discarding the effect of tone and frequency. Therefore, the problem with the dB measure is that it represents only one part of the complex sound taxonomy. Still, interpreting sound beyond dB is challenging to understand for people who are unfamiliar with the physics of sound.

SOUNDscapes is a digital platform that maps and localizes sound events occurring at the NICU. It displays sound trends in real time and assesses the quality of the environment by having two main visualization pages: sound level trends and constellation map.

The goal of providing real-time feedback is to make nurses aware of specific (sound) behaviours and their consequences. Additionally, they can assess and observe their collective impact on the unit. This dashboard motivates them to change their attitudes towards harmful sound events by ultimately triggering a behaviour change. The dashboard is a tool that will help nurses understand, assess and change their sound behaviour and patterns of harmful sound sources, ultimately having valuable feedback for reducing high sound levels at the unit.

First, the proposed solution provides the first step for permanent sound monitoring, mapping, and visualising real-time sound-producing events. Additionally, supporting nurses and giving them the confidence to act upon harmful sound sources occurring at the NICU. Secondly, the suggested design, apart from advocating for a nurse's sound quality, is also a tool that can go beyond their caring role.

For the Neonatology department at ErasmusMC, this platform means a new source of data streams that healthcare developers can use for measuring and evaluating the care quality they are delivering. The new system provided opens new research possibilities in the future that will allow researchers to link the quality of the physical sound environment to physiological and psychological effects on listeners.

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Chapter 1

# Introduction



## Chapter introduction

This chapter introduces the context of this project and the problems that it aims to solve. Additionally, an overview of the approach is visualised.

# 01
# Introduction

### 1.1 Assignment introduction

A soundscape is the acoustic environment that is constantly surrounding us (Southworth, 1969). We, as a society, have developed a certain tolerance towards these sounds and noises, and to some extent, they are not extraordinary for us anymore. Yet, some of them are very harmful.

Studies have shown that noise pollution has adverse effects on many populations, starting from the fetus, infants, children, adolescents to adults (Gupta et al., 2018). Among different areas, hospitals are unique places where soundscapes are particularly difficult to assess. Some examples of noises are caused by the continuous activities of visitors and patients, by medical alarms and instruments. Moreover, professionals' hectic activity generates a tremendous amount of nuisance.

In complex sonic environments, people are unaware of the noise they produce or the noise they are exposed to. There is an urgent need to create a shared awareness about the sound pollution that individuals generate and the tolerance towards the sound. Inside the hospital's ecosystem, there are several environments worth investigating.

This project will focus on the Neonatal Intensive Care Unit (NICU). Compared to adult ICU, NICU is carefully designed for premature new-borns who need assistance to survive and whose likelihood of getting sick is very high. It has the technology and trained healthcare professionals that can take care of the babies (Standford Children's Health, 2021). In this unit, the number of alarms and nuisances is very high, and studies show that it negatively affects both the well-being of patients and the performance of healthcare professionals (Bliefnick et al., 2019). The way we can monitor and communicate these soundscapes at NICU is the starting point of this thesis.

**Problem statement**

As stated above, soundscapes in NICU might adversely affect neonates, their families, and healthcare providers. Sound studies within NICUs have only focused on short-term outcomes such as monitoring sound levels in decibels (dB) and limiting on just reporting the results, with no further implications. Current market solutions give only feedback on high dB levels, limiting medical professionals' complete understanding of the cacophonous environment - an environment with an unpleasant composition of sounds. Merely measuring sound in dB discards the effect of sound tone and fequency. The problem with the dB measure is that it represents only one part of the complex sound taxonomy. Still, interpreting sound beyond dB is challenging to understand for people who are unfamiliar with the physics of sound.

**Solution space**

Previous projects from the Critical Alarms Lab (CAL) had monitored sound individually, investigating how staff members in the NICU environment experience sound (Lee, 2019; Y. Liu, 2020). However, this design project aims to monitor and map sound collectively rather than in individual moving objects. The overarching goal is to make sound understandable for individuals working mainly at NICU, such as nurses. The proposed solution collects sound data to detect and map sound-producing events in the space, while also representing the areas most affected. The new system provided opens new research possibilities in the future that will allow researchers to link the quality of the physical sound environment to physiological and psychological effects on listeners.

**Research question**

Given the explained background of the project, a research question was proposed, followed by sub research questions. The main research question and sub-questions were used as guidelines in different phases of this thesis.

Main research question (RQ):

**"How can medical staff and individuals at the NICU be supported through sound monitoring for their sound wellbeing?"**

Sub research question 1: How have studies monitored sound levels in NICU to assess the sonic environment?

Sub research question 2: How can sound be interpreted and monitored by smart technologies?

Sub research question 3: How can the avoidance of sound pollution be promoted through behaviour change techniques?

Sub research question 4: How can we enable human computer interaction for medical staff without overwhelming them with technology?

### 1.2 Project stakeholders

**TU Delft**

This project is realised in collaboration with three parties: Delft University of Technology (TU Delft), Critical Alarms Lab (CAL) and Erasmus University Medical Center (ErasmusMC). This thesis is the final module for obtaining the master's in Strategic Product Design from the Industrial Design Engineering faculty (IDE) at TU Delft, as well as part of the Medisign healthcare programme.

**Critical Alarms Lab**

The Critical Alarms Lab (CAL) is part of the Delft Design Labs and aims to shape the future of alarms and soundscapes in socio-technological environments. One of the focuses that the lab has is in healthcare, where it investigates and explores the urgent needs of alarms at Intensive Care Units (ICU).

**ErasmusMC**

Erasmus MC is one of the largest academic tertiary referral hospitals in the Netherlands. With its roots in Rotterdam, it treats patients with complex healthcare issues and rare diseases. Highly known internationally and recognized as one of the best hospitals in Europe, Erasmus MC is dedicated to improving our understanding of diseases and their prediction, prevention, and treatment. Formally founded as Erasmus MC in 2002, as part of Erasmus University Rotterdam and Rotterdam University Hospital, the hospital will soon celebrate its 55th anniversary.

**Erasmus MC Sophia Children's Hospital**

Under the umbrella of Erasmus MC, multiple important specialised centres, one of which is the Erasmus MC Sophia Children's Hospital. This hospital provides care from premature infants to teenagers up to 18 years old. It has multiple departments highly specialised depending on the child's condition. Among different departments such as general paediatrics, child psychiatry and paediatric cardiology, this thesis is developed in the context of the Neonatal Intensive Care Unit (NICU). NICU provides high care to infants born with acute conditions or to premature infants who need vital assistance.


Figure 1: strategy Course23 based on technology and dedication

## Project approach

This project is performed from a strategic design perspective. The research approach guiding this project is the double diamond (Design Council, 2005), a leading design methodology commonly introduced at the faculty of Industrial Design Engineering at TU Delft.

This innovation model is not linear since it allows for iterations, diverging to explore the thinking and converging to set the focus. The model is presented in two diamonds and is divided into four phases: discover, define, develop and deliver. Figure 2 shows how this thesis has followed the double diamond.

<u>Discover</u>
In the discovery phase, the three first chapters are introduced. The goal of this phase is to understand and explore the research question that has been formulated. By conducting literature research and performing a semi-systematic review, knowledge gaps from literature emerged.

<u>Define</u>
This second phase involves three chapters. The goal is to understand the users, their context, and the technology that will enable the design intervention. Observations and interviews are performed to study nurses as primary users. The insights gathered from the knowledge gaps in phase one, user insights and technology scouting, lead to the opportunity areas. These areas manifest potential design focus where the project can develop further.

<u>Develop</u>
This phase consists of two chapters. The first one, where design requirements are listed, then a design goal is formulated, and an ideation phase explores multiple design solutions. The chapter concludes with one design concept selected. The second chapter elaborates on the design concept.

<u>Deliver</u>
The last phase involves the evaluation and conclusions chapter. The goal of the evaluation chapter is to, on one side, test the design concept with expert interviews, and on the other side, test the impact that the design intervention has on nurses. The last chapter elaborates on implications about the design and suggests future recommendations.





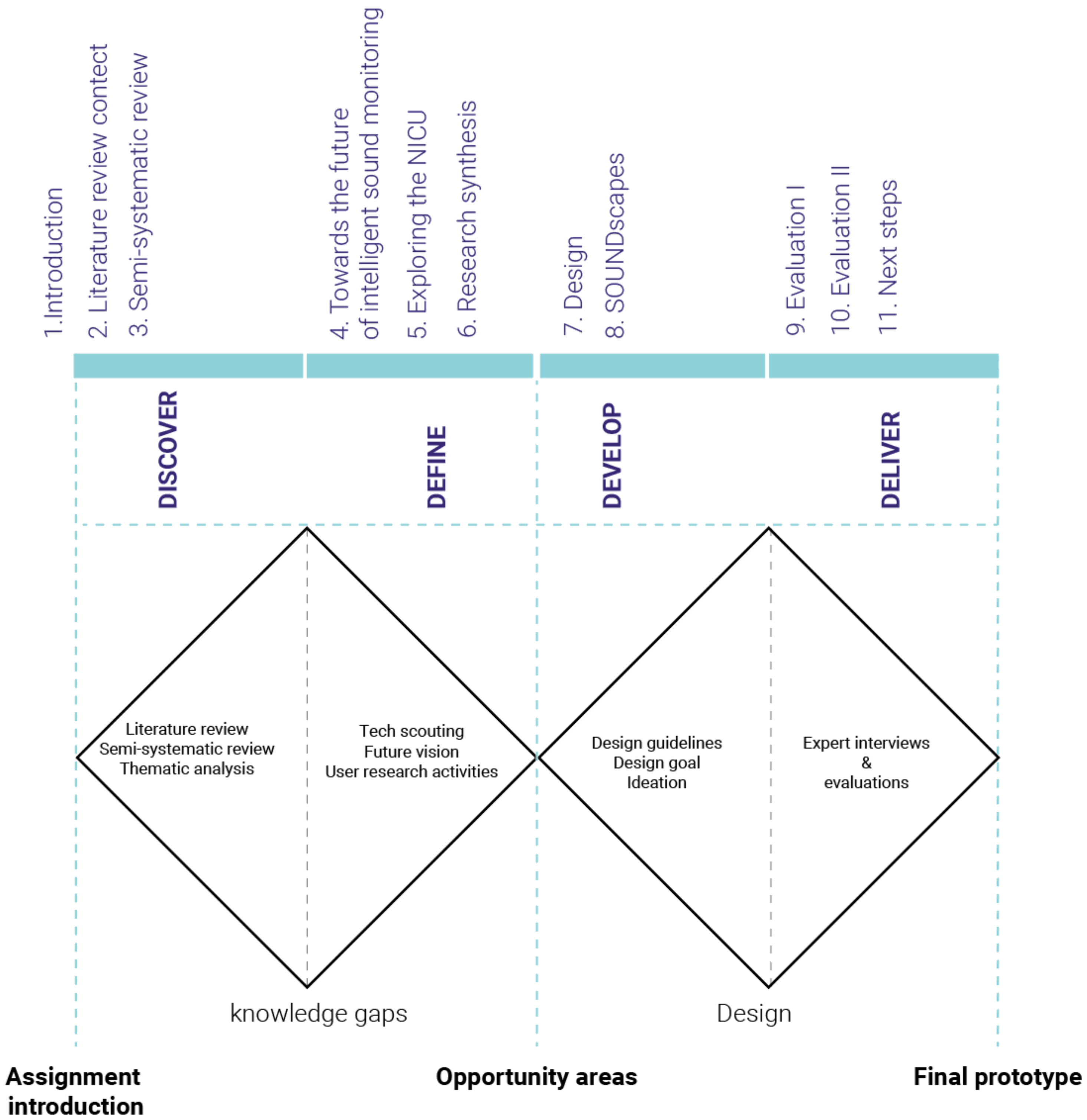


Figure 2: design process followed.

2

Chapter 2

## Literature review context



## Chapter introduction

This chapter deepens on the project and its underlying problems. It gives an overview of what has been researched so far, and which is the current situation concerning high sound levels in hospitals.

# 02
# Literature review

### 2.1 Soundscapes as a phenomenon in society

**Introduction**

The term soundscape has been defined as "the relationship between a landscape and the composition of its sound" (Pijanowski et al., 2011). The first uses of this term in literature come from Southworth (1969), where he defines it as the "overall sonic environment of an area, from a room to a region". His work explored the sonic environment in urban areas and the perception that citizens had from it. Later, Schafer (1977) argued about how design could be used to improve the acoustic environment by eliminating sound through noise reduction methods. Some of these methods were later introduced by Brown and Muhar (2007) who claimed that sound monitoring could use strategies for action: "control the sound source, manage the transmission path between source and receiver, and protect the receiver".

The interest in acoustic environments and the study of noise levels indicated a need to reduce sound levels regardless of the place. Even though some of the first strategies had an architectural approach, methods such as staff behaviour and redesign of key elements were used for reducing the hospital's cacophonous environment (Elander & Hellström, 1995; Graven & 2000; M. K. Philbin & Gray, 2002). The continuous sound exposure that people had to face in their daily lives was proved to cause them sleep disturbance, cardiovascular diseases, and impact on their mental health (WHO, 1999).

Currently, there is an increasing need to quantify how all the environmental sounds negatively affect people and stay within limits established by the World Health Organisation (WHO). According to this organization, data collected in European Countries shows that 40% of people in urban areas are exposed to sound levels exceeding 55 dB (A) at daytime, and 20% are exposed to even higher levels exceeding 65 dB (A). Moreover, during nighttime, levels are reported to be 55 dB (A) which goes beyond the established limits and can cause sleep disturbance.
Besides, considering the physics of sound, it is also important to consider how humans perceive all these sounds.

**Humanising sound**

Sound is created by any source of vibration, generating sound waves, and thus transporting energy that travels through the air or any other medium. The perception that we have about sound depends on: vibration source to form sound wave, the medium and the receiver to detect the sound producer (Vinod & Nayak, 2016). Additionally, there are different aspects that differentiate sound: its amplitude, frequency, and wavelength. Additionally, frequency and intensity can also be divided depending on the physical phenomena (frequency and intensity) or the physiological phenomena (loudness and pitch).

Frequency, also referred to as the pitch of sound, measures the sound vibrations in one second and it is reported in Hertz (Hz). Amplitude measures the loudness of a sound; it is reported in decibels (dB) and it is measured in a logarithmic scale. This scale means that if the human ear perceives a sound of 30 dB and an increase of 10 dB, so in total 40 dB, it will be perceived as 10 times louder (Sataloff & Sataloff, 2006). Regarding sound frequency, the spectrum in which the human ear can hear go from 20 Hz to 20 kHz (Purves, Augustine, & Fitzpatrick, 2001).

**Sound psychoacoustics**

As mentioned in the previous section, sound can be interpreted either through its physical or physiological component. Sound psychoacoustics is a scientific field that is described as "the relations between the physical representation of sounds and the hearing sensations elicited by them"(Fastl, 2006). Therefore, psychoacoustics measures such as loudness, sharpness, fluctuation strengths, and roughness are used (Fastl, 2006).

For instance, in one study, subjects from Germany and Japan were given the sound of a bell. German subjects were, it reminded of the sound of a church bell, and therefore it had pleasant connotations. Contrary to Japanese subjects, which the bell reminded of a fire engine, inducing to dangerous or unpleasant connotations (Fastl, 2006). This also applies to sound occurring at neonatal intensive care units, where the diversity of noise from equipment, medical devices and staff can vary on the physiological perception depending on the subject (Czaplik et al., 2016).

### 2.2 Hospitals that make us sick

Hospitals are the most susceptible areas where extra attention needs to be paid. The concept in itself is a paradox. Hospitals are the places where most of the people come to the world, and unfortunately, leave. A place where ill patients go to receive better care, but instead it is filled with sound threats that prevent them from recovering. Thus, potentially making their stay longer. Despite the many attempts of the healthcare providers in reducing the cacophonous environments in hospitals, in four decades, it loudness has increased about 20 dB, as seen in figure 3. Figure 3 plots how the dB levels have increased throughout eleven years.

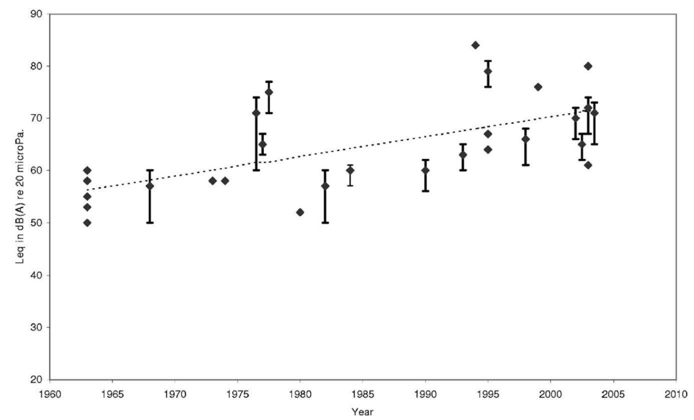


Figure 3: sound pressure levels measured in hospitals during daytime hours (Busch-Vishniac et al., 2005)

On the one hand, the US Environmental Protection Agency (USEPA) recommends that sound pressure levels in hospitals should be limited to 45db during the day and to 35 dB during the night (EPA, 1974). However, hospitals are busy environments with a continuous in and out of patients, families, medical staff, medical equipment, and alarms. Thus, complex to reduce since it is hard to monitor such an unpredictable sound environment. Specific units in hospitals need to be more controlled in terms of the acoustic environment. Patients are more vulnerable and have fewer capabilities to cope with the stress that noise might cause. For instance, rooms, where patients are treated and visited, cannot exceed 30 dB (WHO).

This specific interest in monitoring sound pressure levels has existed for some quiet time now. Back in the days, it was showed that loud sound levels in our environment could negatively affect people; therefore, the awareness in places where people were in more vulnerable situations increased, such as in hospitals. In the early 1970s (Lawson, Daum, & Turkewitz, 1977), there were already studies quantifying the importance of good sound quality in hospitals. Specifically in intensive care units where sound hazards could alter patient's sleep and interfere in their recovery.

### 2.3 Neonatal Intensive Care Unit (NICU)

**Urgent need**

Regardless of the sound monitoring studies in hospitals in general, each department needs to be evaluated separately and independently. Implementations that work in emergency rooms (ER) might be difficult to follow in NICU and vice versa. However, NICU patients are more fragile and weaker compared to other patients in other units. When they arrive at NICU, preterm infants are not necessarily sick; nonetheless, they need special care to grow and survive.

Their likelihood of getting sick is much higher since their bodies are not fully developed. On top of that, they are likely to experience physiologic limitations, central nervous system limitations, and dependency on intensive care, which makes them vulnerable to the whole NICU acoustic environment (Blackburn, 1998).

Figure 4: infant being treated inside an incubator

**Initial studies in sound monitoring: What has been done so far?**

Preliminary studies in literature in the 1970s (Lawson et al., 1977) responded to concerns regarding the importance of sound in the NICU. Later in the 1990s, there was an increased awareness of how the environmental stimuli affected neonates' clinical conditions and their neurodevelopment (Philbin et al., & 2000).

Back in those times, sound in NICU was reported to be between 58 dB and 66 dB inside rooms and reported ranges from 59 dB to 67 dB inside incubators with peak values of 88 dB, which is very high. Such levels are at least 10 points higher than the NICU guidelines that the American Academy of Pediatrics (AAP) suggests. On average, sound levels in NICU should not be higher than 45 dB.

Thomas and Uran (1989) conducted a sound monitoring study and concluded that most of the sounds found were related to medical equipment and nurses' activities. The outcome of their study also matched with Elander's and Hellström's (1995) findings, which demonstrated that the main sound sources were conversations between care personnel and between parents and care personnel. Figure 5 exposes in dB the levels that care activities, alarms and unintended actions can cause and help to make an estimation of the impact of such sound events.In the early 2000s studies continued to provide more direct measurements from the monitoring studies.

After almost two decades, Thomas and Uran (2007) decided to update their study. They compared the current noise levels in 2005 back to the ones they monitored in 1989. Figure 6 provides the comparison between sound levels at the room and inside the incubator. From their study they concluded that overall, sound intensity was lower mostly outside the incubator areas. However, for the rest of the areas, sound intensity was found to be the same or even higher.

| *Within NICU* | *Decibel Level* |
|---|---|
| One nurse reporting to another at the bedside | 50 |
| Bradycardia alarm | 55-88 |
| General conversation | 58-64 |
| Using incubator top as writing surface | 59-64 |
| IV pump alarm | 61-78 |
| Turning sink on and off | 66-76 |
| Opening plastic sleeve of incubator | 67-86 |
| Closing an isolette cabinet | 70-95 |
| Closing a solid plastic incubator porthole | 80-111 |
| Dropping head of mattress | 88-117 |
| Placing bottle of formula on top of the incubator | 96-117 |
| Banging incubator to stimulate apneic premature infant | 130-140 |

Figure 5: decibel values for routine activities in neonatal ICU (Bremmer, Byers, & Kiehl, 2003)

Sound studies at NICU continued throughout the years, yet providing the same recommendations: redesigning rooms considering sound attenuating materials, implementing educational noise programmes and using earmuffs on neonates to increase their sleep quality (Darbshire & Young, 2013; Fernandez.,2018). Nonetheless, a study from Darbshire and Young (2013) already envisioned that smart alarm systems could be a potential solution to address high sound levels at NICU.

**Implementation of behaviour change strategies**

Among recommendations such as structural changes and using earmuffs, behaviour change strategies and the implementation of educational programmes is a recurrent pattern in literature. For instance, Elander and Hellström (1995) implemented a noise reduction program at NICU that consisted of three parts: watching a child's post-operation care assistance, reviewing decibel values for different care activities, and discussing the issue observed in the first two steps. Three months after the program, they reported a significant noise reduction in cots. However, one year later the sound levels were the same as prior to conducting the experiment.

The downside of implementing behaviour programs is their sustainability throughout the time. Even though studies attempt to change people's behaviour, they monitor sound levels for a short period and report the improvements. In fact, some of the limitations that these studies presented are related to their continuity. Suggestions are to repeatedly use the same method until nurses and families get used to talking within acceptable sound ranges, but this is like leaving open strings and does not ensurecontinuity of the new, improved behaviour

| Location | Sound | 1989 dB(A) | 2005 dB(A) |
|---|---|---|---|
| Room | Quiet | 58-62 | 47 |
| | Talking | 58-64 | 49 |
| | Radio | 60-62 | 53 |
| | Sink faucet | 66 | 57 |
| Incubator interior | Writing on hood surface | 59 | 62 |
| | Incubator alarm | 67 | 68 |
| | Motor off | 38-42 | 38 |
| | Motor on | 55 | 60 |
| | IV pump alarm | 56 | 61 |

Figure 6: study from Thomas and Uran comparing dB levels from both studies in the 1989 and 2005 (Thomas & Uran, 2007).

**Smart behaviour change**

A latent part of this thesis is the behaviour change elements that are needed to change people's attitude towards soundscapes. In literature, there are various scientifically proven theories under the same umbrella of behaviour change. For instance, the theory of health beliefs (Rosenstock, 1974), change of noise producing behaviour (Ikaö, 2010) and theory of planned behaviour (Ajzen, 1991).

The theory of planned behaviour suits to this thesis context because it sees "an individual's beliefs about the consequences of a behavior as one major reason for performing that behavior"(Oinas-Kukkonen et al., 2019). Figure 7, shows the interconnections between the framework's components.

However, one of the main problems with following behaviour change models is the implementation in their context. The cause of this misfit is that all behavioural change models are models to map all of the factors contributing to a behaviour change, rather than a method to make a change effective.

Therefore, models are used as lose inspiration rather than something methodological. It is unnecessary to follow the same order as shown in figure 6.Instead, you can first change behaviour and then let the attitudes change, then let the belief change followed by the behavioural change. This same explanation applies to the behaviours that occur within NICU. However, in this thesis I use persuasive technology as a smart component to enhance behaviour change, and influence humans experiences and practices at the NICU (Verbeek, 2009). The overarching concept of persuasive technology and behaviour changes is shown in figure 8, in the persuasive technology framework.

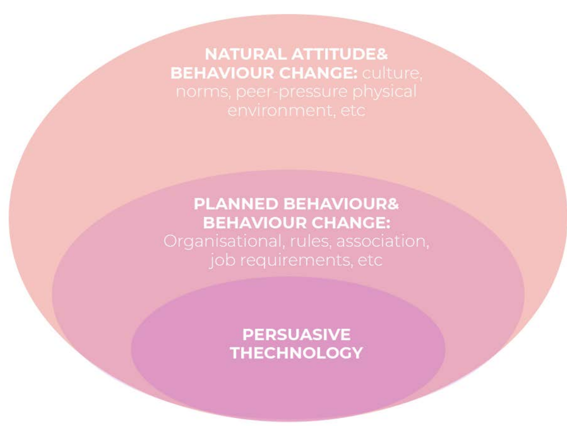


Figure 8: Persuasive technology onion(Wiafe, Nakata, & Gulliver, 2011)

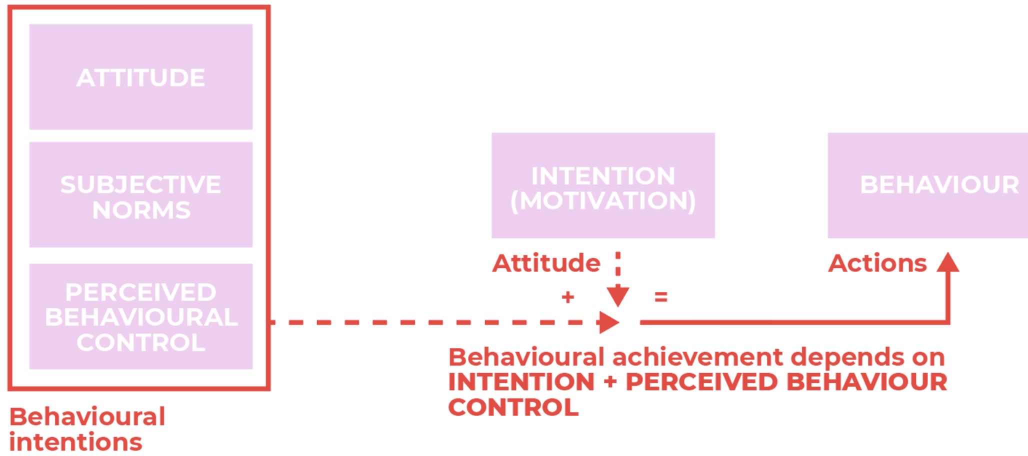


Figure 7: Theory of planned behaviour (Ajzen, 1991)

## Chapter conclusion

Initial literature research has shown that high sound levels at NICU have been an issue in the psychoacoustic environment for almost four decades. The strive from scientists but also from medical professionals in changing this situation is evident. However, the proposed recommendations, such as structural redesigns and educational programs, might not be that easy to implement. On one side, for obvious reasons, structural change is mainly restricted to the space available and budget from the organisation. On the other side, behaviour interventions that promote accepted sound-related practices are challenging to maintain.

Chapter 3

## Semi-systematic review





## Chapter introduction

The literature research presented in chapter 2 gave some insights into the main components of this thesis: a complex sound problematic at NICUs, behaviour change and persuasive technology components. This project aims to provide a novel solution that will address the unsolved issue of sound at NICUs. Therefore, a semi-systematic review was conducted to examine the studies performed at NICU, how they were executed, and the outcome they provided.

# 03
# Semi-systematic review

### 3.1 Methodology
The literature review evidenced many studies providing the same knowledge and making an attempt to control soundscapes at NICU. However, given the initial take-aways that monitoring studies usually make a very basic sound interpretation, a semi-systematic literature review was performed to investigate which sound monitoring studies had been conducted at NICU and to see how this thesis could identify knowledge gaps and translate them into market opportunities.
The semi-systematic review was conducted based on the Systematic review process framework, although with slight adaptations. Unlike systematic literature reviews a semi-systematic literature review examines the research areas and follows their evolution over time, has a broad research question, and concludes with themes from the literature (Snyder, 2019).

Scoping
The scoping phase started by identifying relevant studies in the NICU field. The research from (Graven, 2000) was an anchor point from the literature. This paper provided references that were either cited in this paper or that cited this paper.

Planning
The planning phase includes the search strategy and keywords used to find relevant literature. The search engines used were Google Scholar, Research Gate and PubMed. Regarding the keywords the combination "sound monitoring NICU" was the mainly used one.

Identification-search process
In this step the main search was performed based on the strategy established in the first two steps. A total of 100 papers were identified.

Screening articles
Once all the research articles were identified, the reference manager EndNote was used to create the reference list. Duplicated papers were eliminated. Moreover, a table was also created to generate an overview of different factors that were considered relevant and could hinder potential themes among the research. Such factors were: type of listener, methodologies used for assessment, which effect the study was measuring and type of study.

Eligibility assessment
In this step, the final articles were selected following the criteria of only including articles that had conducted research in monitoring sound levels at NICU and that they had reported the corresponding sound levels.

Interpretation presentation
The final sample included 30 papers. Once the 30 papers were gathered, I selected a method to analyse the data. Figure 9 shows an overview of the process. Thematic analysis was conducted to analyse all the qualitative data. This qualitative data method consists of identifying, analysing, and reporting patterns in the form of themes (Braun & Clarke, 2006). The identifying phase consisted of writing codes, also known as labels, in the data (literature papers) and concluded with a total of 373 codes. Atlas.ti 9 software was used for the coding phase. Once codes were written in all documents, categories were formed from patterns that emerged in the literature (see appendix A). The total number of categories was 21. Lastly, categories were clustered in four themes. When interpreting and explaining the themes, the insights that emerged where translated into knowledge gaps, further explained in subsection 3.6. Later, these knowledge gaps were turned into potential market opportunity areas where this thesis could build on and that are presented in chapter 5.

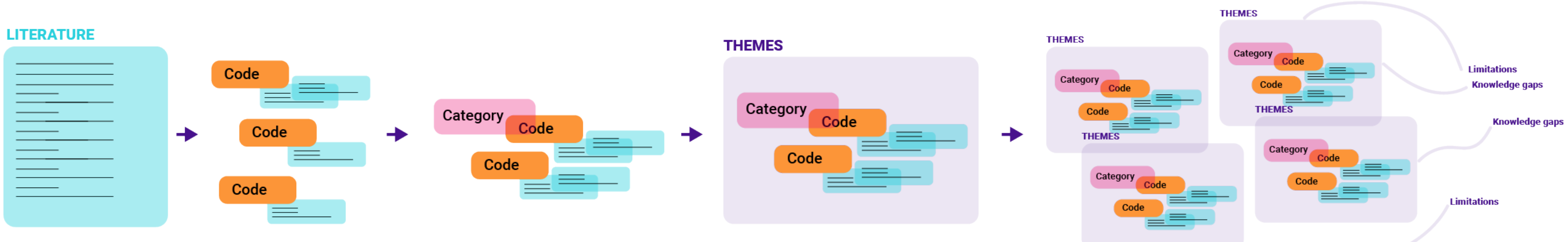


Figure 9: thematic analysis followed for analyzing the semi-systematic review data.





### 3.2 Results
Below there is an overview of the four themes that emerged from the thematic analysis. In each theme, the titles of the categories they belong to are listed and also the codes each category has are marked in between brackets.

Theme 1: collecting and processing sound
Length of the study (22)
Analysing the results (17)
Measurement intervals (6)
Sound outcome variables (17)
Calibration of the devices (5)
Monitoring devices (13)

Theme 2: environment distribution and description
Sound organisations (8)
Placing the device (7)
Occupancy in the NICU (14)
Selecting the monitoring area (10)
Comparing NICU environments (6)

Theme 3: sound interactions
Sound control (9)
Environmental non-acoustic variables (9)
Staff advocating for NICU (7)
Smart environment (5)
Sound source in NICU (16)

Theme 4: beyond sound and observed measures
Bias from people (13)
Implementing behavioural change (15)
Sound assessed qualitatively (9)
Structural change (12)
Sound education (6)

When analysing and elaborating on the themes, it was observed that each theme would lead to various insights. Consequently, insights were created which provided knowledge gaps and limitations. Table 1 presents an overview.

| THEMES | INSIGHTS | KNOWLEDGE GAPS | LIMITATIONS |
|---|---|---|---|
| T1: collecting and processing sound | Insight 1<br>Insight 2<br>Insight 3 | Knowledge gap<br>Knowledge gap | |
| T2: environment distribution and description | Insight 4<br>Insight 5<br>Insight 6 | | Limitation<br>Limitation |
| T3: sound interactions | Insight 7<br>Insight 8 | Knowledge gap<br>Knowledge gap | Limitation |
| T4: beyond sound and observed measures | Insight 9<br>Insight 10 | Knowledge gap<br>Knowledge gap<br>Knowledge gap | |

Table 1: overview of themes, insights, knowledge gaps and limitations

**#Theme 1: Collecting and processing sound**
This theme focuses on methods used for sound recording and how the results from the studies are analysed.

**Insight 1:** Recording spans are very scattered, and researchers hardly follow the same periods. For instance, 24h every 7 days for a total period of 44 weeks (Brandon, Ryans, & Barnes, 2006) 24h during seven days (Aita et al., 2021) or eight 1h recordings (Krueger, Schue, & Parker, 2007).

**Knowledge gap:** Currently, all we can find are intervention studies that are episodic rather than continuous. They focus on measuring sound levels to report how harmful the environment can be, but they do not focus on potentially implementing long-lasting sound monitoring and recording solutions. Instead, they are just counted as intervention programs.

**Insight 2:** The outcome of the recordings is based on decibels (dB) measurements. However, fewer studies also conduct a more complex sound analysis by performing spectral analysis and therefore analysing the frequencies. (Elander & Hellström, 1995; Johnson, 2003; Slevin et al., 2000). However, the decibel measurement is just a part of the sound taxonomy. Loudness is amplitude, which is expressed in decibels (dB) while pitch is frequency, expressed in hertz(Hz).

Nonetheless, there are cases in the literature in which authors record frequency levels because it gives broader knowledge about the sound environment. (M. K. Philbin & Gray, 2002; Surenthiran et al., 2002). spectral sound analysis (SSA) uses specialized equipment to measure frequency. Excluding frequency analysis from a sound recording limits a complete perspective about sound events.

**Knowledge gap:** Researchers started by reporting dB, then comparing it with frequency. They do not go beyond any other variable. Even though multiple sound events occurring at NICU can fall in the same amplitude or frequency range, the impact that they can have on individuals can be completely different.

**Insight 3:** Sound meter levels are the most used devices for sound monitoring, followed by dosimeters (Elander & Hellström, 1995; W. F. Liu, 2010; Ramm et al., 2017). Nevertheless, the most conventional, since other studies use smaller and more innovative methods that can be placed closer to the patient's body (Kellam & Bhatia, 2008; Surenthiran et al., 2002) or others that even assess sound by analysis speech exposure (Aita et al., 2019; Pineda et al., 2017). The difference between using conventional devices and more innovative methods is that the first only studies the sound physically instead of analysing the effect that it can have on humans, as the latter does.

**#Theme 2: Environment distribution and description**
This theme is about areas that have been compared and elements that have been described in the environment and methodology.

**Insight 4:** The goal of the studies is to report sound levels exceeding the established thresholds. The baseline is permanently established by international organizations such as American Academy of Pedriatrics(AAP) or the World Health Organization (WHO) (Darcy, Hancock, & Ware, 2008; Santos et al.,2017; Williams & Lasky, 2007).

**Insight 5:** Studies focus on not only reporting sound levels in a specific unit but comparing different environments: open bay units with Single-Family Rooms (SFR) (W. F. Liu, 2012) or a new structural change in the unit (Krueger et al., 2007). These comparisons aim to report and give evidence on the most suitable environment for the well-being of infants, parents, and nurses.

**Limitation:** The NICU characteristics in which every study is conducted are unique. Patient census, numbers of beds, nurses working on the shift, parents, infants acuity. All these factors can potentially contribute to increasing the sound levels. Therefore, it is even more challenging to assess every study's sound outcome since none share the same setting characteristics.

**Inisight 6:** In the literature, researchers explain where they position the devices. If the goal is to measure the environmental noise, devices are positioned at the center of the room(DePaul & Chambers, 1994). Conversely, microphones are placed closed to the infants head if the goal is to measure the sound the infants are exposed to or measure the care activities nearby the incubator area (W. F. Liu, 2010; Slevin et al., 2000). Nonetheless, there are studies that give a complete environmental notion and measure the central area as well as different incubators areas (Krueger et al., 2005; Elander & Hellström, 1995; Thomas & Uran, 2007.





**Limitation:** the main limitation to these insights is the access to equipment. Occasionally, studies place the devices one by one instead of having a complete system. The main reason is the lack of resources and budget.

**#Theme 3: Sound interactions**
Nurses are discussed to be the agents that can be the catalyst to change the sound to optimal levels at NICU.

**Insight 7:** There is the will for monitoring sound more continuously instead of doing period measurements without any feedback or output measure (Aita et al., 2021; Cardoso et al., 2015).

**Knowledge gap:** The NICU wants to be more monitored and have more intelligent technologies that can help its inhabitants.

**Insight 8:** There is a common consensus on the most relevant environmental sound sources in NICU. The most repeated categories are equipment noise (considering alarms, ventilation system, heating) (W. F. Liu, 2012; M. K. Philbin & Gray, 2002) and voice communication(conversations, caring activities) (Krueger et al., 2007; Santos et al., 2017). In the latter categories, many scholars suggest that staff might be the cause since they are the caregivers who spend the most time at NICU (Krueger et al., 2007; Ramm et al., 2017; Santos et al., 2017).

**Limitation:** Alarms, ventilation systems, noise inside incubators and all the noise that the equipment generates can be lowered to a certain level, but the alarms cannot be turned off. Medical equipment manufacturers cannot design equipment in which alarms can be turned off. This issue must be addressed through medical rules and regulations and other stakeholders involved in the manufacturing and supply chain.

**Knowledge gap:** It is very difficult to avoid voice communication, specially in such a human environment. The goal towards decreasing sound levels must go in accordance with the care activities that happen at the unit. The problem is that staff are unaware of how loud is the impact of the noise they produce can be and how susceptible their environment is.

**#Theme 4: Beyond sound and observed measures**
The theme contains future recommendations that can be implemented as strategies to reduce sound levels.

**Insight 9:** The experience of sound requires for subjective measures. Sound is a wave transmitted through space, a subjective measure that varies upon everyone. The literature presents two different assessments conducted with inhabitants at NICU. On the one hand, when sound is evaluated with new-borns, it is correlated with alterations in heart rate, blood pressure, and oxygen saturation since the alteration of these values gives an approximate representation of how noise affects their well-being (Slevin et al., 2000). On the other hand, questionnaires are a regular method used to evaluate staff tolerance and perception towards sound (Darcy et al., 2008; Santos et al., 2017; Williams et al., 2007).

**Knowledge gap:** Most of the literature focuses on studying the consequences of sound for either nurses or infants. However, the studies that focus on the sound repercussions for parents are scarce. Indeed, they are not the principal sound sources, yet the acoustic environment can also damage their healing process.

**Knowledge gap:** There needs to be a sound interpretation beyond the established measures that gives people a value or interpretation related to a situation in their daily lives.

**Insight 10:** Behavioural change strategies are recommended in multiple studies (Johnson, 2003; Kellam & Bhatia, 2008), although some authors already point that, for some reason, they are not efficient enough (W. F. Liu, 2010, 2012).

**Knowledge gap:** It is uncertain to which extent these behavioural strategies can be sustained in the long term. Consequently, after implementing the program, it can be possible that the sound levels are as high as it used to be before because there is no reinforcement of these strategies. On the other side, why not go beyond intervention programs and using smart and persuasive technologies to help people change their behaviour?

## 3.3 Emerging knowledge gaps

**Conclusion**

The emergence of insights developed to knowledge gaps, which indicated differences between the knowledge that academia had provided and the needs of the current users. In order to fulfill these needs with innovative and user-centric solutions, mapping and developing the knowledge gaps was relevant to then building on future opportunity areas.

However, I first conducted an assessment of the knowledge gaps from a user-centered design perspective (see figure 10).

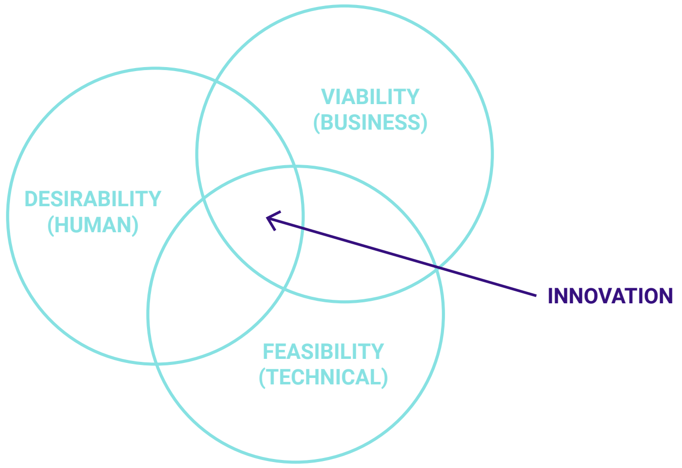


Figure 10: design thinking framework

In order to assess the knowledge gaps and limitations, the following questions were formulated to each one of knowledge gaps and limitations. Each component was assessed with a rating from 1 to 5 for desirability, viability and feasibility.

*Desirability:* Does it address the needs of the current stakeholders at the NICU, especially the nurses's needs?

*Viability:* Is it technically possible within the future technology?

*Feasibility*: Which is the likelihood that ErasmusMC will adopt it?

After conducting the assessment, a final of six knowledge gaps were selected. This selection of these gaps will be applied later on in this project to formulate the opportunity areas (sub-section 6.2).





**Selected knowledge gaps**

**Knowledge gap:** It is uncertain to which extent the behavioural strategies can be sustained in the long term. Consequently, after implementing the program, it can be possible that the sound levels are as high as it used to be before because there is no reinforcement of these strategies. On the other side, why not go beyond intervention programs and using smart and persuasive technologies to help people change their behaviour?

**Knowledge gap:** Researchers started by reporting dB, then comparing it with frequency. They do not go beyond any other variable. Even though multiple sound events occurring at NICU can fall in the same amplitude or frequency range, the impact that they can have on individuals can be completely different.

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**Knowledge gap:** There needs to be a sound interpretation beyond the established measures that gives people a value or interpretation related to a situation in their daily lives.

**Knowledge gap:** The NICU wants to be more monitored and have more intelligent technologies that can help its inhabitants.

**Knowledge gap:** It is very difficult to avoid voice communication, specially in such a human environment. The goal towards decreasing sound levels must go in accordance with the care activities that happen at the unit. The problem is that staff are unaware of how loud is the impact of the noise they produce can be and how susceptible their environment is.

**Discarded limitation**

**Limitation:** The access to equipment is a limitation. Occasionally, studies place the devices one by one instead of having a complete system. The main reason is the lack of resources and budget.

**Limitation:** Alarms, ventilation systems, noise inside incubators and all the noise that the equipment generates can be lowered to a certain level, but the alarms cannot be turned off. Medical equipment manufacturers cannot design equipment in which alarms can be turned off. This issue must be addressed through medical rules and regulations and other stakeholders involved in the manufacturing and supply chain.

**Limitation:** The NICU characteristics in which every study is conducted are unique. Patient census, numbers of beds, nurses working on the shift, parents, infants acuity. All these factors can potentially contribute to increasing the sound levels. Therefore, it is even more challenging to assess every study's sound outcome since none share the same setting characteristics.

## Chapter conclusion

The main take-aways from the semi-systematic review are the following:

- There are limitations regarding how sound is evaluated and interpreted. The complexity of the physics of sound makes it difficult to interpret for people who are not familiar with it. Therefore, most studies report the results in dB even though this is not the only measure. The problem with the dB measure is that it is too generic and does not represent the sound quality being evaluated at the NICU.

- The studies are temporal rather than permanent. The devices used are independent of the unit, instead of being a whole interconnected system.

- None of the recommendations, such as structural changes, single-family rooms, wearing earmuffs, and educational programs, have been proven effective so far. Even though single-family rooms would improve the situation, they are the least feasible solution for hospitals.

4

Chapter 04

# Towards the future of intelligent sound monitoring





## Chapter introduction

Chapter 2 and 3 have focused on deeply understanding the context through conducting literature research and a semi-systematic review. Chapter three has focused on the technology enabling the design intervention.

This chapter starts in the present, but it already steers where the future is going. The motivation for this chapter is to map the products that are currently available in the market and identify the solutions they are providing. At the same time, it provides a brief overview of the challenges of using machine learning. It continues with a concise analysis of trends and finalises with the future vision statement.

# 04

# Towards the future of intelligent sound monitoring

**4.1 Current monitoring solutions**

Literature showed how researchers conducted studies at NICU and the devices they used. Nonetheless, it was unclear which products where available in the market and the existing characteristics they could provide for this thesis context, the NICU. The search was initially based on sound monitoring applications for hospitals but was then further extended into companies that did nott specifically cover the hospital market but that had interesting products and services (see appendix B). An initial exploration with various factors displayed in a two-dimensional axis was conducted (see appendix C). The final competitor analysis consisted of a two-dimensional axis to evaluate two principal factors that were both predominant in the literature research but also provided a market gap.

**Why this axis?**

Interpreting: the interesting part about having a sensor system is that it reports that data and displays it in a way that gives feedback to people while also informing them. It not only reports the data on itself, but it gives people a subjective measure.

Predicting: the other factor that showed to be most relevant is clustering the sound events that occur at the unit whether they are alarms, speech, equipment, and other types.

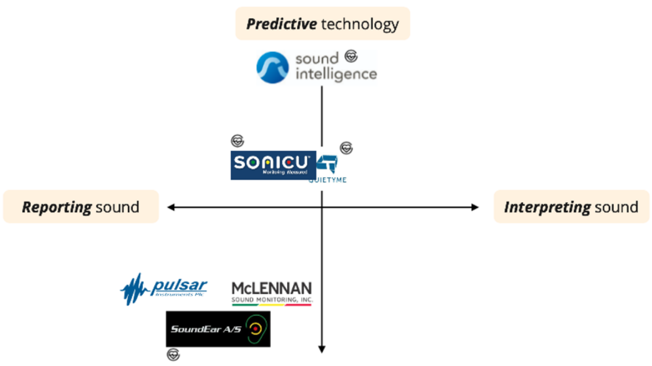



Figure 11: competitor axis about the current product solutions.

**4.2 Technology available: what has been researched so far?**

The market solutions that have been explained in the previous section, are a representation of what can be found in the market as most state-of-the-art solutions for sound monitoring. Most of the applications mentioned in the previous section do not show to use advanced methods such as machine learning for sound clustering, but rather just report sound levels. In fact, in the last decade there are numerous researchers who have tried to find the most optimal way to cluster sound events by using advanced methods such as machine learning (Jaiswal et al., 2011; Piczak, 2015).

**Challenges in mapping sound events**

The fact that makes it hard to detect sound at the NICU is the numerous sound events happening at the same time, the overlapping sound signals. However, given the multiple sound events occurring at the NICU, alarms are the first cluster that can be easier detected, since they are designed to have a repeated pattern, as shown in the spectrogram of figure 12. As exposed in the literature research, it is not enough to have the sound data only relying on dB to categorize a particular sound event, but also use spectral analysis to have the frequency (M. K. Philbin & Gray, 2002; Surenthiran et al., 2002). The spectrograms shown in figure 12 and 13 represents the frequencies over time, where colour represents the amplitude, the brighter the higher.

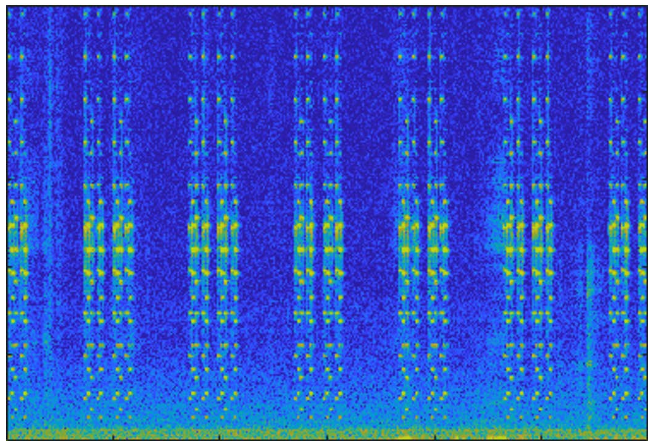


Figure 12: alarm spectrogram (Image prepared by S.Spagnol).





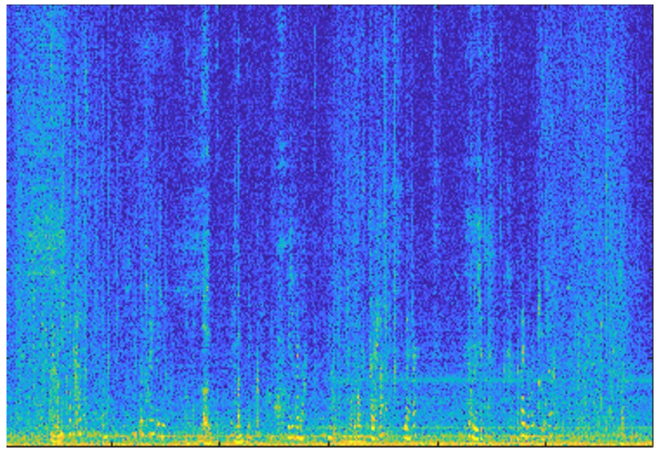


Figure 13: speech spectrogram (Image prepared by S.Spagnol).

There is not a defined machine learning approach for addressing sound detection events, that is what makes the task so complex and challenging. Most of computational analysis systems are based on supervised learning, where the system is trained using labeled data of sound events that are targeted (Heittola, Çakır, & Virtanen, 2018). The typical components of a system analysis are pre-processing, feature extraction, and pattern classification. Figure 14 show a basic overview of the system analysis process.

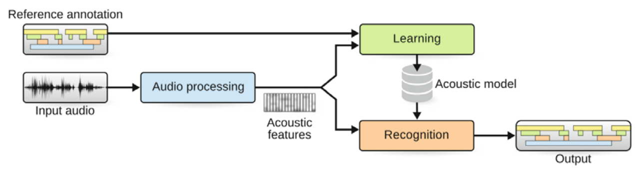



Figure 14: basic structure of an audio analysis system (Heittola et al., 2018).

However, in recent years machine learning developments became more sophisticated, by applying beamforming the sound source could be localized (Chiariotti, Martarelli, & Castellini, 2019; Tiana-Roig, Jacobsen, & Grande, 2010). This is the case in (Darbyshire et al., 2019) research, in which they installed a microphone array in an intensive care unit and localized the sound sources in real time. The distribution of microphones is also a challenging issue when trying to localize the sound sources. As mentioned previous times, in the real context there would be an overlap of sound sources occurring at the same time. Most of the studies explain theories and methods for detecting two sound events at the same time, which is by far an unlikely case (Liaquat et al., 2021). However, given the microphones configurations, three geometric shapes are mainly presented: triangle, square and spiral (Fan, Luo, & Ma, 2010; Müller-Trapet et al.,2018). For the area where the solution needs to be implemented, the square shape, which can form an array grid, is assessed among researchers as better than circular shapes. Compared to the spiral configuration, the grid can be equally distributed among the squared area at the NICU.

Unfortunately, no matter how relevant all the applications might be in the scientific field, they fail to apply a human-centred design approach. These applications fail to build empathy for the people they are designing for, understanding their needs and the context (IDEO, 2021).

**4.3 Future trends for 2025**

Intensive care units are fast changing environments, where future developments must be considered to properly plan future implementations. In order to spot developments in this fast-changing world, creative trend research and future visioning were used as methods to gather relevant factors within a given timeframe.

As explained by Simonse (2017) creative trend research "combines the designer's crafts of intuitive observations with the strategic scanning of the environment". The future vision instead, expresses a desired future as a direction point (Simonse, 2017). In a way, future visioning learns from the past and positions the critical issue in a way that no one has solve yet.

To evaluate which future factors could potentially be a driving force within the NICU, trends were selected following the DESTEP taxonomy as a checklist. As a result, technology trends provided a vision on how new methods could shape the healthcare sector. Sociological trends provided insights related to human actions and behaviours.

Selected trends:

**Technology trends**
The world is changing from a technical perspective, with tremendous amount of trends happening in the technological landscape. The main driving force among technology trends will be Artificial Intelligence and Machine Learning, with its ability to learn and act intelligently and creating smart environments (Marr, 2020). However, 5G network providing multiple levels of connectivity and environments and richer streams of data will also play a major role in the healthcare ecosystem (PwC, 2019). Additionally, with the digitalisation the amount of data that hospitals will have to deal with will be enormous. Therefore, the need to deploy all this data in operational centres will arise (Philips, 2021).

**Healthcare trends**
In healthcare it will not only be important to improve patient experience but also staff experience. This means, caring for their environment and their wellbeing. Consequently, care model innovation can help in delivering patient and clinician experience (Deloitte, 2021). It goes without saying that innovation in hospitals does not happen overnight but given the COVID-19 pandemic there is going to be more emphasis on monitoring intensive care departments with pervasive changing for the patient, staff and environment (Davoudi et al., 2019).

**Sociological trends**
Current challenges in healthcare are an aging population and an enormous rise in chronic disease (Philips, 2021). Besides that, it is expected that millennials will play a main role in the workforce by 2025. This generation is surrounded by technology screens and digital interactions. External stimuli are not a major burden for them (Vogels, 2019).





**4.4 Future vision**
The trends that have been mentioned previously set the scene and hinted to potential directions of the future vision. However, when steering all these factors into the future vision the designer is who decides how to shape all these considerations and create the future vision (Simonse, 2017).

My interpretation of the future

<u>What it is</u>
The implementation of new technologies will undoubtably continue to increase. NICU will continue to employ more accurate sensors and equipment that continuously monitor infants. This leads to the following situation: sensors will trigger more alarms, creating a cacophonous environment that disables the capacity of healing and wellbeing for infants. Consequently, nurses will have to react to a broader alarm range stimulus, either sound, vibrations, notifications, wearables and so on. This will affect their capacity to perform and focus, and ultimately causing overstimulation and inability to react anymore. In fact, providing them with the ultimate technology and with all means to perform at their best, does not necessary mean that they will interact directly with it.

<u>What it could be</u>
The NICU of the future should be a place that uses technology to map and assess the quality of the environment that nurses are working in. However, this should not mean overloading them with devices and dashboards to interact with. The assistive technology should not prevent nurses from focusing on their patients. Smart methods such as AI should be capable to assess the sound events occurring at NICU and interpret the quality of the environment to then further assess with stakeholders what needs to be improved.

**Future vision:**
**"I want the NICU of 2025 to be an intelligent space that maps soundscapes, contributing to a seamless interaction sound experience for patients, nurses, and families"**

## Chapter conclusion

This chapter has found the current market gap for the sound monitoring products, which is interpreting sound-producing events and predicting sound events. However, sound detection is easier said than done.

The current products are not providing this feature, not because they have not found the market gap, but because of the complexity that lies in sound event detection. As proposed in figure 13, one of the approaches would be labelling certain sound events. In the case of the NICU, the first sound events to label would be the alarms.

The chapter also discusses the future trends, which are mainly driven by technology how in the upcoming years, there is going to be a paradigm shift within alarm management.

Chapter 5

## Exploring NICU





## Chapter introduction

This chapter aims to understand the underlying problems at the NICU, which the literature review could not uncover. It explores the human factors and the physical environment.

The goal of this chapter is to gain insights from the NICU, by being physically on-site. The first three sections, which focus on the user, explain the methodology for the observations and the user research activities conducted with nurses. The last subsection, which focuses on the physical environment, is related to technology and presents three potential scenarios to place the microphone system.

The results from the observations and interviews will be presented in chapter 6.

# 05
# Exploring NICU

### 5.1 Introducing the NICU environment
As mentioned in chapter one, the context of this thesis is the NICU department of Sophia, which is part of the neonatology department of ErasmusMC-Sophia. The NICU has four different units that provide care for sick or premature infants. The units differ basically on the type of care they provide to infants, being unit 1 and 2 for high care and unit 3 and 4 for intensive care. The unit can assist infants that are born at a gestational age of less than 32 weeks or infants who were born with health related issues.

Goal of the research:
a) Explore how nurses perceive their sound environment.
b) Identify how different sound sources are perceived

### 5.2 Observations
Observations were the opportunity to understand the interactions and behaviours between nurses and other medical professionals (e.g. neonatologists, ambulance staff). I conducted a total of three observation rounds. The first session, carried out in unit 3, helped to get a sense of the environment. The second round allowed me to shadow a senior nurse and observe the different care activities during her shift. Finally, the third one, which took place at the new unit 4, was useful for comparing the new structural changes and how they affected the overall sound environment. The observations provided new insights but also resurfaced patterns observed in the literature. The primary insights are listed below but further elaborated on together with the interview insights in chapter 6.

- The nurses' work station gets very busy when there is the shift overlap since there is double the personnel. The sound is increased by either vocal communication of informal conversations or nurses doing patient handovers to other nurses, as observed in literature (Santos, 2017).
- The only pattern of sound events are alarms. Care activities and other medical professionals entering the unit are unpredictable.
- There are different listener segmentations, depending on how they cope with sound. This insight matches with Schokkin's (2019) thesis. Some nurses are more sensitive towards loud speech levels than others.

### 5.3 User research with nurses
**Participants**

| PARTICIPANT | SENIORITY | SENSITIZING BOOKLET | INTERVIEW |
|---|---|---|---|
| Participant 1 | 6 years | Yes | No |
| Participant 2 | 3 years | Yes | No |
| Participant 3 | 4 years | Yes | Yes |
| Participant 4 | 25 years | Yes | Yes |
| Participant 5 | 23 years | Yes | Yes |
| Participant 6 | 30 years | Yes | Yes |

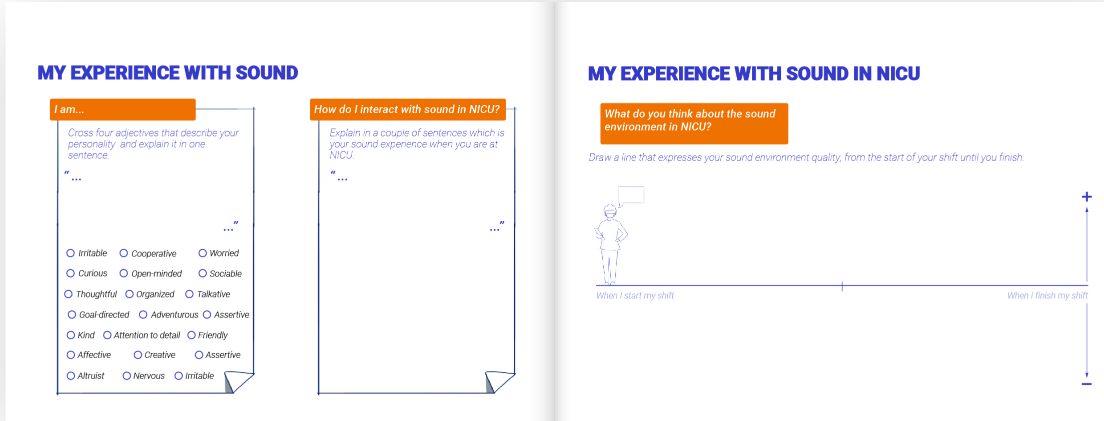
Table 2: user research participants

I conducted user research with nurses to collect more insights about their thoughts and experiences. As discussed in chapter 2, literature was advocating for nurses without emphasising on their underlying needs. Participants were recruited from ErasmusMC, all working in the neonatology department. A total of 6 participants were involved in the study. However, due to time availability, some participants did not participate in both parts. Table 2 displays a detailed description of each participant.

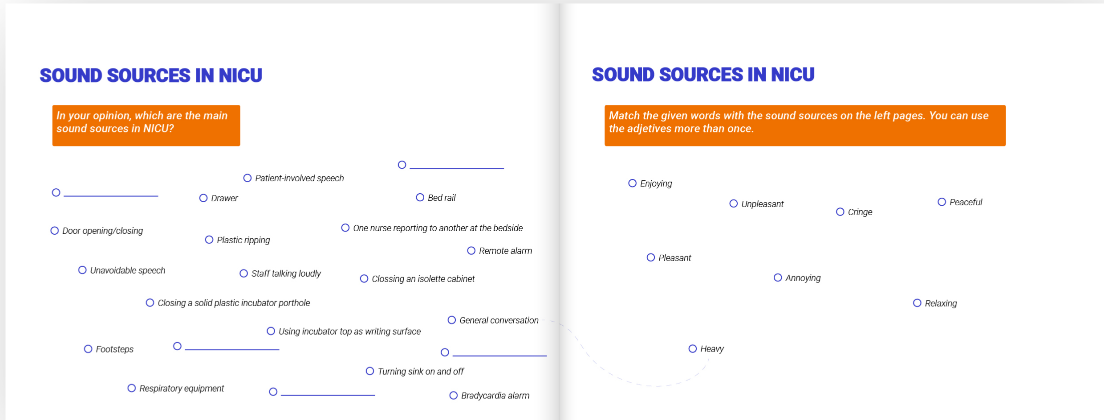
**Sensitising booklet**
A sensitising booklet (see figure 14) was designed to engage participants in their sound experience at the NICU. The booklet was intended to immerse participants to get familiar with sound and their experience, prior to conducting an interview with them. The sensitizing tool followed the principle of "the path of expression" (Sanders & Stappers, 2012), where the participant first thinks about the present, is then brought into the past to understand underlying needs and is finally guided into the future.

**Interviews**
The interviews were a follow-up activity after

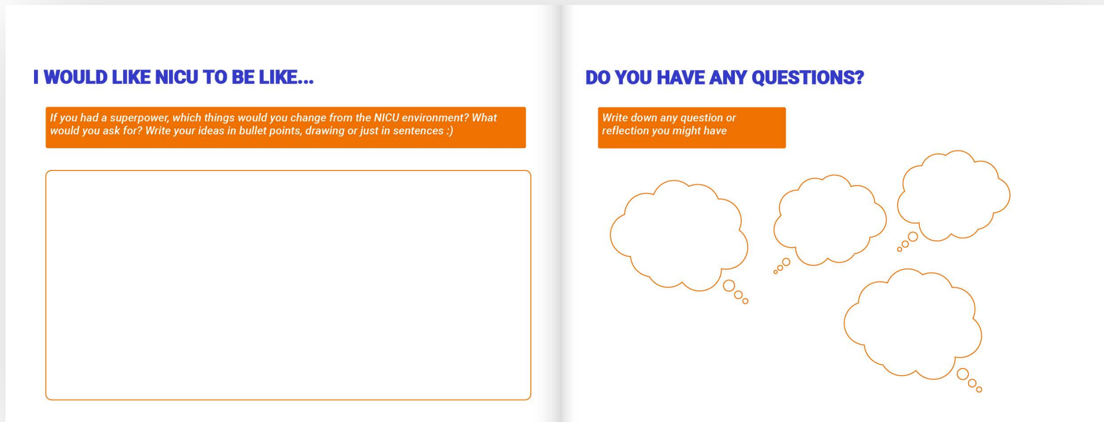





Based on the observations, I wanted to explore how different personality traits could influence having loud speech levels at the unit. The examination was based on the "Big five" personality traits Openness, Conscientiousness, Extraversion, Agreeableness and Neuroticism (Susman, 2021).




(Left) Sounds found during observation and literature (Bremmer et al., 2003) - (Right) Subjective sound state (Bones, Cox, & Davies, 2018).




This last part is aimed at helping participants to think about the future.

Figure 15: sensitizing booklet

the booklet. The interviews consisted of a semi-structured interview divided into three parts that were aimed at providing more rich, detailed, and in-depth data (Braun & Clarke, 2013) and lasted 30 to 45 minutes. The interview guide set-up was according to Patton's (2002) guidelines for qualitative research (see appendix D). The booklet that was filled before the interview was analysed prior to the interview and used as an ice breaker for starting the conversation. The first part of the interview explored their experience with sound. The second part was to identify how they felt about certain sound events, actions that triggered such events, and related behaviors. The third and last part consisted of exploring how familiar the participants were with technology and with e-learning.
The participants signed a consent form allowing me to audio-record the interview and transcribe it. The interview transcript allowed me to go through the data back and forth and generate themes.

**Data Interpretation**
To analyse the data from the interviews thematic analysis was employed. Thematic analysis is a flexible method used in qualitative data analysis, that aims to find patterns in the data set and spot emerging themes (Braun & Clarke, 2012). The digital whiteboard software Miro was used in this data analysis process. As a first step, quotes from the interviews were selected and placed on digital sticky notes. Then, I interpreted what the quote mean for the user. Afterwards, themes emerged from the data. Then, I wrote my interpretation for that quote. This process was conducted through all four interview transcripts. An overview of the resulting process is shown in appendix E.

**4.4 Sound test configuration**
As explained in chapter 3, the literature gave insights into potential microphone configurations and how they could be distributed in the area. The downside was that all information provided was generally based on theories, and the best way to investigate the system's accuracy was by testing it. Therefore, the test set-up was designed based on three potential scenarios which are explained further in the section. The experiment was performed by two researchers, Dr. Ir. S. Spagnol and Ir. T. Goos, but it only included testing scenario one. Even though this thesis is developed for unit 3, unit 1 was empty for a certain period, being the most suitable place to conduct the test.

Prior to conducting the test and presenting the three potential scenarios, the insights gathered through research contributed to listing the following assumptions:
**i)** Microphones will be omnidirectional (Liaquat et al., 2021)

**ii)** The microphones should be suspended from the ceiling to avoid activities happening too close to them and causing too much noise. These insights follow the guidelines that Gray and Philbin (2000) provided in their study.

**iii)** Ideally, each bed should have a microphone, so a total of 10 microphones in the bed area, plus at least 4 microphones in the nurses' working station.

**iv)** Microphones should be distributed in a square. Trying to cover the area where the biggst number of sound events are likely to happen (Fan, Luo, & Ma, 2010; Müller-Trapet et al., 2018).

Based on the above assumption, three scenarios are proposed (see figure 16, 17, 18).

**Results**
The only scenario that could be tested was scenario 1. Nevertheless, the following conclusions were extracted:
- As shown in figure 17, the distance between the microphones is notably large. As a consequence, it is difficult to estimate the direction of arrival and location of each sound producing event. The more microphones that can cover the area, the higher performance the system will have. Therefore, out of the three scenarios, the minimum numbers of microphones should be 14, as proposed in scenario 3.
- Alarms sound simultaneously in patients and nurses monitors. This makes the sound detecting task more complex due to a small delay between the same alarm, which is replicated.
- First focusing on alarm producing events might be the best strategy. The main alarms that occur at NICU are heart rate (HR), respiration rate (RT), oxygen saturation (SpO2) and the infusion pump. These four alarms share the same tone, however, what differentiates them is the number of tones, duration and the silence phases in the pattern (see figure 16).

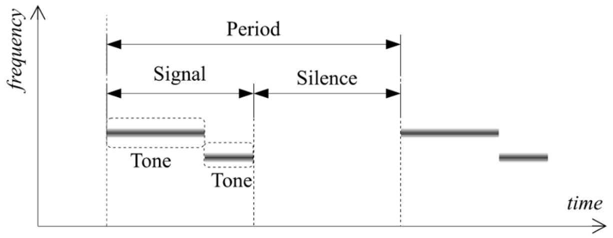



Figure 16: General strcuture of alarm sounds (Jaiswal et al., 2011).





***Scenario 1***
*Option tested:* Yes

*Number of microphones:* 4

*Pros:*
- Only option that can be tested in the short term due to the microphone availability.

*Cons:*
- Given the sound source A, the system will not be able to position it in the space since it has the same distance from both microphones.
- Four microphones are insufficient to cover the whole area.
- Low performance.

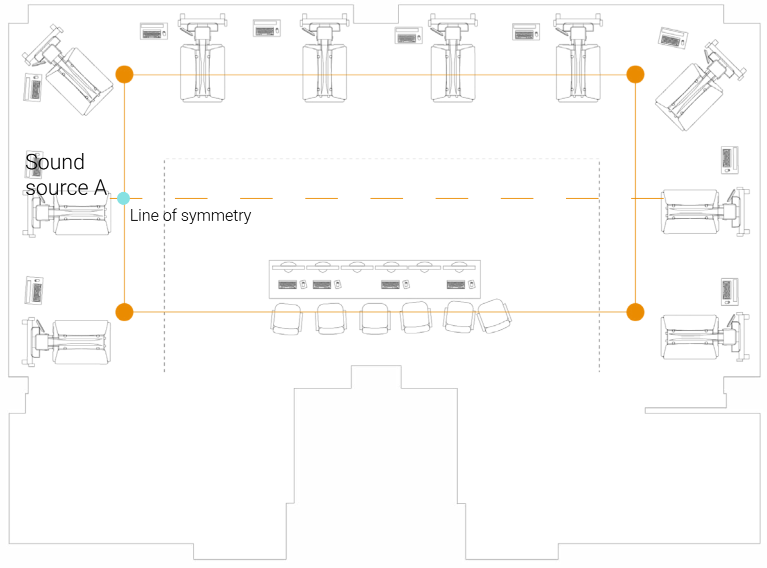



Figure 17: Scenario 1. Four microphones

***Scenario 2***
*Option tested:* No

*Number of microphones:* 6

*Pros:*
- Might present better perfomance than scenario 1.

*Cons:*
- Reflections in the walls might create ambiguity.
- The range of sound sources that the grid covers might not be enough.

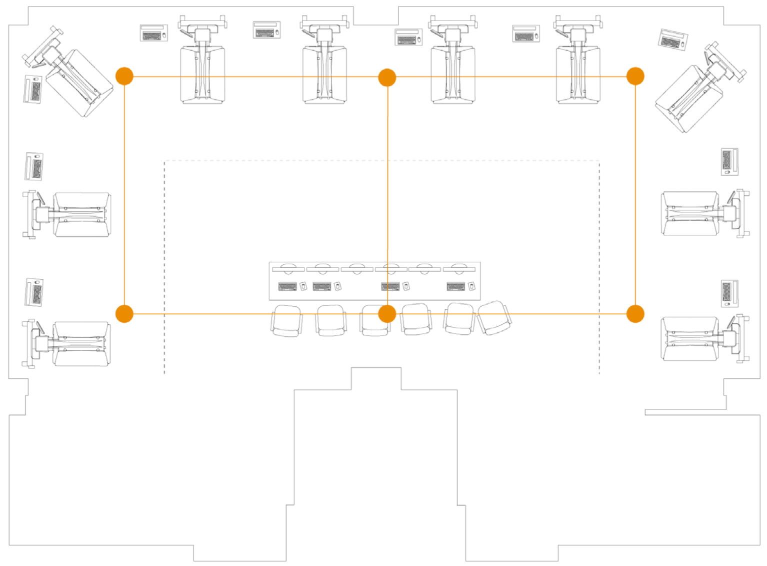


Figure 18: Scenario 2. Six microphones

***Scenario 3***
*Option tested:* No

*Number of microphones:* 14

*Pros:*
- The main areas with sound sources (beds and nurses work station are covered by microphones). The microphones are within the ranges of the primary sound sources.
- Increasing the number of microphones increases the estimation performance (Liaquat et al., 2021).

*Cons:*
- Reflections in the walls might create ambiguity.

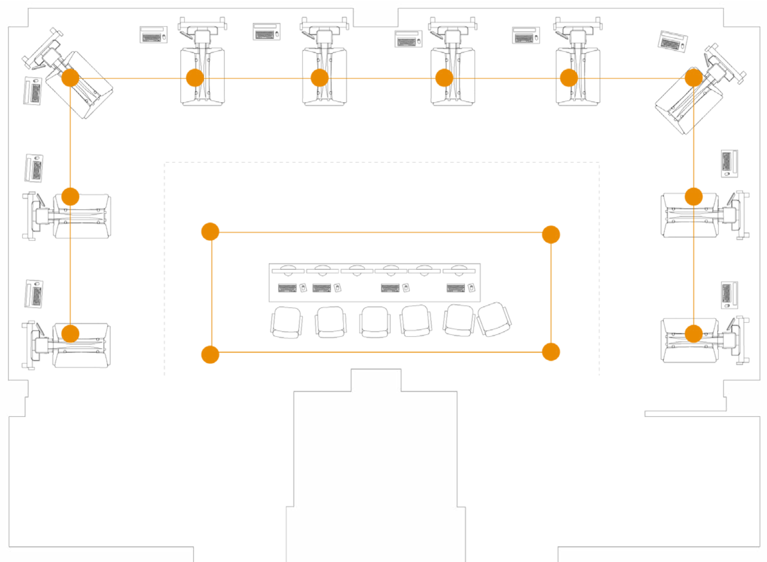


Figure 19: Scenario 3. Fourteen microphone

## Chapter conclusion

This chapter described the research activities conducted with nurses, together with the sound test setup. The next chapter will elaborate on the results from the user research activities. Nonetheless, the main takeaways from this chapter are:

User research with nurses

- Informal conversations with nurses gave some insights into how the acoustic environment is perceived at the unit. Some nurses reported being disturbed by colleagues talking loudly, while others did not show any annoyance. This insight matches Schokkin's (2019) research, where she reported three different sound cultures at the ICU: opinionated professional, assertive ally, and docile novice.
- The first unpleasant sound source for nurses is alarms, followed by speech.
- Alarms are repeated at the patient's monitor and nurse's workstation.
- The care routines do not follow a pattern since they depend on the infant's health development. It is also unpredictable when other medical professionals will visit the unit regarding other individuals visiting the unit. However, during the evening shift, families usually come after 18h.

Microphone grid

- The test has met the assumption that four microphones are insufficient to cover the whole unit area. Adding two microphones (scenario 2) would slightly increase the performance of the system. However, given that alarms are repeated at the bed area and nurses' workstation, having scenario three would increase the detection performance. If each bed can be assigned to one microphone, the sound events will be captured with higher accuracy because they will localised closer to the microphone range.

6

Chapter 6

## Research synthesis





## Chapter introduction

At this phase of the project, the insights gathered from literature, trends and state-of-the-art solutions were quite significant. This chapter is the last section which evaluates data from the research phase and finally brings together all the insights collected throughout the project. Firstly, categories that emerged from the interviews with nurses are presented, followed by the opportunity areas that have been mentioned in previous chapters. Finally, one opportunity area is selected, which will be used as an inspirational guide for the design goal.

# 06
# Research synthesis

The goal of this chapter is to provide opportunity areas based on the previous findings from the semi-systematic review (chapter 3), tech scouting & future trends (chapter 4), and user research activities (chapter 5). The chapter is divided into two sub-sections to explain the focus. The first sub-section, reports the results from the user research activities (chapter 5). The second sub-section maps and assesses the resulting opportunity areas. The chapter ends with the proposal of one opportunity area, which is used as a guideline to formulate the design goal.

**6.1 Results from user research at NICU**
The user research conducted with NICU nurses (observations, booklet, and follow-up interview) showed how nurses perceived different sound events and their sound experience.

The data analysis was conducted in the following order:
Sensitizing booklet
I first clustered the data from the sensitizing booklets to map the most recurrent sound sources. The result of this analysis was figure 20, in which I visualized the most selected sounds and how nurses perceived them. Overall, the bradycardia alarm and staff talking were the most ranked.

Interviews
Secondly, I analysed the interview data as explained in chapter 5. The following categories emerged from the thematic analysis:

- Low perceived sound control
- Helpless in interpreting sound
- Overstimulation of alarms
- External stimuli that contribute to a pleasant environment
- Changing actions and behaviours

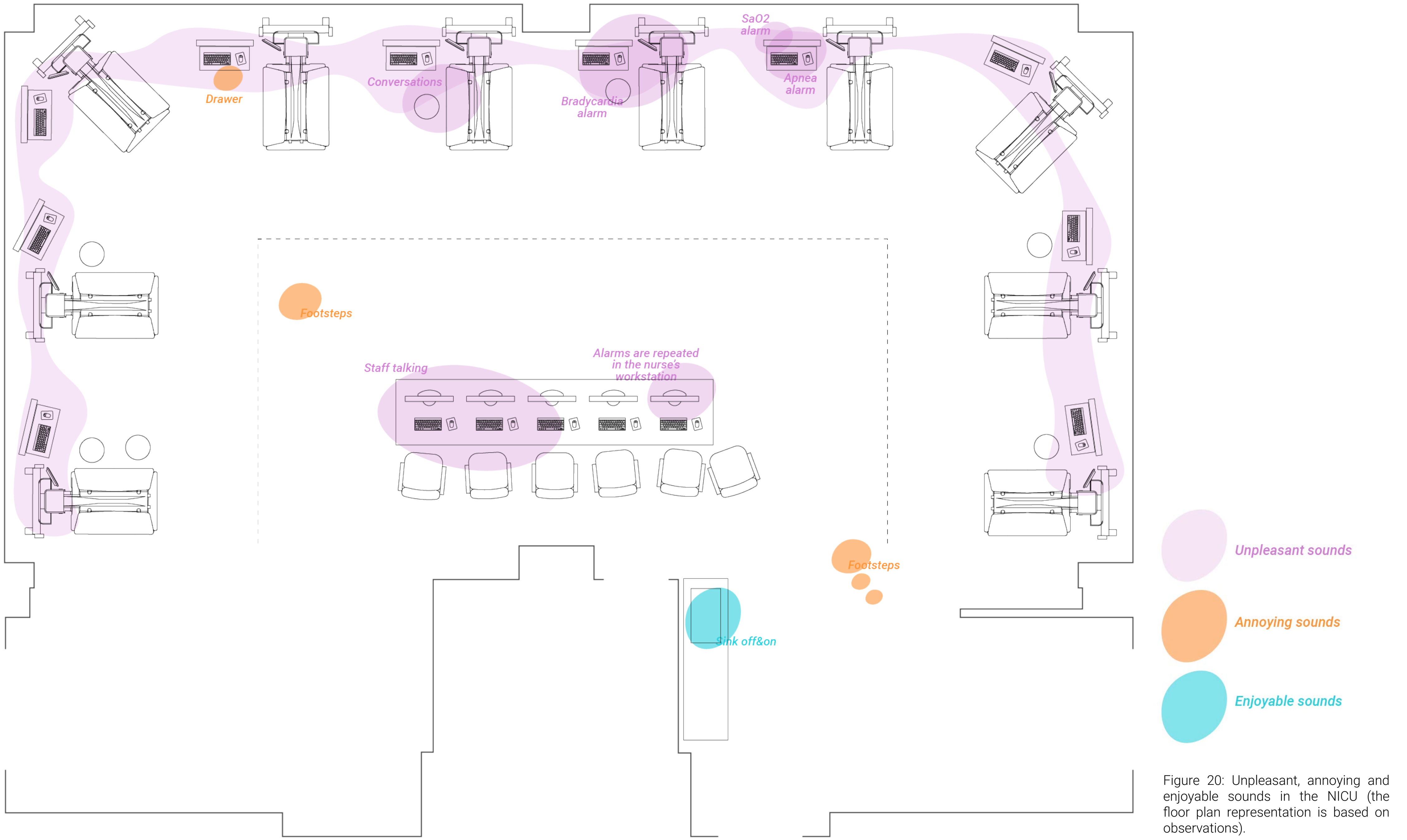



Figure 20: Unpleasant, annoying and enjoyable sounds in the NICU (the floor plan representation is based on observations).

**Low perceived sound control**
This category describes the mass of effect that sound provokes at the unit. Some participants described that when someone starts talking a little loud, the next person will speak a little louder, then the next one, and so on. It is quite unbalanced the sensitivity between individuals while having vocal communication. If it is between nurses, it can be more controlled because some suggest lowering their voice, but it becomes more complex when other medical professionals are at the unit as well. Lastly, participants frequently mention that people are unaware of where they should have conversations, and the most common place where this happens is next to the infant's bed. This insight matches Krueger et al.'s (2007) study, where they categorize these conversations as an operational sound that must be addressed.

**Helpless in interpreting sound**
While discussing with nurses past sound-reducing strategies, they mentioned the SoundEar product (mentioned in section 4.2). SoundEar was used for a period of time but was not successful because it did not provide meaningful information to nurses. They all agreed on implementing sound-reducing strategies. One of the participants mentioned that when the results from a sound study were reported to her, she was incredibly surprised by how loud the results were. However, products providing red light feedback were reported to not be impactful for them.

*"When they told us the results from that sound study, that was an eye opener for me. I thought: that it's very noisy"*

**Overstimulation of alarms**
Alarms were undoubtedly the most unpleasant sound that nurses mentioned, mostly bradycardia and apnea alarms. It was observed that senior nurses were slightly more sensitive to sound than mid-senior nurses were. They were presenting bigger alarm fatigue than their colleagues. It did not show to be a factor that immediately affected them at the beginning of their shift, but instead something that was accumulative. Additionally, participants reported that it was mentally draining for them to constantly scan the alarms and detect straight away when an alarm was critical. In extreme cases, some participants even reported using protective gear, but only occasionally because they were afraid to miss alarms.

It was hard to detect sound events, other than alarms that they could recall as unpleasant and annoying when interviewing with the nurses. The assumption is that the current NICU environment is much smaller compared to other environments where alarms are common, such as the adult intensive care unit. Therefore, all the sounds are mixed in the same cacophonous environment.

**External stimuli that contribute to a pleasant environment**
Even though the noisy environment at the NICU, participants could recall moments of more peacefulness. For instance, when the light was very soft, people would be more careful when speaking since that could be a cue for them to act more silently. Moreover, moments in which nurses were focused on conducting care activities were also reported to be more pleasant. Lastly, another factor mentioned being relevant in having a pleasant environment was the participants' colleagues working with that shift.

*"(...)and then they speak fairly soft because it's a little bit dark on the unit and then you see a lot of change "*

**Changing actions and behaviours**
This last category refers to actions and behaviours that participants reported as being relevant for a pleasant environment. Most of the time, it was about small actions such as responding to alarms, although sometimes it was not possible either because colleagues would ignore doing it or because they would be conducting care activities. On the other hand, participants also mentioned numerous behaviours that are not thought to be noisy for some people, but they are. To some extent, certain behaviours can be controlled by the nurses, however, sometimes, the unit gets really crowded and other staff members are not as considerate as they should be when it comes to making an unnecessary sound. Even though these actions are unintended, participants agree that already changing these behaviours would change the sound atmosphere in the unit significantly.

*"Sometimes you can't switch the button off and it'll go on and on and on..."*

*"Sometimes it's just a lot of people and everybody's running around and talking(...) everybody's too busy with their own stuff. So they do not see the whole picture"*





**Conclusion**
The research activities with nurses have helped to understand better their current situation at the unit. The sounds that are unpleasant, annoying, and pleasant have been mapped. Moreover, the interviews have also shown that sound has to be addressed collectively, and it requires changing certain behaviours that not everyone is aware. For nurses who are less sensitive towards sound, it is hard to imagine and interpret sound's consequences on their environment.

## 6.2 Mapping opportunity areas
The opportunity areas try to gather all insights that have been collected until this sub-section. The knowledge gap provided areas provided potential focus areas. Throughout the trend research, tech scouting and user research, the knowledge gaps have been translated into opportunity areas.

The opportunity areas represent a loose design guideline, providing a path where this thesis could develop further. A total of 6 opportunity areas are listed below:

**1. Continuous monitoring:** sound monitoring must go from episodic recordings to continuous and permanent.

**2. Smart NICU:** There is an increasing interest in having intelligent systems that provide sound control, and AI can be the enabler to map all soundscapes.

**3. Individual sound perception:** providing people a visual representation of their sound footprint since they are not aware of it.

**4. Designing for everyone at NICU:** the ultimate goal is to provide a pleasant sound environment for everyone: staff parents and premature infants.

**5. Sonic analogies:** translating the standard measures (decibels and frequencies) to tangible interpretations for nurses.

**6. Behaviour reinforcement:** behavioural strategies have been in the form of intervention studies. If there is a reinforcement from digital tools of their behaviour, they can have their outcome rewarded.

Each opportunity was mapped in the innovation framework (see figure 21), used for strategic choice in design innovation options (Simonse, 2017). The goal was to have a clear overview of which could be the most suitable opportunity to implement at the NICU. The variables that were taken into consideration for placing the opportunity areas into the framework were the following:

x-axis:fit for implementing smart technologies at the unit.

y-axis: value for improving the sound environment at the unit.

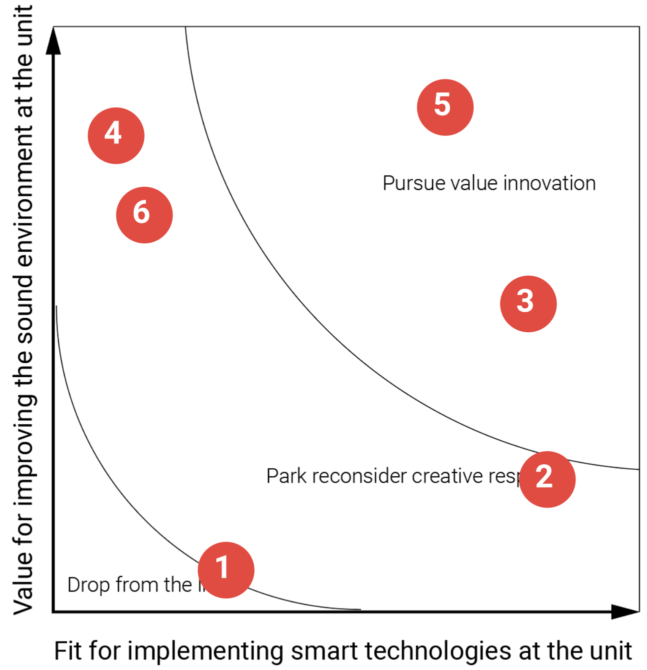



Figure 21: Innovation framework adapted from Simonse (2017)

The opportunity area that scored higher in the grid is sound analogies, and therefore can be chosen as a design focus.

## Chapter conclusion

The insights from the user research activities were a result from observations andinterviews. The resulsts show that the main sound concern from nurses is alarms, followed by speech caused by either colleagues, medical professionals, or families. It also demonstrates that they actively want a quieter environment, but they have not been provided with the tools to change it.

This insight is important because the literature research was already pointing to human behaviour as a way to address the sound problem. Additionally, the opportunity areas' assessment has examined which one out of the six opportunity areas has more potential to contribute. Sonic analogies –translating physic sound measures to tangible interpretation for nurses, has been selected as a design inspiration for this thesis.

Chapter 7

# Design





## Chapter introduction

The goal of this chapter is to provide a final concept for this thesis. To achieve this goal, the chapter presents three sub-sections. First, the design brief lists requirements, considerations, and challenges that will address the final design. Then, I formulate the design goal, which gives a clear direction for the final concept of the project. Finally, in the following ideation section, potential solutions are mapped, and the final design direction is assessed.

# 07
# Design

The insights from the previous research phases helped in developing requirements for the design intervention. All the findings gathered from literature and interviews lead to the opportunity areas discussed in chapter 5. The assessment concluded that sound analogies was the design opportunity which scored best in the innovation framework. Even though the initial briefing of the project hinted at some idea of creating a digital sound dashboard, I wanted to explore different design directions to enhance my creative process.

## 7.1 Design brief

Prior to starting the ideation, I created a design brief that could integrate all the insights gathered and be used as a guideline tool during the ideation process. The design requirements are listed below and are divided into requirements, considerations, and challenges, depending on the impact level they have on the design intervention.

Design requirements are functional needs that the design must have. Design considerations are areas that can affect the design. Lastly, design challenges are difficulties that might interfere with the design in any level or its architecture.

**Design requirements:**
- The system must consist of an array of at least 14 microphones, considering that at least one microphone is positioned on the ceiling in each bed area.
- The system must be permanent and integrated into the unit, meaning that it has hardware that senses the environment and software that processes the data and displays it in an interface.
- The system must give feedback about the current sound levels to nurses, at least the most common sound measure, dB.
- The system must go beyond the standard physics of sound measures and interpret the values for individuals working at NICU.
- The interface should provide real-time data to enable users to react to the potential sound hazard.

**Design considerations:**
- The system should retrieve the data for a maximum of three months in case the user wants to compare past values.
- It should provide behaviour change components to boost motivations, change attitudes and beliefs, and ultimately help the user to achieve the desired behaviour.
- The interpretation that the system will make about the sound environment should be inspirational and visually appealing.
- Persuasive technology can be a smart way to help users on their behaviour change progress, making them visually aware of the current situation.

**Design challenges:**
- The system should start by first mapping alarms, then taking a different approach for speech and medical equipment.
- The cacophonous environment at NICU is crowded with overlapping sound-producing events. It is a challenging task to map all sound events considering that some might be unexpected.
- Given the multiple sound producing events happening simultaneosuly, the accuracy on localisig and detect the sound event will not be high.
- Nurses' workstations already have various screens displaying vital data from their patients. The new technology introduced cannot be at the same level of importance.





## 7.2 Design goal

Considering the integration of the selected opportunity area and the insights gathered in the design brief, the following design goal was formulated:

***"I want to strengthen the sound understanding of nurses at NICU while supporting them to take action regarding sound issues"***

Design characteristics are understanding, confidence, actionability, and awareness.

## 7.3 Ideation

For the ideation phase, I needed to use a method that could help me on reformulating how to provide potential design solutions given the design goal (subsection 6.2). I used "How might we" questions (Heijne & Van der Meer, 2019) to generate creative solutions without losing the focus on my design goal. To receive input from people with an objective perspective on the project, I conducted a small creative session with two peers that followed the template that I had prepared for the "How might we" questions. The listed "how might we" questions were used as inspirational sources for the idea generation.

How might we reinforce behaviour change programs?

How might we create sound-source awareness to nurses?

How to design for a psychoacoustic environment that speaks for nurses at the unit?

**Idea generation**

The most promising ideas generated in the creative session were visualized in concept cards. Concept cards help to structure and summarize early-stage ideas by answering critical questions and being a great way to expose all-important concept components (Board of Innovation, 2021). Figure 21 explains the components that each card had.
A total of 5 concepts were generated, and visualized in figure 22.
While working on the concept cards, I wanted to have a clear view on the limitations and advantages that each concept could provide. Thus I used vALUe evaluation (Heijne & Van der Meer, 2019), an evaluation method used to screen ideas in a systematic way by stating the advantages, limitations and interesting points of each concept.

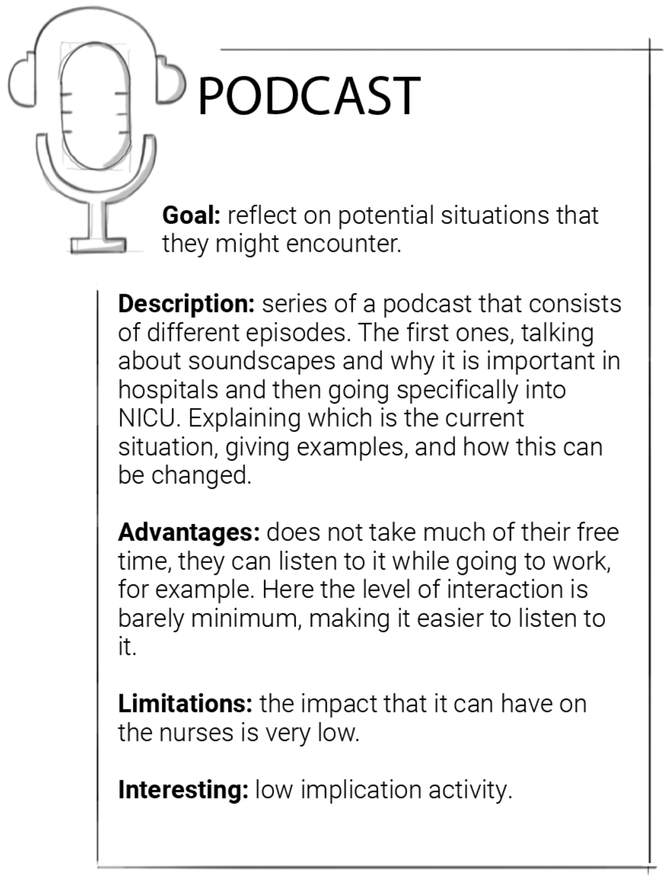
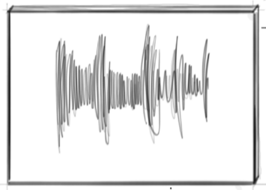



Figure 22: Concept card example



## SOUND FOOTPRINT

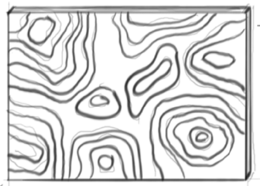
**Goal:** see the individual contribution in the sound environment pollution.

**Description:** giving an overview of the sound contribution that every individual generates. Staff can visually see their "sound behaviour" and therefore act upon it.

**Advantages:** visually representing the "sound behaviour" can be a motivation for change.

**Limitations:** it very difficult to track everyone to collect the sound they produce as individual moving objects. The downside is that you can target individuals who produce more sound, which is not within work-ethics.

**Interesting:** it is like a digital representation of your behaviour & digital twin.



## SOUND HEATMAP

**Goal:** have an overview of the soundscapes that happen at NICU.

**Description:** on the one hand, it shows an aggregated visualization of soundscapes that occur at NICU. On the other hand, it displays decibels and frequency levels more understandably by interpreting them with analogies that people can comprehend.

**Advantages:** it visualizes the most critical areas for people.

**Limitations:** the challenge here remains in the technology. It is difficult to design a system capable of detecting the different sound events at the same time.

**Interesting:** it is an entirely novel way for sound data visualization.

## PODCAST

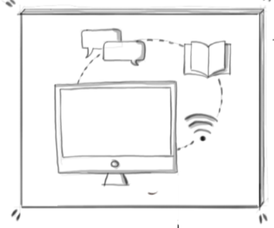
**Goal:** reflect on potential situations that they might encounter.

**Description:** series of a podcast that consists of different episodes. The first ones, talking about soundscapes and why it is important in hospitals and then going specifically into NICU. Explaining which is the current situation, giving examples, and how this can be changed.

**Advantages:** does not take much of their free time, they can listen to it while going to work, for example. Here the level of interaction is barely minimum, making it easier to listen to it.

**Limitations:** the impact that it can have on the nurses is very low.

**Interesting:** low implication activity.



## E-LEARNING

**Goal:** reflect on potential situations that they might encounter.

**Description:** the training is based on a series of objectives that the nurses have to achieve. In this way, the training gives them knowledge and tools to reduce sound levels.

**Advantages:** it is not a new way of learning for nurses since they do e-learning regularly. Therefore it can have a major adoption.

**Limitations:** not that much disruptive. It just follows the same type of learning that they regularly have.

**Interesting:** this type of learning is similar to gamification, although it has fewer user engagement elements.

## GAMIFICATION

**Goal:** increase engagement and motivation to reduce sound levels.

**Description:** it is an emphatic way to train personnel in how their contribution can reduce sound levels at NICU. It allows for immediate feedback on good sound performance and gives the chance to staff to see where they are among their peers.

**Advantages:** it is a nice digital way to involve everyone by contributing as a community and awarding them new knowledge.

**Limitations:** it only gives knowledge but not real-time data about the current NICU. There should be another implementation that could measure the efficacy of such a strategy.

**Interesting:** high user engagement

Figure 23: Concept ideation cards





**Idea selection**

The concept cards brought interesting design directions, however, they differed on the pros and cons that each concept had. A first exploration was made to evaluate the impact that each concept would have on the user. At this point, it was clear that the final solution could integrate components of other concepts.

As figure 23 shows, I highlighted the components that made each idea attractive (light blue) and components that were critical points (light red) for further developing a specific concept. Additionally, I triangulated the results with the framework that was used to analyse the current market solutions in section 4.1.

The process concluded with two ideas that were developed in parallel, sound heat map and gamification. The one which is presented in this thesis is the sound head map. After some iterations on the gamification prototype, I decided to continue further with it and focus on one final solution, giving more consistency to the project. The next chapter will present the final solution, based on the concept card of **sound heatmap.**

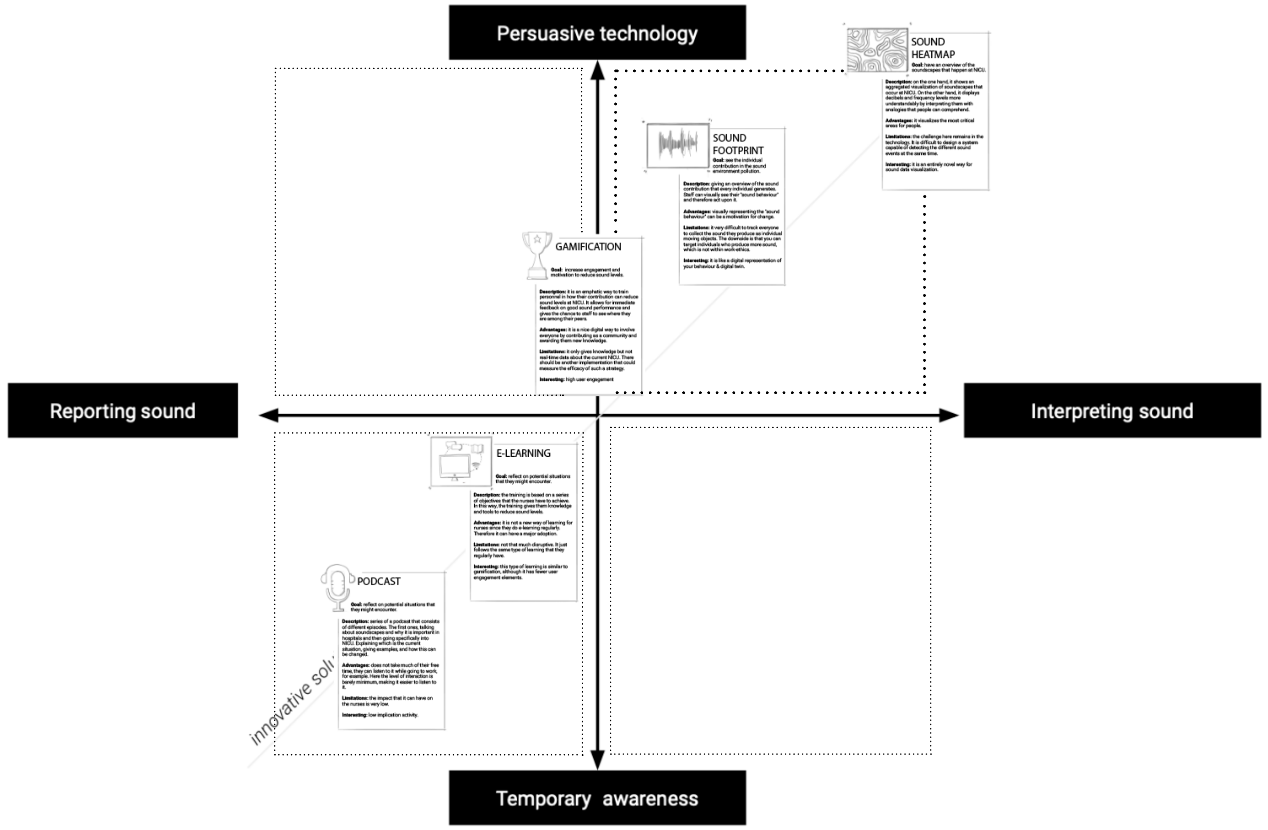



Figure 24: framework for assessing all 5 design concepts

## Chapter conclusion

This chapter has shown how the synthesis of the insights were transformed into design requirements and then later into design directions. Additionally, it has also explained how the gamification and sound heatmap were seen at the beginning as two potential solutions embedded in one. Unfortunately, developing both solutions was beyond the project, and therefore I proceeded with developing the sound heat map, which is introduced in the next chapter.

Chapter 8

# SOUNDscapes





## Chapter introduction

This chapter introduces the final solution. Four sub-section explain the design into different levels. First, a description of the design is provided, explaining the principal goal and its implications for nurses. Then, the elements of each screen are introduced, followed by an explanation of the system architecture. Finally, the last sub-section explains how the design is intended to be used.

# 08
# SOUNDscapes

**8.1 Description**
SOUNDscapes is a digital platform that maps and localizes sound events occurring at the NICU. It displays sound trends in real time and assesses the quality of the environment by having two main visualisation pages: sound level trends and constellation map.

The goal of providing real-time feedback is to make nurses aware of specific (sound) behaviours and their consequences. Additionally, they can assess and observe their collective impact on the unit. This dashboard motivates them to change their attitudes towards harmful sound events by ultimately triggering a behaviour change.

This dashboard is a tool that will help nurses understand, assess and change their sound behaviour and patterns of harmful sound sources, ultimately providing valuable feedback for reducing high sound levels at the unit.

The system aims at mapping and localising sound collectively, from alarms to speech and medical equipment. The system consists of a microphone grid that captures, processes, and localises multiple sound events. The integrated system goes from capturing, processing and displaying sound data. Moreover, it is also a collaborative tool for health care managers and developers to assess the quality of the environment for everyone: neonates, families, nurses, and medical professionals, and therefore evaluate the care quality that the hospital is delivering.

The next sections will explain each screen in detail and will clarify what exactly is visualised with each component. Last, the system architecture is explained.


Figure 25: SOUNDscapes dashboard

**ENGAGE**
**MOTIVATE**
**CHANGE**

## 8.2 Dashboard elements

**Sound level trends: description**

The dashboard has two main screens: sound level trends and the constellation map. In this section, I explain first the sound level trends screen followed by the constellation map.

The aim of this screen (see figure 26) is to give an overview of all the data the system is processing and visualising. The system will be capable of real-time data processing, with a delay of less than one second.

**Sound level trends**

The sound level trends screen displays sound levels together with sound events detected. The goal of this screen is to give an overview of dB levels at the unit.

**Current sound levels**

The three tabs; current sound levels, past sound levels and compare sound levels provide graph trends of dB levels coming from alarms, speech and medical equipment. The next page elaborates and explains more in-depth each one of the tabs.

**Maximum reach**

This tab provides the maximum dB levels reached in the last 24 hours.

**Today's trend**

The goal of displaying this value is to compare the overall current levels to the last 24h. In this case, 10dB up means that the current sound levels are 10dB higher than 24h ago.

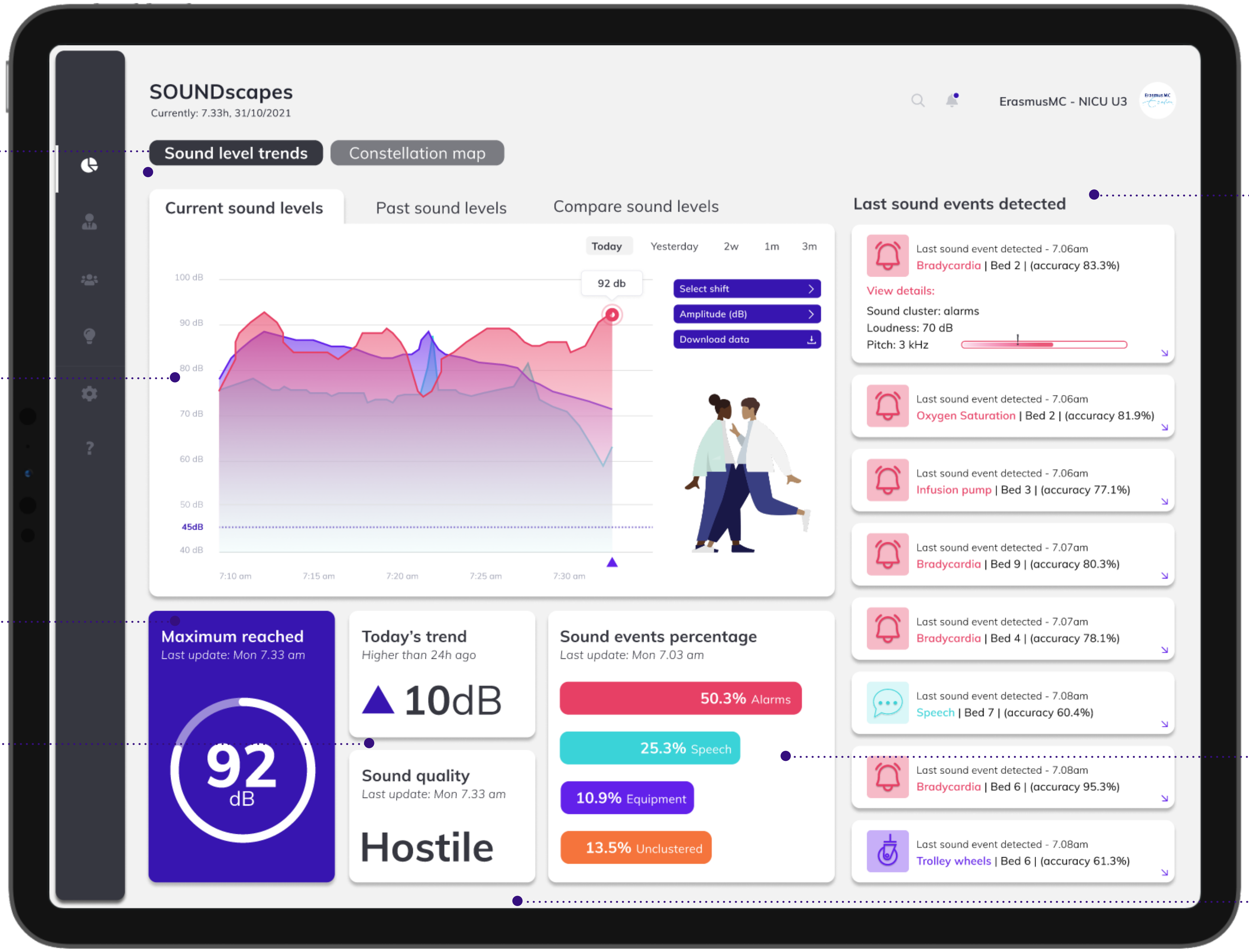



Figure 26: sound level trends screen

**Last sound events detected**

This section shows the last sound events that the system has detected, which area, and the accuracy of the system's performance. As explained in subsection 4.4, alarms are designed with a specific pattern, and therefore heir detection is easier than other sound events such as speech. The estimated accuracy rate for alarms displayed here is based on literature studies (Carmel, Yeshurun, & Moshe, 2017).

*View details*

Nurses are not familiar with sound taxonomy, but it is important to display loudness and pitch as basic sound characteristics. Even though this thesis did not conduct sound measurements, the dB level of the alarm and the frequency are extracted from literature (Thomas & Uran, 2007; Darbyshire et al., 2019).

**Sound events percentage**

The system displays the percentage of detected sound events from the four different clusters.

**Sound quality**

Sound quality is assessed in the next screen, the constellation map. However, since this screen provides an overview of the system's data, sound quality is also represented with a written expression.

## 8.2 Dashboard elements

### Sound level trends

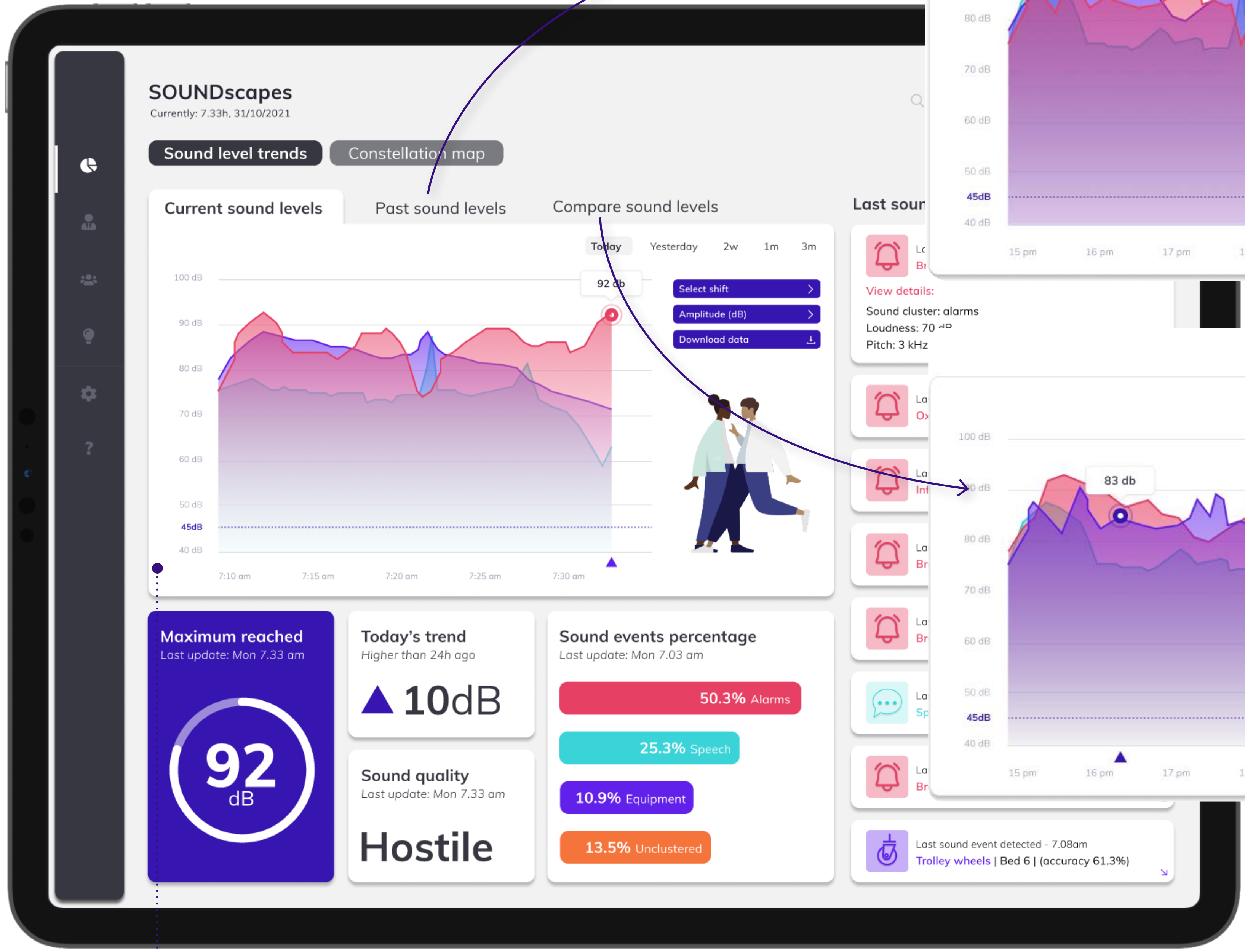



Figure 26: sound level trends screen

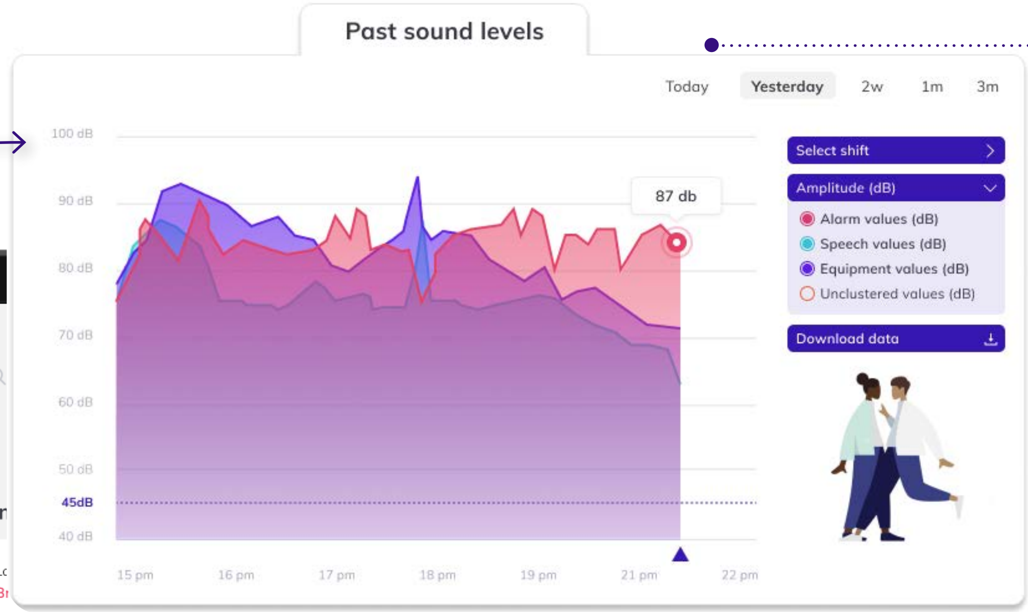



Figure 27: past sound levels tab.

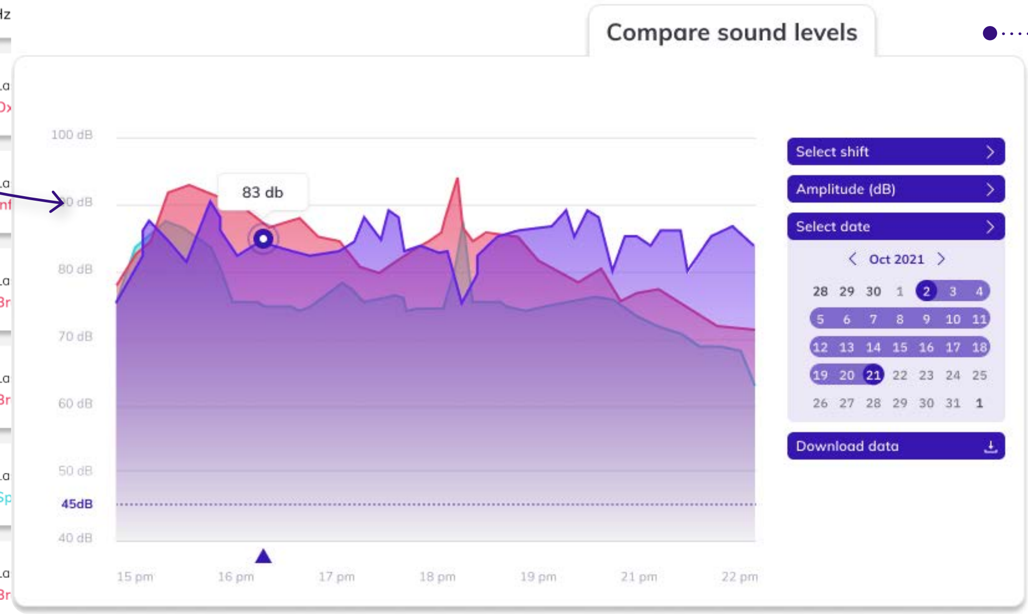



Figure 28: compare sound levels tab.

**Past sound levels**

The past sound levels tab retrieves data from the day before (yesterday), two weeks, one month, or three months ago. As studies from the literature indicated, there should be a significant improvement in the sound levels after three months. Therefore, the maximum that the dashboard can retrieve is three months (Elander & Hellström,1995).

**Compare sound levels**

This tab aims at comparing the trends between two periods to see how they have changed. For instance, as shown in figure 27, the system would compare trends from October 2nd with trends from October 21st.

**Current sound levels**

This tab displays real-time sound levels during the last 20 minutes. It provides three graphs that show the dB average trend. The graph differentiates between alarms (purple), speech (green), and purple (medical equipment). A horizontal doted line shows the limits of sound levels the unit should not overpass, as recommended by the WHO.

Moreover, the user can choose to see the trends levels within different shifts (on the same day), select the sound level graphs or download the data for further analysis with healthcare managers.

## 8.2 Dashboard elements

### Constellation map

The goal of the second screen is to map the multiple sound events that the system localises. The analogy of a constellation map was extracted from the ideation process (see appendix F).

The idea is that each sound cluster (alarms, speech, medical equipment) is mapped in the area and is represented by an icon (see legend in figure 29).

Ultimately, this screen will help nurses have real-time feedback on unpleasant sound sources in each bed and workstation.

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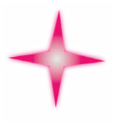
**Real time video**

The constellation is a real time video that translates each sound cluster into a constellation element.



***Alarms***

*Brightness of the star:* Alarms' frequency usually goes from 2.5 kHz to 3.1 Khz (Darbyshire et al., 2019). The more the alarm repeats and the higher the frequency, the more brightness it will have.

*Size of the star:* The size of the star will vary depending on the loudness of the alarm. Ranging from 56 dB to 88 dB (Bremmer, Byers, & Kiehl, 2003; Thomas & Uran, 2007).

***Speech***

*Brightness of the star:* Fundamental frequencies from human voices go from 85 Hz to 255 Hz (Baken, 2000). The more the alarm repeats and the higher the frequency, the more brightness it will have.

*Size of the star:* The size of the star will vary depending on the loudness of the speech. Ranging from 49 dB to 64 dB (Bremmer, Byers, & Kiehl, 2003; Thomas & Uran, 2007).

***Medical equipment***

Medical equipment will be challenging to detect given the multiple sound tags that would have to be created in advance. Therefore, the system will only change the size of the star based on the loudness of the sound event. Ranging from 50 dB to 140 dB (Bremmer, Byers, & Kiehl, 2003; Thomas & Uran, 2007).

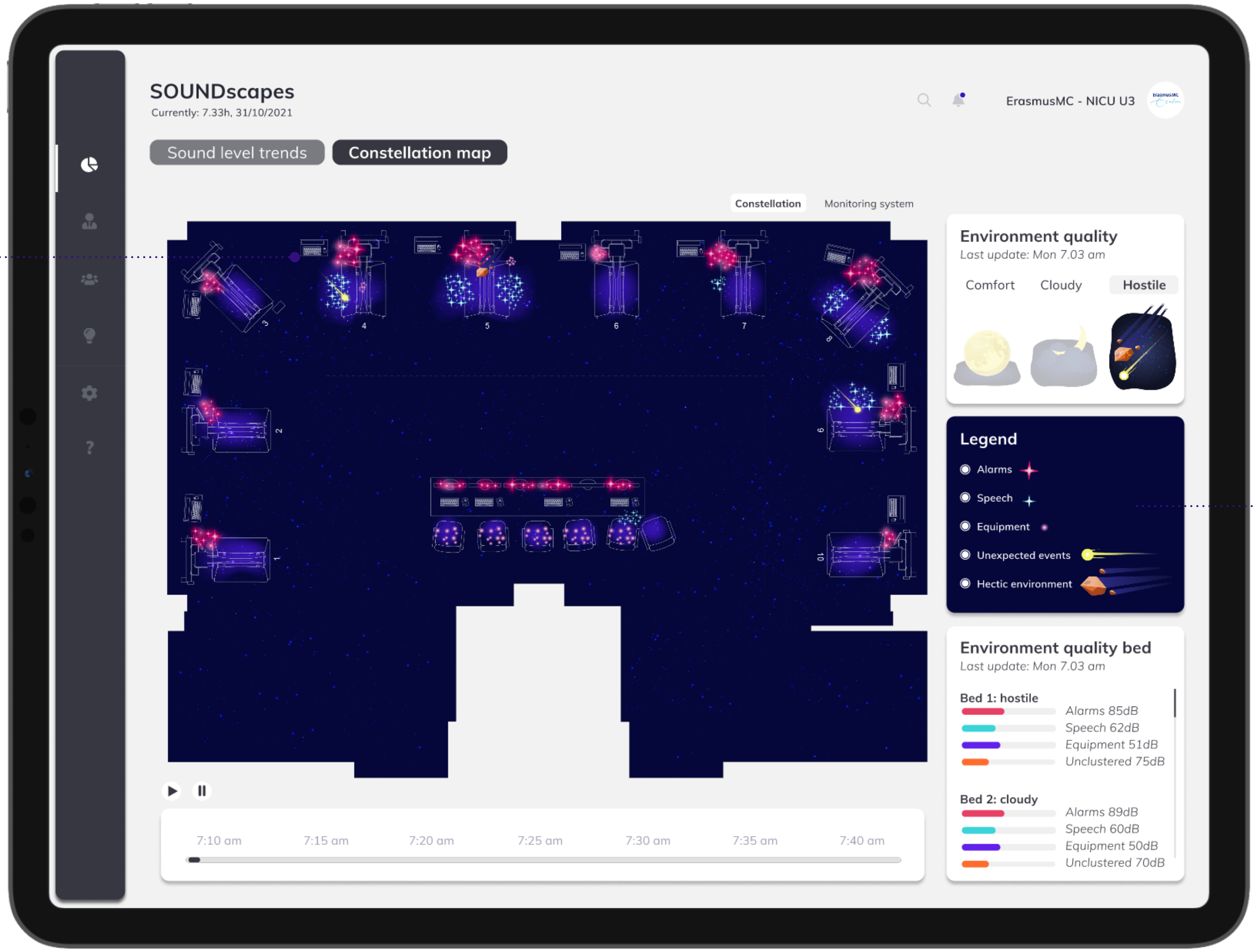



Figure 29: constellation map screen

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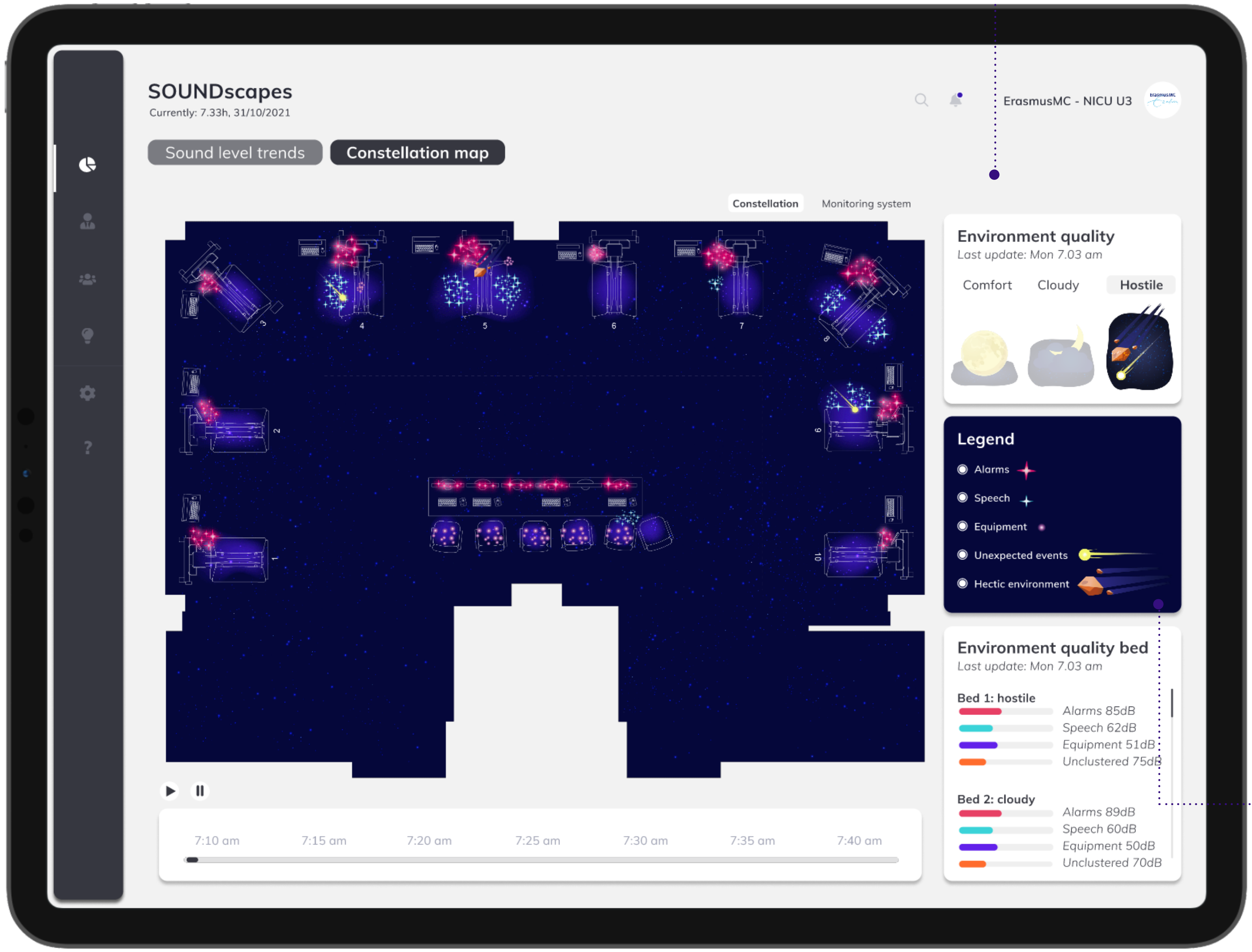



Figure 29: constellation map screen

**Environment quality**
The goal of this component is to evaluate the sound quality, depending on how people perceive the sound events detected. The system will assess the quality of the environment every 20 minutes. There are three modes: comfort, cloudy and hostile. Based on the insights gathered in the user research, the following assumptions are made:

***Hostile***
The hostile environment has unpleasant sounds for people. Based on the user research activities, the most unpleasant and annoying sounds for nurses were: the bradycardia alarm, apnea alarm SaO2 and speech.

***Cloudy***
The cloudy environment is a midpoint between the hostile and comfort environment. It is a degree less than the hostile environment.

***Comfort***
The comfort environment is the most pleasant. Almost no speech is detected nor unexpected events.

***Unexpected events***
The meteorite will fly over the NICU area when an unexpected sound event is detected.

***Hectic environment***
Asteroids will fly over the NICU area when alarms repeatedly sound at high frequencies for more than 10 seconds, together with the contribution of speech levels higher than 65dB.

## 8.2 Dashboard elements
### Constellation map (sensors system)

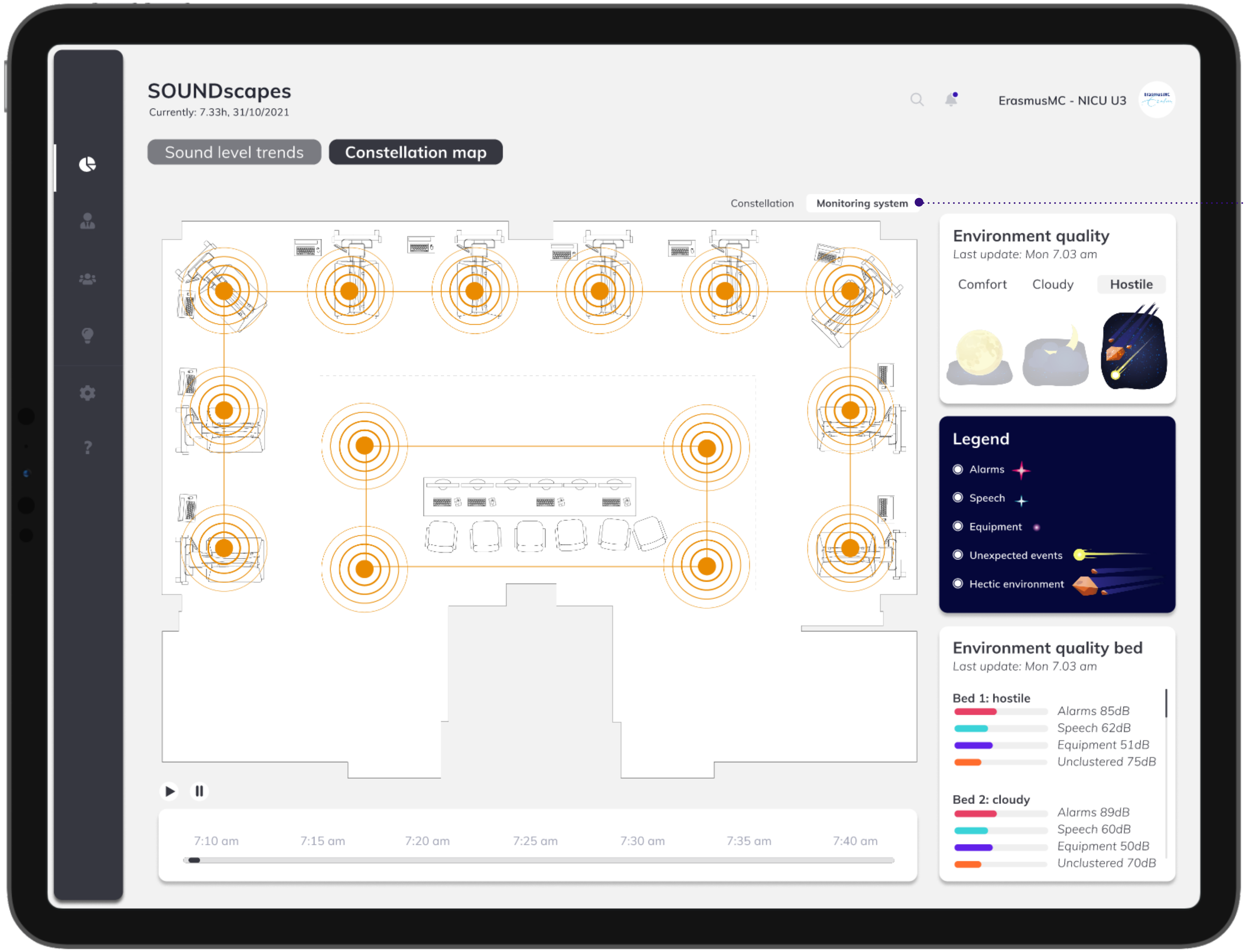



Figure 30: constellation map screen

**Monitoring system**
The monitoring system will consist of a grid of 14 microphones that will be at the ceiling. The system will slightly delay from the moment sounds are localized and clustered until they are visualized at the dashboard.

**8.3 System architecture**

SOUNDscapes, apart from being visualised on a screen, has a system architecture behind it that composes the whole system. The proposed architecture for the monitoring system is visualised in figure 32. The system continuously captures sounds occurring at NICU with the arrangement of 14 microphones positioned on the ceiling. The sound signals are sent to a computer where the sound processing is run.

**Machine listening**

With the help of machine learning (ML) technology the detected sound data will be interpreted. As shown in figure 31, to allow this data interpretation through a ML algorithm, the algorithm must be trained upfront with training data. This will lead to a trained algorithm. Ultimately, the trained algorithm will be fed with the captured data by the sensors. Finally, the application algorithm interprets the input data and classifies individual sound events and their intensity.

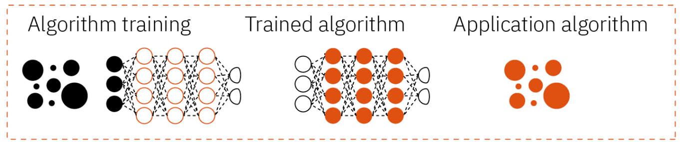



Figure 31: machine learning approach for algorithms applications

Each category of sound - alarms, speech and equipment - will be displayed in the system and visualised through the platform. The data that the platform will visualise will have two main users.

- Nurses

The principal users of the platform are nurses. The data displayed informs them about the current sound levels, past sound level trends and sound sources. The platform is aimed at providing them with a better sound representation and understanding.

- Healthcare developers

Nurses are not supposed to take the lead in evaluating the outputs of the platform. Instead, healthcare developers should discuss and compare the trends and then, together with nurses, discuss the issues causing uncomfortable sound levels.

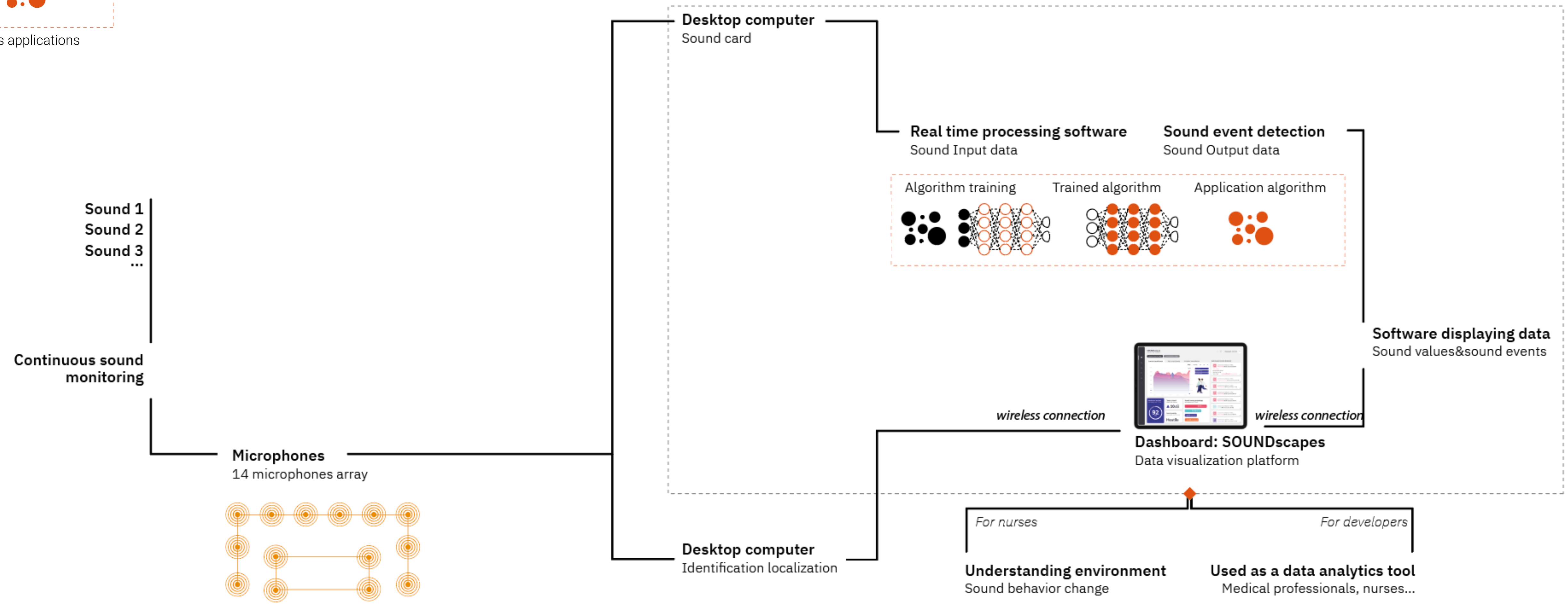



Figure 32: system architecture

Image source: ErasmusMC

Figure 33: NICU unit 3 at ErasmusMC

## 8.4 Implementation

### Physical settings

As seen in figure 33, the nurses’ workstation is already filled with screens displaying patient data. The dashboard would be displayed on an iPad device in the same workstation. The advantage of using this device is that it is small, does not take much space, and can be moved to other units if necessary.

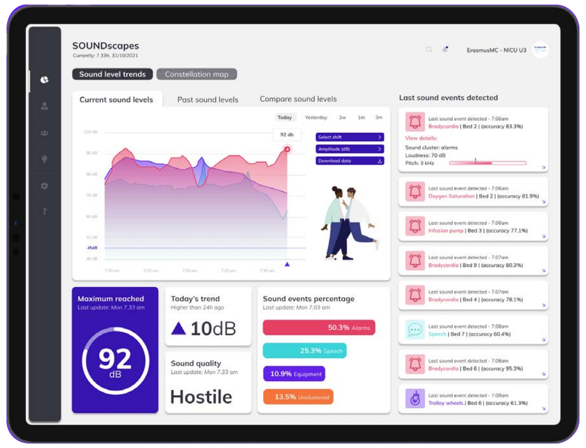
Nurses have multiple devices that they have to attend to, therefore adding this new dashboard in their working environment might be sensitive to not get enough attention. Instead of desplaying data 24/7 the dashboard will have three different modes - available, night and constellation.

The design of the three different modes, was a section iteration after conducting the evaluations



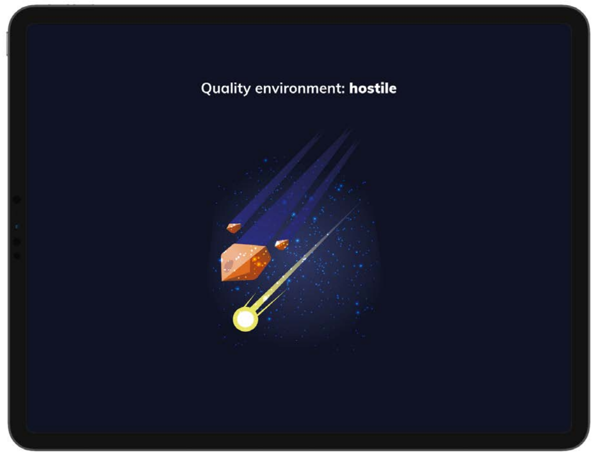


**Available mode**




This mode will be turned on when someone interacts with the interface.

**Night mode**




This mode is like a screen saver. When there is no interaction with the device, the dashboard will display the quality of the environment.

**Constellation mode**

This mode will be on when there is a hostile environment, so nurses can directly see critical areas in the unit and take action. Probably, during shift overlap, this mode will be activated.

## Chapter conclusion

The design solution that has been presented in this chapter is the first step towards mapping and addressing sound hazards at NICU. It is the first tool that will give a visual sound representation to nurses and potentially increase their awareness of the different types of sound sources that occur at NICU.

The resulting solution is seen as a high-fidelity prototype that must be tested with the different networks of stakeholders to evaluate the challenges and the impact it will have. This part is addressed in the next chapter.

9

Chapter 9

## Evaluation I: expert interviews





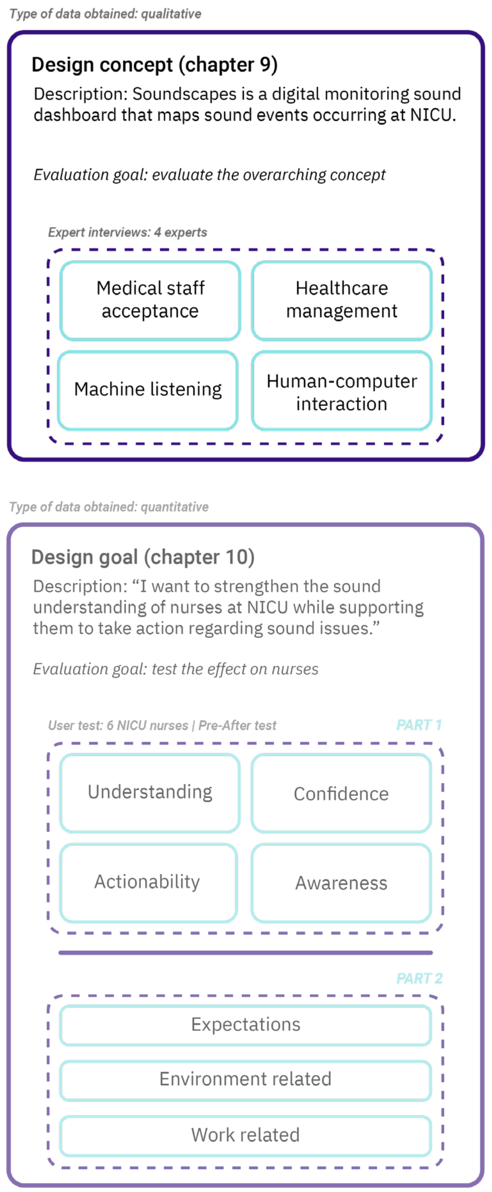
## Chapter introduction

The following two chapters present two types of evaluations conducted: expert interviews and user tests with nurses. Design concepts, products or services need to be evaluated by the network of stakeholders who will interact with them. The main goal of conducting evaluations is gathering insights to continue the iterative process to ultimately improve the design.

However, evaluations are not one-size-fits-all, and consequently, different methods need to be tailored depending on the aim of the evaluation and what needs to be evaluated. Certainly, an assertive way is to involve users and individuals who are experts within the project's area. With that said, I decided that I needed two types of evaluations: expert interviews and desirability testing with nurses. I divided these two types of evaluations in two chapters separately.

# 09
# Evaluation I: expert interviews

**9.1 Purpose of the evaluation**
The expert interviews aimed to do a more overarching evaluation to point out common pitfalls and enhance the design concept. Therefore multiple perspectives were needed. User testing could not provide this data because it relies only on the perspective of the user. Four key aspects of the design were evaluated, with experts in that field that could provide a representative and critical view on the design. The four aspects were the fields that the design touches upon:




Medical staff acceptance: nurses as principal users
Healthcare management: healthcare managers
Machine listening: sound evaluation
Human-computer interaction: digital dashboard

Figure 34 provides an overview of the differences between both evaluations.

**9.2 Experts**
Given the four areas of interest – medical staff acceptance, healthcare management, machine listening, and human-computer interaction – people who are experts within each of these areas were contacted. The experts were either part of Delft University of Technology or Erasmus MC and are listed below:

<u>Prof. Dr. Ir Alessandro Bozzon</u>
Alessandro Bozzon is a professor from the Department of sustainable Design Engineering at the faculty of Industrial Design Engineering (IDE) and part-time professor at EEMCS faculty of Delft University of Technology. His expertise is at the intersection of human-computer interaction, human computation, user modelling, and machine learning.

<u>Prof. Dr. Dave Murray-Rust</u>
Dave Murray-Rust is an associate professor in Human-Algorithm Interaction Design at the faculty of Industrial Design Engineering (IDE) of Delft University of Technology. His research lies in the messy area between humans and technology, and he has a particular interest in AI and creative practice, particularly applied to music.

<u>Prof. Dr. Irwin Reiss</u>
Irwin Reiss is head of the neonatology department at Erasmus MC-Sophia hospital, with almost 30 years of experience in preterm children. He has co-written approximately 250 scientific publications. His expertise lies in neonatology, lung chronic disease in premature infants, healthcare transformation and family-centred care.

Figure 34: Evaluation framework. The outlined part is the part evaluated in this section.





<u>Lieke Zuidema V.H.</u>
Lieke is an intensive care unit nurse who works at the neonatology department.

**9.3 Methodology**
All experts were contacted via email. The interviews were conducted online with video call software, and experts were interviewed separately. The interviews all followed the same structure: first there was a brief explanation of the project's context, problem definition, and design solution.

The prototype was shared with them to see the main functions and used as an artifact to initiate discussion. Nonetheless, as all experts were available for a restricted time, semi-structured interviews were prepared to make sure that all key aspects of the expert field were covered. The semi-structured interview questions can be found in appendix F. The questions prepared for each expert were used as statements to initiate discussion and evaluate certain aspects of the design.

The interviews provided insights that were analysed and clustered in five different categories. Each cluster is supported with quotes from the interviewees, divided into **strengths** and/or **challenges**.

**9.4 Product evaluation results**
The data that was generated during the interviews was analysed and the following clusters emerged: *general observations about the product, activating behaviour change, bridging the human factor with technology, envisioning a data coordination centre and challenges of machine listening in AI applications.*
In each cluster, a summary of the principal observations is provided and supported with quotes from the experts. Abbreviations for the experts' names are used to indicate who the quotes belong to:

- Prof. Dr. Ir. Alessandro Bozzon (AB)
- Prof. Dr. Dave Murray-Rust (DM)
- Prof. Dr. Irwin Reiss (IR)
- Lieke Zuidema (LZ)

**General observations about the product**
The prevailing opinion was that the project was a good starting point for sound management and that it was relevant enough to be considered as a minimum viable product (MVP). However, from a critical perspective, there were some prevalent concerns. The first point is regarding the technology challenges in mapping sound sources in such a noisy environment and the level of accuracy that the system could achieve. The second one was about the overload of dashboards and the interaction that individuals have with such technology. Implementation is key in providing clear steps on what the product is going to be used for, because otherwise, it would be an addition that would not succeed in the long run. Both subjects are addressed more in-depth in the following subsection.

*"But in some way, to me, software and hardware are not a problem anymore. How are you going to implement it? (...) here is where people fail. Sometimes, the idea is very nice. It is either authorities' issues, or it has failed because it is not well implemented." (IR)*

**Strengths**
*"(...) I think this is the first time that people are making visible what they listen, and this is perfect!" (IR)*

**Challenges**
*"A classical issue with dashboards is that they are designed to impress, but not to be useful." (AB)*

*"We have to think about the next step. How are you going to implement this and then by the implementation process, how to adapt nurses' needs to your system?" (IR)*

*"(...) you have to change behaviour, and you are not going to change it in between one day. At this moment, we do not know what happened in the unit, and with this platform, they have fantastic insight from all the sound events." (IR)*

**Activating behaviour change**
The experts reported that the ultimate goal of such a dashboard would be to trigger behaviour change in individuals working permanently at NICU. In this case, nurses are targeted as the primary users of this dashboard. However, the network of professionals that this product should reach also includes staff who perform their work at the unit but more sporadically, such as doctors, ambulance staff, and care assistants. Additionally, implementing this dashboard in the NICU is not necessarily imperative of success. Dashboards need to be actionable, which means that they need to tell or suggest people what to do with that information. Otherwise, we designers or developers showcase performance instead of providing actionable and useful information for the user. Experts also reported another point that was also linked with actionability: awareness. It goes without saying that the digital dashboard will provide awareness regarding the sound environment at the NICU. However, the experts outlined that awareness must be applied in a specific context. Otherwise, it might lead to a stressful situation for the user. The system must suggest potential actions to take, instead of just displaying data and analysis.

**Strengths**
*"If I look at the constellation, I see that there is a lot of noise due to speech… I would approach my colleagues and suggest them to move the conversation somewhere else." (LZ)*

**Challenges**
*"Awareness makes sense in a given context and it is also useful if it is actionable." (AB)*

*"So I think if you really wanted to give something which is really useful to them, I think you need to try to maybe elicit some reactions, not only about the UI per se, but also about what they will actually use it for." (AB)*

*"(...) the dashboard will provide information that you know, somehow it will lead to some actions." (AB)*

**Bridging the human factor with technology**
Some of the expert concerns were how to address the interaction that nurses would have with technology. On one side, technological implementations are aimed to ease the workload of medical professionals. However, if not appropriately designed, they might do more harm than good, leading to a situation in which people do not make use of the implementation.

Currently, nurses are oversaturated with dashboards and devices. Certainly, they are a great tool for conducting their clinical work, but to some extent all the amount of alarms that they have can overstimulate them. If this growth continues to be exponential, they will not be able to attend all the information provided. This critical point was stressed by the experts, who claimed that designers are the advocates for bridging between technology and humans. Providing the proper implementations and strategies that address this issue.

*"We have to take care that we are not going to overload our nurses and if you would put this on the wall on a unit app people are looking, but how are you going to catch them and see: here is a problem." (IR)*

*"You know, you have to attend to all the alarms, but sometimes you are with one baby and cannot attend all of them at once and they keep going on and on and on." (LZ)*





*"You show things just because you can, but then people need the dashboard not because it is just a nice thing to see but because they can do something with it (...) but that is what needs to be designed to support those affordances otherwise it is just a nice showcase of what could be done. " (AB)*

**Challenges**
*"What you say is, what is a challenge? It is quality improvement, you know, when you implement something, you have to educate people, and always to show again, where are we now? Where are we coming from? What do we need? This is bringing technology and the human factor to this is what we need." (DM)*

*"Interesting, because reducing sound levels feels a bit like one you might want to do in real time. You might want to have a big red light that goes on when people are making too much noise which would be quite an interesting intervention to play with." (DM)*

**Envisioning a data coordination center**
According to some experts, creating a data coordination center would be one alternative to move away dashboards from nurses, and let them focus uniquely on care activities. In this department, professionals would analyze the level of care they provide and act consequently in sound issues spotted by the system. By analyzing all these data streams from the NICU, they could address problems directly with nurses.

However, in this vision, it is not clear either how such a data coordination center would deal with all the quantity of dashboards. Otherwise, there would be the same problem of actionability: lots of data streams but not actionable information. In any case, there is a consensus that this dashboard can provide excellent analytics data for nurses and healthcare developers. It is a useful measurement tool to evaluate the sound quality and localize harmful trends in the data.

**Strengths**
*"In my opinion, there should be a specific position in this data center (...) My ideal vision is to have such an operation coordinator center that you sit, and you see dashboards, you see real time alarms. Then, people who are managing this coordination center, take responsibility." (IR)*

*"If you see a unit with 10 beds, and we see that the optimal decibel is below 40dB but we see that in the last week, it was impossible to go below 80dB (...) which should be our goal then? (...) There might be a reason why we had so high dB levels. This product enables us to understand all these sound trends." (IR)*

*"Perhaps in the next day, we have to sit together, we see that there is one unit with high sound levels. In my opinion I think it does not help to people if you show that there are high sound levels… It is helpful for management, people like me to deliver high quality of care." (IR)*

*"Let's compare also other hospitals. We can also learn why in Rotterdam is 90dB but in Leiden, it is 40 dB, let's learn from each other. So you can also make benchmarking, you are now developing tool for benchmarking." (IR)*

**Challenges**
*"There are so many monitors that it is impossible for nurses to look at them simultaneously...But this sound dashboard*

*"Nurses are over fluted with technology, how are you bringing technology and the human factor? They are still a human factor. I'm a nurse, I want to take care of the neonate I want to talk to the parents etc, etc. But I can't do my job because I have to monitor everything. This can't be the future. I think we have to think about this." (IR)*

*or real time visualization of data, they are not looking to this continuously. This is something which has to be in such operation and coordination data center. Where people are sitting, looking to those dashboards, looking to real time visualization and making also priorities of which patient is now at the highes risk according to the data." (IR)*

**Challenges of machine listening within AI applications**
Among experts, there was a strong concern regarding the technical feasibility of the product. The main point they all reported was having a system with such big accuracy, which is very difficult given all amount of noise and overlapping sounds that occur at the unit. In fact, not only being so accurate about the sound sources but also the localisation of these sources is ambitious. Nonetheless, some sound sources might be easier to cluster than others, which is the case of alarms. In fact, the design of alarms itself, makes the detection and the sound characterisation easier.

The evaluation that the system does regarding the quality of the environment was seen as positive, and experts suggested that characterising the sound qualities might be easier than characterising the whole sound events.

**Challenges**
*"I think getting some characteristics is easier than getting the individual sound effect of sound events, by quite a long way, because there's a lot of them that are properties of the system." (DM)*

*"It is certainly not easy in general, I guess the good thing is that alarms are designed to be distinctive. So you have a good hope that you might be able to pull them out and other very useful thing I suspect is that you can make alarm sounds on purpose." (DM)*

*"Careful, because being so accurate about the source of noise, it is difficult. With the current techniques it is very difficult to obtain such high accuracy." (AB)*

*"My guess is, it is mostly not terrible if you get that wrong. So if you misclassify, I do not know, a crying baby as an alarm… But it is probably not terribly bad, because you're not using this to respond to the alarms and it probably has similar psychological effects." (DM)*

*"I definitely think you have a noisy environment with lots of things that overlap and lots of things that are poorly defined, so I think doing all of it is probably hard specially to do a full-on source separation thing, but I suspect doing a classification thing is a lot more doable, but definitely not impossible." (DM)*

## Chapter conclusion

This chapter has been very inspiring, not only for the quality of feedback but also for obtaining an unbiased perspective from stakeholders how have not been involved in the development process. The major takeaways from this first evaluation are:

- The dashboard is an excellent starting point for sound monitoring. However, an evaluation plan would give healthcare managers guidelines on the implications of such a product.
- The dashboard must show clear actionability to nurses. Otherwise, it is a showcase of what the system is capable of doing.
- It might be very challenging to map all the sound-producing events at the unit. Given the designed pattern that alarms have, starting with mapping these events should be the priority.

10

Chapter 10

## Evaluation II: product evaluation with nurses





## Chapter introduction

This chapter presents the second evaluation. The aim of this evaluation is to see the impact that the design could have on nurses, the actual users. The chapter is divided as follows: first, the purpose of the evaluation is presented. Then the participants are introduced, followed by the methodology of the evaluation. Finally, the results of evaluation II are presented and discussed. The limitations that the testing has faced are presented at the end.

# 10
# Evaluation II: product evaluation with nurses

## 10.1 Purpose of the evaluation
The first part of the evaluation was to obtain overarching feedback on the design concept. Conducting expert interviews was very valuable to substantiate the strengths and weaknesses of the design concept.

However, the second part of the evaluation aims to validate the effect on the nurses. The goal is to test the desirability of the design rather than usability. The design goal is used as the guideline for the evaluation, and the design characteristics explained in subsection 7.2 are used as assessment criteria. The process followed in evaluation II is explained in figure 35.

*Design goal: I want to strengthen the sound understanding of nurses at NICU while supporting them to take action regarding sound issues.*

*Assessment criteria: understanding, confidence and actionability and awareness.*

## 10.2 Participants
Contrary to the expert interviews, which could be well scheduled in advance, recruiting nurses in advance for this second evaluation was more complicated. Therefore, I decided to go from their lunch break until the day and evening shifts overlap. The test was conducted within the mentioned time and a total of 6 NICU nurses participated in the evaluation, as shown in table 3.

| PARTICIPANT | GENDER | SENIORITY | AGE |
|---|---|---|---|
| Participant 1 | Male | 8 years | 38 |
| Participant 2 | Female | 21 years | 55 |
| Participant 3 | Female | 18 years | 52 |
| Participant 4 | Female | 4 years | 31 |
| Participant 5 | Female | 13 years | 47 |
| Participant 6 | Female | 20 years | 58 |

Table 3 : participants characteristic for the product evaluation


Figure 35: Evaluation framework. The outlined part is the part evaluated in this section.





## 10.3 Methodology
Prior to conducting the second evaluation, an evaluation plan was designed. The full evaluation plan can be found in appendix G. The evaluation test with nurses consisted of two parts.

Part 1
The first part was a pre and post-test. The purpose was to see the design intervention's effect on nurses' awareness and understanding of the soundscapes at the NICU and validate the design goal. The test consisted of four questions with a Likert scale (1=strongly disagree, 5=strongly agree).

Part 2
The second part of the test also consisted of a Likert scale questionnaire (1=strongly disagree, 5=strongly agree) to assess how the design intervention would impact the nurses' workflow. This second part was proposed to be in an interview format. However, since nurses had restricted time to perform the test, it was changed to a questionnaire format.

## 10.4 Product evaluation results
Part 1
The aim of this project is to map sound events happening at the NICU, and help nurse understand better sound sources and the quality of the environment they work in. Ultimately supporting them in taking actions and triggering behaviour change. In this evaluation section, I introduce and discuss the results from the four core elements of the design intervention: Understanding, confidence, actionability and awareness. The results are the outcome of the pre-after test questionnaire (see appendix H).

### Confidence
The results from the confidence gained are shown in table 4. Tabe 4 shows relevant values from the data analysed comparing before and after test: minimum score, maximum score, mean, median and standard deviation. The scores from the before and after design intervention show a slight increase of 0,33 points. These values provide evidence that the design intervention helps nurses to feel more confident when knowing sound levels at NICU. Additionally, figure 36 supports this statement since the number of cases scoring 3 and 4 on the likert scale has increased.

| | | | Min. | Max. | Mean | Median | Std. deviation |
|---|---|---|---|---|---|---|---|
| CONFIDENCE | I'm confident in knowing the sound levels at NICU | Before test | 2 | 4 | 3,17 | 3 | 0,7527 |
| | | After test | 3 | 4 | 3,50 | 3,5 | 0,5477 |

Table 4: Minimum, maximum, mean, median and standard deviation scores obtained in the pretest and posttest. The aspect analyzed is confidence.

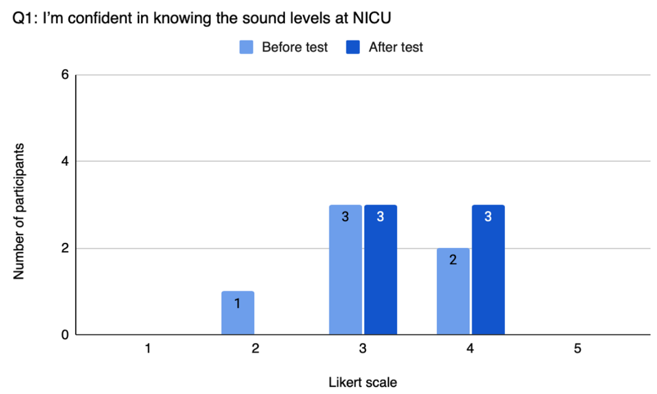



Figure 36: Number of scores increased before and after design intervention.

As the results from both figures 36 and table 4 show, overall participants scored better after the digital dashboard was shown to them. I can interpret that the design intervention supports nurses in their confidence when they want to know or guess the sound levels at the NICU.

## Awareness
Table 5 & figure 37 show the results from the awareness factor. Table 5 provides an overview of the variables measured in the pre-test and post-test.

Even though the mean scores for both before and after show no significant difference, figure 31 scores provide a more consistent significance. Cases are higher and more concentrated on the after-test, 4 participants scored 4 and 2 participants scored 3. These results show that the design intervention does show to improve their awareness.

| | | Before test | | | | |
|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | Median | Std. deviation |
| AWARENESS | I'm aware about the sound levels at the NICU | 2 | 5 | 3,67 | 4 | 1,0327 |
| | | After test | | | | |
| | | Min. | Max. | Mean | Median | Std. deviation |
| | | 3 | 4 | 3,67 | 4 | 0,5163 |

Table 5: Minimum, maximum, mean, median and standard deviation scores obtained in the pretest and posttest. The aspect analyzed is awareness.

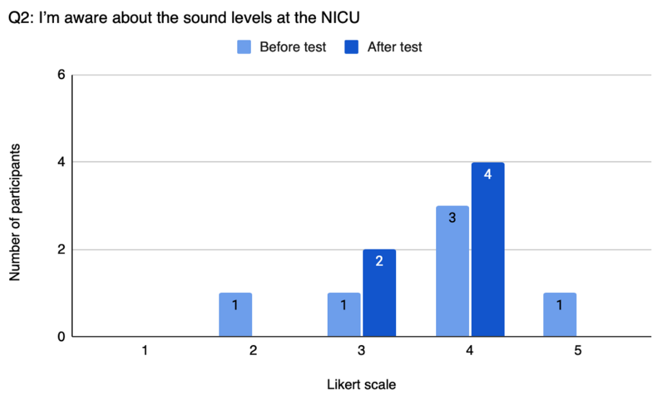



Figure 37: Number of scores increased before and after design intervention.

## Understanding
The following figures, table 6 and figure 38, show the results from the understanding factor. The mean score from both pre-test and post-test questionnaires shows a significant difference of 1,16 points, being higher in the post-test. The pre-test scores fluctuate more than the after-test, which look more consistent. Consequently, the standard deviation is 0,80 points lower in the post-test. These values indicate that participants are more consistent in scoring, strongly agreeing that the design helps them understand the sound sources at the NICU.

| | | Before test | | | | |
|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | Median | Std. deviation |
| UNDERSTANDING | I'm knowledgeable regarding the sound sources at NICU | 2 | 5 | 3,67 | 3,5 | 1,211 |
| | | After test | | | | |
| | | Min. | Max. | Mean | Median | Std. deviation |
| | | 4 | 5 | 4,83 | 5 | 0,4082 |

Table 6: Minimum, maximum, mean, median and standard deviation scores obtained in the pretest and posttest. The aspect analyzed is understanding.

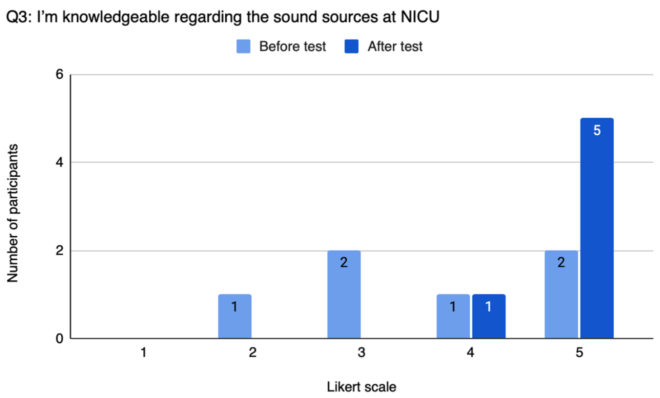



Figure 38: Number of scores increased before and after design intervention.

## Actionability
The last aspect considered for the design goal is actionability. As figure 39 shows, the mean values are 0,33 points higher in the pre-test. According to this value, the design intervention does not show to improve the actionability. Additionally, figure 39 also indicates that the results from the post-test fluctuate more than before the intervention, indicating less consistency and therefore less confidence in participants responses. However, still 4 out 6 participants scored the same in both cases, pre-test and post-test.

| | | Before test | | | | |
|---|---|---|---|---|---|---|
| | | Min. | Max. | Mean | Median | Std. deviation |
| ACTIONABILITY | I'm confident in taking action to reduce certain sound sources at NICU | 4 | 5 | 4,33 | 4 | 0,5163 |
| | | After test | | | | |
| | | Min. | Max. | Mean | Median | Std. deviation |
| | | 3 | 5 | 4 | 4 | 0,6324 |

Table 7: Minimum, maximum, mean, median and standard deviation scores obtained in the pretest and posttest. The aspect analyzed is actionability.

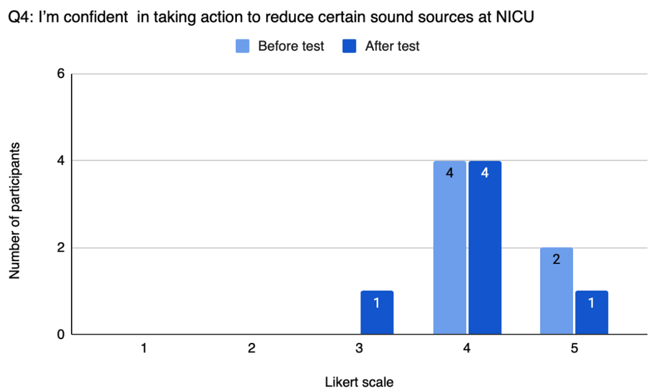



Figure 39: Number of scores increased before and after design intervention.





## Overview
Figure 40 shows an overview of all mean scores for the pre-test and post-test. Understanding the sound sources shows the most considerable significance after using the design intervention. Followed by confidence, which has little effect after the design intervention. Then awareness, which participants scored the same results on the pre-test and post-test. Lastly, actionability is higher before the design intervention. It can be interpreted that after using the interface and observing all the data displayed, participants feel less confident to prioritize the actions they have to take about certain sound events.

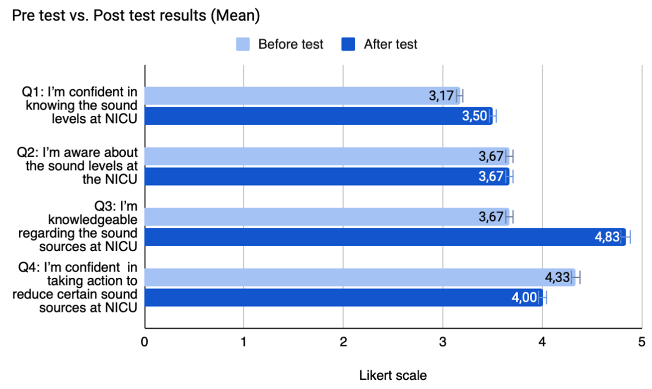



Figure 40: Overview of mean scores comparing pretest and posttest. The graph displays confidence, awareness, understanding and actionability.

Part 2
This section focuses on the effect that the design intervention would have on nurses' clinical work. It measures the desirability that nurses have for the design intervention. The three factors that were evaluated were: expectations, environment related, and work related. The data collected can be found in table 8, and the elaborated version of the user test in appendix H.

## Expectations
Table 8 shows the results from the expectations factor. The mean value for this statement is 4,17 points which indicates that according to participants, they strongly agree that the information that the platform provides is excellent. The data in table 8 show this statement to be strongly believed by participants since the range between minimum and maximum score is by just 1 point.

## Environment related
As shown in table 8, two characteristics of the design are being evaluated. On the one hand, providing data about the sound sources that occur at NICU, and on the other hand, providing an interpretation of the sound quality. The latter is evaluated lower, with a score of 4 points. In fact, supporting them in mapping the sound sources scored the highest with 4,17 points, out of the six statements provided in the questionnaire. This score indicates that for participants the platform provides clear and enough information for them to regarding the sound sources.

## Work related
The lowest scores from this part of the questionnaire are work-related. table 8shows, the platform that would support their well-being is scored with 3,83 points. Everyone mostly agrees on this statement since the minimum and maximum scores have a range of 1 point, and therefore the standard deviation is low with 0,40 points. Covering their sound-related needs and easing their clinical work, both scored 3 points. However, the standard deviation is 0,63 and 0,82 points, which shows the high fluctuation between scores. These values in the data indicate no joint agreement on whether the platform would support their well-being and ease their clinical work.

The conclusion that table 8 provides is that understanding the sound sources is considered the highest characteristic that this product would provide.

| Assessment criteria | Abbreviation | Statement/Question | Mean | Median | Min. | Max. | Std.dev |
|---|---|---|---|---|---|---|---|
| Expectations | S1 | I would define the level of awareness that this product brings as... | 4,17 | 4 | 4 | 5 | 0,4082 |
| Environment related | S4 | This product would speak for my sound quality at the NICU | 4 | 4 | 3 | 5 | 0,6324 |
| | S3 | This platform would support me in understanding the sound sources | 4,33 | 4 | 4 | 5 | 0,5163 |
| Work related | S2 | This platform would support my well being | 3,83 | 4 | 3 | 4 | 0,4082 |
| | S5 | This platform would cover my sound related needs | 3 | 3 | 2 | 4 | 0,6324 |
| | S6 | This platform would ease my workload | 3 | 3 | 2 | 4 | 0,8944 |

Table 8: score values for the assessment criteria evaluation. (1=overwhelming, 5=comforting) for statement 1, (1=strongly disagree, 5=strongly agree) for the 4 other statements.

**10.5 Evaluation discussion**

In this section, I present a discussion where I cross reference the findings from the expert interviews and the questionnaires. I address how the evaluations answer the design goal and how the findings present challenges for the upcoming future scenarios in the hospital ecosystem.

**Addressing the design goal**

The design goal aims to strengthen the sound understanding of nurses at NICU while supporting them to take action regarding sound issues. The constellation map proved to be a powerful way of giving a sound interpretation of the environment, but not actionable enough for all participants. Overall, the evaluation results show that SOUNDscapes provides enough data to inform the primary sound sources at the unit but does not provide enough tools to act. One main takeaway from the evaluations is that providing information to the nurses is not enough unless this information becomes actionable.

Actionability became a key concept during the evaluations. In fact, from the expert interviews, awareness- which this product aims to provide- was found to be only applicable to a given context and only if it was actionable. It is quite interesting that actionability was not considered a significant requirement for the dashboard, but it became more relevant towards the end of the project. In the following subsection of recommendations, I address future project could continue investigating the actionability of this dashboard.

**Collective sound behaviour change**

As mentioned in previous chapters, at the beginning of this project, the core element was behaviour change. During the literature study, it was found that behaviour change interventions for reducing high sound levels where found to be unsuccessful (W. F. Liu, 2010).

Sound-related issues at NICU were found to be the consequence of a collective set of actions. Other interventions in CAL had focused on addressing sound issues on an individual level (Lee, 2019). However, this project focused on addressing sound-related problems collectively. Changing behaviours was not only about one single individual but the whole community in the NICU. Sound reduction is about behaviour change, and it is more difficult when the change concerns multiple users.

Nonetheless, the dashboard is a very good starting point, to at least visualize and map potential sound events that can be a problem at the NICU. This might be a more feasible strategy, than trying to solve the overarching problem of high sound levels.

The drawback that this design presents, is the difficulty of displaying the correct information for every potential user, since the impact that sound has on nurses might be different. While doing this thesis, I thought I was only designing a dashboard for nurses.

Throughout the evaluation process, I realized that the nurses are the starting point of using such a dashboard. In the upcoming years, this dashboard could go beyond nurses as principle users and be used for developers to analyze and quantify the quality of care they deliver.

**New data streams**

From my perspective, when discussing about my design, I faced more questions rather than answers. From one side, the role that nurses would have to develop in an environment full of dashboards and, on the other side, the centralization of all data streams coming from dashboards.

<u>Reframing the nurses' role</u>

The future direction that this dashboard provides is a scenario where nurses must deal with tones of data analytics dashboards. Even considering that SOUNDscapes has to be improved with more iterations on mainly the actionability part, nurses' role could have major changes. Reframing their role could mean:

- Emerging role of nurse as a technical operator. A nurse profile where they are trained in technical and operational skills.
- In the upcoming years, more dashboards and devices displaying clinical data will be incorporated into the units. Removing unnecessary dashboards that do not contribute to primary care will allow nurses to have more cognitive time to devote to their clinical job.

<u>Data coordination center</u>

Medical professionals will not be able to keep up with the exponential growth of dealing with so many data dashboards. The data coordination center means a more centralized way of managing data and where experts manage, control, and analyze data. This analysis of trends and certain unit areas provides more accurate information of recurrent sound events or derived high sound levels.

- Which advantage does the data coordination center present?

One of the main advantages of having such a coordination center is that nurses will be moved away from interacting with technology and have more time to devote to their patients. The technical specialists working in this centre would address sound-related issues with the nurse lead and the department head. However, the discussion about the data coordination center is not limited to NICU but would go beyond other departments such as the adult intensive care unit (ICU).

**9.6 Limitations**

In this section I address the limitations of the evaluations. The ideal context to test the design was in the hospital. However, participants were quite busy with their daily work, and therefore, only 6 participants could be recruited. The data sample was enough to provide an idea of the evaluation, but it would be more suitable for future evaluations to have a more significant sample.

The aim of doing a before and after test was to observe the impact the design intervention had. However, due to time restrictions the test was conducted right after the evaluation. Ideally, participants should test the design for a week and then see the effect with the questionnaire.

11

Chapter 11

## Next steps





## Chapter introduction

This is the last chapter of this thesis. It presents the overarching conclusions about the project. Then it gives future recommendations regarding different paths where the project could continue or be improved. Finally, I present my personal reflection where I explain the challenges that I have encountered and the learnings that I have made working on this thesis.

# 11
# Next steps

### 11.1 Conclusion

**Addressing the research question**
*How can the medical staff and individuals at the NICU be supported through sound monitoring for improving their sound quality?*

The proposed solution provides the first step for permanent sound monitoring by mapping and visualising real-time sound-producing events. Firstly, it supports nurses by giving them the confidence to act upon harmful sound sources occurring at the NICU. Secondly, the new design advocates for nurses' sound quality, but it is also a tool that can go beyond their caring role. In the future, the neonatology department at Erasmus MC can use this platform as a new source of data streams. Healthcare developers can use its metrics to assess and evaluate the care quality that Erasmus MC aspires to deliver.

This thesis provided a holistic approach on how to address soundscapes at NICU. The evaluations proved that this project matches the current and future NICU needs, and therefore it is validated for further development. However, three areas need further improvement: implementation (healthcare management), actionability (nurses), and machine learning (technical developers).

An implementation plan would provide more specific guidelines to healthcare managers on how to embed the dashboard in nurses' workflow, considering the interactions that nurses would have with it and the technical phases that the testing would have to go through. The evaluation with nurses tested the concept's desirability, but usability should be tested to further develop and iterate on the components of the dashboard.

Lastly, the challenge in this thesis is covering more in-depth sound analysis and developing the technology that will enable the detection of sound events. The project has touched upon how other studies have used machine learning techniques to detect and localize sound levels at ICUs. However, this requires technical knowledge and in-depth reading about research that goes beyond this thesis and my capabilities.

### 11.2 Future recommendations
The proposed conclusions provided new paths in which the project could develop on further. Here I present six future recommendations:

*1*. The proposed design needs further study and exploration to facilitate the action component. Sound reduction is not only about decreasing the sound producing events but also about changing behaviours. As explained in the 9.5 section, the constellation map can be used as a tool for providing actionability, however, the evaluations demonstrated that more iteration needs to be done on the actionable components.

*2.* User research regarding sound semantics should be conducted. One of the biggest burdens when working with hospitals is the access to medical staff to conduct user research. For future interventions, I suggest to study what semantic effect each specific sound event at NICU has on nurses. This would help to substantiate the sound interpretation that the dashboard provides and to customise it in a better way.

*3*. This project has provided a prototype and evaluated how a sound dashboard would be perceived. However, the technology part is only theoretically introduced and considered but not tested and implemented. For this, a whole project should focus on mapping and localising sound in such a cacophonous environment. As explained in the evaluations and discussion, sound-producing events should be approached differently for their detection. Starting with alarms should be the priority.

*4*. The design should be tested and evaluated with bigger sample size. The evaluation and the data gathered was enough for having a slight idea about the design. Still, I suggest testing it with at least 60 participants for future implementations, which would provide enough data to do a proper statistical analysis.

*5.* I personally believe that the result of this project can go beyond only being a dashboard. As a future step, I would propose investigating how such a product can be used for nurses and how other stakeholders can embed it as a data analytics tool.

6. In line with the above recommendations, the project should be evaluated using the Value Based Health framework (VBHC) by Michael Porter, to assess the impact that this implementation could provide. Currently, Erasmus MC is working on the implementation of this framework, although not being fully implemented in all Dutch healthcare organisations.

### 11.3 Personal reflection
This thesis has come to its end, and so has my journey as a TU Delft student. I want to dedicate this last part to sharing some thoughts about what this journey has meant.

Completing this master, considering the pandemic situation, has not been an easy ride at all, rather a rollercoaster. Coming here and almost finishing my master's behind my computer was not at all in my plans, knowing that opportunities such as internships and collaborations abroad with other companies would not be allowed as long as the pandemic would continue. One of the biggest challenges has been handling frustration regarding all the opportunities that I thought I was missing in my career due to the pandemic. Nonetheless, I am proud to have completed this master's with a design specialisation - a direction that fascinates me and truly speaks for the career path I want to continue on.

Perhaps one of the biggest challenges for me initially was to stay confident in the quality of work I was producing, since I was working in a completely new topic for me. The systematic review gave me a broad basis for the research that I needed, but at the same time it was a hard nut to crack. It took me quite long to make sense out of all the data that I had generated, preventing me from taking a more novel approach on the project and look deeper into other areas such as implementation of behaviour change strategies and human-computer interaction. Having this technology driven project sometimes made me focus too much on reading and understanding technological research, which ultimately was not the purpose of my approach. Additionally, extending the project due to hospital circumstances was a little frustrating at the beginning, but overall I think it paid off to explore more and evaluate the solution that I had provided.

In hindsight, I see that all this pressure I was putting on myself was a consequence of being too hard on myself. For quite some time, I was in the spiral of overthinking whether what I had produced was the best I could deliver or not, but instead, I just kept working anyway. Luckily, I learned to take control of all these thoughts and maintain a balanced work routine, and it was then when I realized I was enjoying more the process rather than the outcome. The major personal takeaways from this project that I take are perseverance and knowing that if you always give your best, you can be fully confident of the outcome of your work.

Lastly, this project has allowed me to work on what motivates me: investigating, researching, and developing future systems for hospitals and the healthcare sector.

I hope I have inspired you with my thesis.
N.

# R

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Appendices

## Overview

# 0

## Project brief



DESIGN FOR our future

4991

TU Delft

# IDE Master Graduation

## Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

**USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT**

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

### STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Viñas Vila

initials: N    given name: Núria

student number:

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): ( ) IPD  ( ) DfI  (★) SPD

2nd non-IDE master:

individual programme: (give date of approval)

honours programme: ( ) Honours Programme Master

specialisation / annotation: (★) Medisign

( ) Tech. in Sustainable Design

( ) Entrepeneurship

### SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair:    dept. / section: Critical Alarms Lab

** mentor: Dr. Simone Spagnol    dept. / section: HCD

2nd mentor:

organisation: Ir. Tom Goos (Sophia Kinderziekenhuis, EMC)

city: Rotterdam    country: NL

comments (optional): Dr.Amila Akdag - Advisor (DOS). She is going to help me to bridge between design and machine learning (ML).

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

**Procedural Checks** - IDE Master Graduation

TUDelft

## APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair Elif Ozcan Vieira date 17 - 05 - 2021 signature EÖzcan

## CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair. The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: 30 EC

Of which, taking the conditional requirements into account, can be part of the exam programme 30 EC

List of electives obtained before the third semester without approval of the BoE

X YES all 1st year master courses passed

NO missing 1st year master courses are:

name C. van der Bunt date 21 - 05 -2021 signature CB

## FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **. Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: V APPROVED NOT APPROVED

Procedure: V APPROVED NOT APPROVED

- also approved for Medisign
- the projectbrief has been submitted late

comments

name Monique von Morgen date 8/6/2021 - signature MvM



**Personal Project Brief** - IDE Master Graduation

TUDelft

Design of a digital sound monitoring dashboard for neonatology project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 21 - 04 - 2021 24 - 09 - 2021 end date

## INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

The environment that surrounds us is full of omnipresent soundscapes that have become part of our daily life. We have developed a certain tolerance towards these noises, and to some extent, they are not extraordinary for us anymore. Yet, they are very harmful. Studies have shown that noise pollution has adverse effects on many populations, from the fetus, infants, children, adolescents to adults (Gupta et al., 2018). If we pay attention, environments with continuous noise pollution are very familiar for us; traffic, industrial areas, workplaces, commercial places, and hospitals. Among the areas mentioned above, hospitals are unique places where soundscapes are particularly difficult to assess. We could find some examples: continuous in and out of visitors, patients, alarms, medical instruments, and professionals' hectic activity generate a tremendous amount of nuisance. In complex sonic environments, people are unaware of the noise that they produce or the noise they are exposed to. Therefore, there is an urgent need to create a shared awareness about the sound pollution we generate, and our tolerance towards sound.

Inside the hospitals' ecosystem, there are several environments worth investigating. This project will focus on the Neonatology Intensive Care Unit (NICU). Compared to adult ICU, NICU is carefully designed for premature newborns who need assistance to survive (See Figure 1). They are very fragile infants whose likelihood to get sick is very high. It has the technology and trained healthcare professionals that can take care of the babies (Standford Children's health, 2021).

Even though it might look like a very fragile unit, the number of alarms and nuisance is very high, and studies show that it negatively affects both the wellbeing of patients and the performance of healthcare professionals (Bliefnick, Ryherd & Jackson, 2019). Moreover, it has also been shown that environmental noise impacts the neonate's neurodevelopment (Graven, 2000).

Given the above situation, this project will attempt to solve the noise levels and provide a meaningful solution for the neonates and staff. Some studies have only focused on nurses. However, all the awareness weight does not only rely on them. Pediatricians, surgeons, parents are stakeholders that also belong to this health value chain.

The current context and partner of the project will be Erasmus MC- Sophia childrens's hospital. The Neonatal Intensive Care Unit(NICU) has more than 700 new admissions of premature neonates and critically ill newborns every year, being an important and large subsection of the pediatrics department (ErasmusMC, 2021). Within these units, there have already been studies of alarms sound recording by implementing machine learning techniques. Moreover, this project will also contribute to the NICU's ambition to redesign the department's architecture in the next five years.

Finally, the project will be performed within the Critical Alarms Lab of IDE / TU Delft, which aims at shaping the future of alarms soundscapes in socio-technological environments, but more precisely in hospital environments.

space available for images / figures on next page

introduction (continued): space for images

image / figure 1: NICU department at Erasmus-Sophia

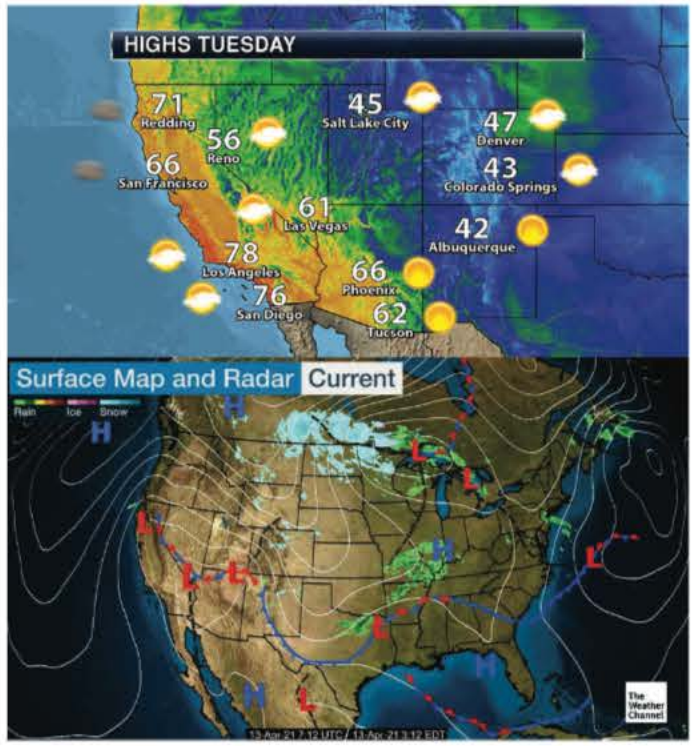



image / figure 2: Main concept idea comes from weather heat maps





## PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

Scope

The soundscapes in NICU might bring adverse effects to neonates, their family and healthcare providers. There have already been studies monitoring the sound and then analyzing and reporting its effects on neonates. However, these studies are just established for a certain period, meaning that they stop when the data recording phase is done. There are systems, such as SoundEar®, that monitor the sound within hospital units. However, there are two main pitfalls; it's not an integrated system, and the sound is given in dB. The latter is a general problem of the current systems. They rely on counting sound on dB and discarting the effect of tone and frequency, making it difficult to understand for people who are unfamiliar with the physics of sound.

Solution space

Previous projects from the Critical Alarms Lab monitored the sound individually (Doplor and CacophonyMapper). This project aims to upscale it and monitor the environment from different points, more as a whole rather than only individual moving objects. The data gathered will give input about the overall sound levels, sound sources, who have been exposed, and for how long. Simultaneously, creating perception around the sound that people generate since they are unaware of it most of the time. There is no interpretation yet about what this sound means, and even less from a human-centered design perspective.This sound monitoring system will also open new reserach possibilities in the future that will allow researchers to link the quality of phsyical sound environment to physiological and psychological effects on listeners.

## ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... . In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

The research outcome will determine the key points where sensors need to be implemented, either statically or through moving objects. By conducting interviews and observation, I will design the most suitable platform for interpreting the sound for nurses, family and healthcare providers.

The solution delivered will be on one side, an analysis of where to place the sensors and how to connect them in software to make predictions. More on a system level, an implementation overview will be provided as the outcome of the thesis.

The focus will rely on developing the digital dashboard that will help nurses, family, and healthcare providers understand and interpret the sound levels at the NICU. The tool provided will give input about different sounds happening in the room and specify which sounds existed, for how long, and who has been exposed to it. This tool aims to provide sound indexes in different parts of the room and give tips on what to do next, such as moving to conversation into another environment. The ultimate goal is to give an understandable measure of sound to decrease the sound pollution in NICU. As mentioned previously, in five years, the distribution of the NICU is aimed to be re-designed in terms of architecure. Therefore, I will create a strategy shown in a strategic roadmap showing the next steps to achieve the system's implementation.

The starting point of this system is anological to the weather forecast maps (see Figure 2) in such a way that sound sources and their identities can be mapped in the archtextural space of the NICUs and problematic areas can be visualised for betetr effect and communication.

# A

## Semi-systematic review analysis

### Collecting and processing sound

| Measurements intervals | Times mentioned |
|---|---|
| 1-s history interval | 1 |
| 90 second period( 30s, 30s, 30s) | 1 |
| recordings every 60s | 1 |
| intervals 5 seconds | 1 |
| recording second by second | 1 |
| intervetion cycles | 1 |

| Length of the study | Times mentioned |
|---|---|
| 24h each week for a total of 44 weeks | 1 |
| 12 months study | 1 |
| 40 12h period (period of three months) | 1 |
| measurements during 8 weeks | 1 |
| every 2s for 7weeks | 1 |
| every two days for a total of 7 weeks | 1 |
| recording for 4 weeks | 1 |
| 24h for an entire week | 2 |
| 24h measurement periods | 1 |
| 28 times measurements of 24h | 1 |
| 7 days recordings | 1 |
| measurements days or weeks | 1 |
| recordings for 1 week 24 h | 1 |
| 120h of data | 1 |
| one 24h period | 1 |
| measuring period 3 days | 1 |
| 31 measurements periods of 1h | 1 |
| daily during 30 minutes and two shifts | 1 |
| eight 1h recording | 1 |
| 8h recording | 1 |
| measuring for 8h | 1 |
| 1h recordings over 8h | 1 |

| Sound outcome variables | Times mentioned |
|---|---|
| A-weighted | 9 |
| level measurements (Leq, Lmax, Lmin, Lpeak, Ln) | [illegible] |
| sound intensity | 6 |
| mean dB | 5 |
| c-weighted | 3 |
| frequencies | 3 |
| measuring SPL in dB | 2 |
| loudness | 2 |
| 3 variables to evaluate sound pressure levels | 1 |
| SPL in frequency A dB | 1 |
| outcome on speech exposure | 1 |
| variations of sound levels over time | 1 |
| frequency bands | 1 |
| frequency bands from 63 to 8000 Hz | 1 |
| high frequency | 1 |
| transforming dB values | 1 |
| measurements of central tendency and dispersion | 1 |

| Calibration of the devices | Times mentioned |
|---|---|
| calibrated | 1 |
| calibrating the system | 1 |
| calibration | 8 |
| sound calibrator | 1 |
| monthly calibration | 1 |

| Analysing the results | Times mentioned |
|---|---|
| sound analysis software | 3 |
| statitical analysis | [illegible] |
| Kolmogorov and Smirnow test | [illegible] |
| Downloading data | 2 |
| Spectral analysis | 2 |
| U-test | 1 |
| ANNOVA | 1 |
| break for downloading the data | 1 |
| analysing with t test | 1 |
| recording for spectral analysis | 1 |
| analysis of loudness leveld and frequency spectra | 1 |
| store sound spectrum data | 1 |
| descriptive analysis | 1 |
| descriptive statistics | 1 |
| recording for spectral analysis | 1 |
| converting the measurements | 1 |
| autocorrelation and Fourier analysis | 1 |

| Monitoring devices | Times mentioned |
|---|---|
| sound meter level | 17 |
| dosimeter | 9 |
| hand-held SPL meter | 2 |
| four dosimeter | 1 |
| two dosimeters | 1 |
| dosimeter integrate to SPL | 1 |
| suggest LENA for speech exposure | 1 |
| lena | 1 |
| digital decibel meter | 1 |
| starling devices for speech | 1 |
| omni-directional microphone | 1 |
| obtaining data via camera | 1 |
| probe microphone tube | 1 |

### Environment distribution and description

| Sound organisations | Times mentioned |
|---|---|
| AAP(American Academy of Pedriatics) | 10 |
| EPA (Environmental protection Agency) | 3 |
| WHO | 2 |
| American National Standards Insitute | 1 |
| American Standards Institute | 1 |
| Australasian health infrastructure alliance | 1 |
| Brazilian Association of Technical Standards | 1 |
| Committe to establish recommended standards for newborn ICU design | 1 |

| Placing the device | Times mentioned |
|---|---|
| mic close to infants ear | 4 |
| mic above and behind patients head | 3 |
| mic bed site | 1 |
| Meter close to patients body | 1 |
| measuring inside incubators | 1 |
| mic in the ear canal | 1 |
| mic in the nose canal | 1 |

| Selecting the monitoring area | Times mentioned |
|---|---|
| measurement inside incubator | 6 |
| measuring outside the incubator | 5 |
| immediate care environment | 1 |
| measurements in traffic zone | 1 |
| measurements in work station | 1 |
| central position within NICU | 3 |
| placed at different heights | 1 |
| measurements in quadrants | 1 |
| diveded in zones | 2 |
| nine locations for the recordings | 1 |

| Occupacy in the NICU | Times mentioned |
|---|---|
| capacity of 25 beds | 1 |
| 10-12beds | 1 |
| 20 beds in NICU | 1 |
| 4 beds in the room | 1 |
| 45 beds | 1 |
| six bed | 1 |
| infants sensus | 1 |
| infants per bay | 1 |
| number of cots | 1 |
| number of incubators | 1 |
| seven incubators | 1 |
| patient sensus | 1 |
| incubator | 1 |
| number of neonates | 2 |

| Comparing NICU environments | Times mentioned |
|---|---|
| From OU to SFR | 3 |
| Level II NICU with NICU III | 1 |
| Comparing different NICUs | 1 |
| Compare day and nights shifts | 1 |
| Open bassinets | 1 |
| Open crib | 1 |

### Sound interactions

| Sound control | Times mentioned |
|---|---|
| awareness control progarams to parents | 1 |
| awareness control progarams to staff | 1 |
| sound control program | 1 |
| recoomend to routinely measure sound levels | 1 |
| conduct ongoing evaluations | 1 |
| continous monitoring to see noise exposure | 0 |
| control of ambient noise levels recoomended | 1 |
| routine monitoring on anual basis | 1 |
| document sound levels | 1 |

| Smart environment | Times mentioned |
|---|---|
| nonrecordable meters that alert staff | 1 |
| product giving output | 1 |
| interpreting results for hospital staff | 1 |
| evaluate parents' perceptions | 1 |
| best environment factors for neonate | 1 |

| Non-acoustic but environmental variables | Times mentioned |
|---|---|
| Air conditioning | 1 |
| Humidity measurements | 1 |
| Light measurements | 1 |
| evaluating light | 1 |
| humidity control | 1 |
| light control | 1 |
| light measurement | 1 |
| temperature control | 1 |
| temperature measurements | 1 |

| Sound sources in NICU | Times mentioned |
|---|---|
| Care activities influencing on noise | 6 |
| equipment noise | 6 |
| environmental noise | 2 |
| noise is caused most likely for staff | 2 |
| operational sound | 1 |
| staff congregate | 1 |
| problematic staff speech | 1 |
| more sound due to technology inside the incubator | 1 |
| structural sound | 1 |
| medical arouns away from the area | 1 |
| background noise | 1 |
| loudness physician hours | 1 |
| constant and disrupting noises | 1 |
| even small modification bring an increase in noise levels | 1 |
| exceeding levels due to equipment, communication | 1 |
| ward round and handover periods contribute to noise | 1 |

| Staff advocating for NICU | Times mentioned |
|---|---|
| consider noise when purchasing equipment | 1 |
| implications for nurses framework | 1 |
| when implementing new modifications, NICU personnel | 1 |
| consult nurseries for equipment changes | 1 |
| evaluating sound levels when purchasing | 1 |
| nurses need to advocate for designgs | 1 |
| nurses taking an active role in industry | 1 |

### Beyond sound and observed measures

| People cause bias | Times mentioned |
|---|---|
| people are influenced | 1 |
| Limitation only in one NICU | 1 |
| limitations determined by building | 1 |
| limitations in terms of people and neonates | 1 |
| limited to sound levels | 1 |
| nurses bias if they know the program | 1 |
| high measurements were temporary | 1 |
| staff modifying the behavior during the recording | 1 |
| studies not reporting frequencies | 1 |
| noise methods don't identify high frequencies | 1 |
| not effecting human behavior strategy | 1 |
| behavior strategy doesn't show improvements | 1 |
| loudness is subjective | 1 |

| Implementing behavioral change | Times mentioned |
|---|---|
| reduce sound: staff education | 1 |
| educate NICU staff | 1 |
| intervention protocol | 1 |
| changing caregivers behavior | 1 |
| changing caregiving behavior essential | 1 |
| modificating by educating | 1 |
| modification of behavior | 1 |
| increaseing staff consideration towards noise | 1 |
| human behavior change | 1 |
| human behavior strategies show no improvements | 1 |
| reinforcement strategies | 1 |
| staff behavior programm | 1 |
| staff behavior programm: discurssing journals | 1 |
| strategies requiere time | 1 |
| period education to families | 1 |

| Structural changes | Times mentioned |
|---|---|
| Modifying pysical elements | 6 |
| reconstruction change | 3 |
| reduce sound: plastic for metal | 1 |
| moving key elements | 1 |
| architectural, material and human resource factors | 1 |
| modifications on the equipment | 1 |
| removing key elements better than staff behavior | 1 |
| renovation better for sound levels | 1 |
| renovation of physical space | 1 |
| recommendations on key elements | 1 |
| sound attenuation flooring | 1 |
| sound dampening | 1 |

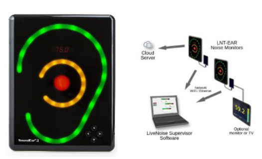
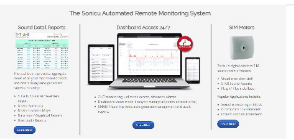
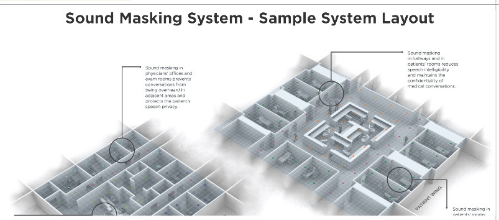
| Sound assesed qualitatively | Times mentioned |
|---|---|
| health constants neonate | 5 |
| sound surveys | 2 |
| surveys do not include observation | 1 |
| surveys give a guidance of stress | 1 |
| questionnaires to staff | 1 |
| measure speech exposure | 1 |
| infants exposed to language | 1 |
| speech exposure | 1 |
| sound contribution pulse oximetry | 1 |

| Sound education | Times mentioned |
|---|---|
| ignore the program | 1 |
| reduction of 5dB from intervention program | 1 |
| patients have their unique exposure | 1 |
| periodic education | 1 |
| monitor conversation levels | 1 |
| diversity of sound | 1 |
| | 1 |

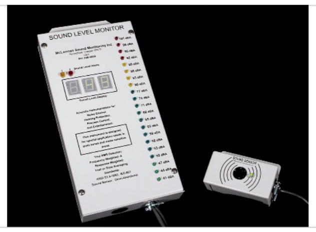
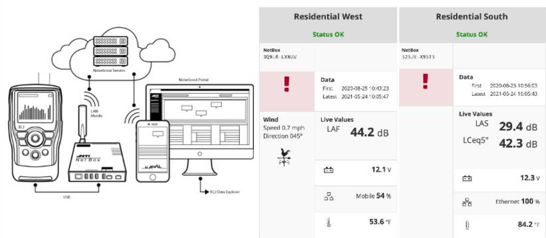
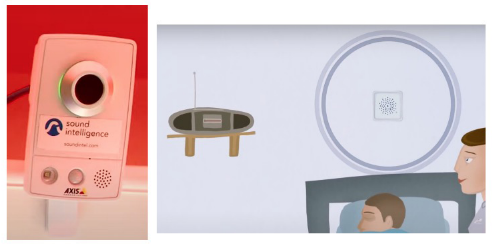
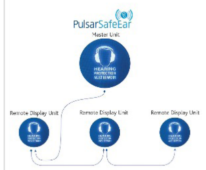
# B

## Current products available

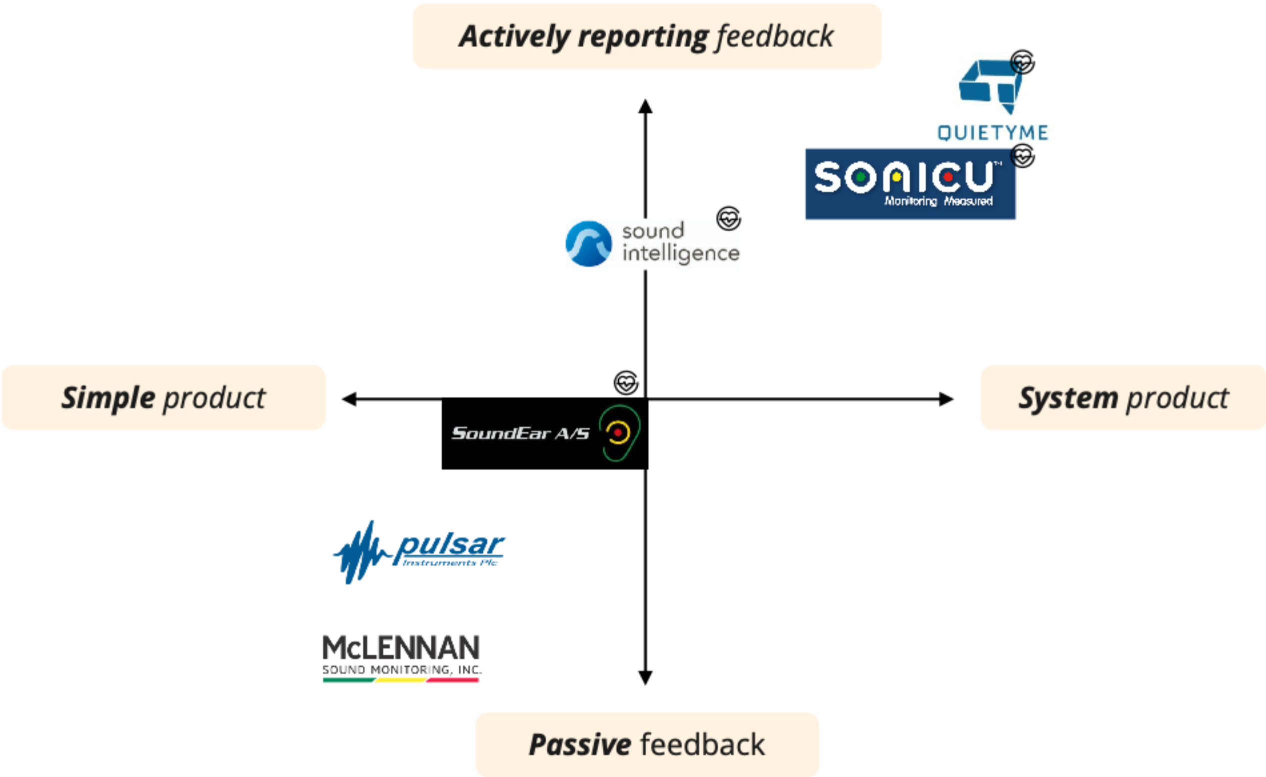
Current competitors

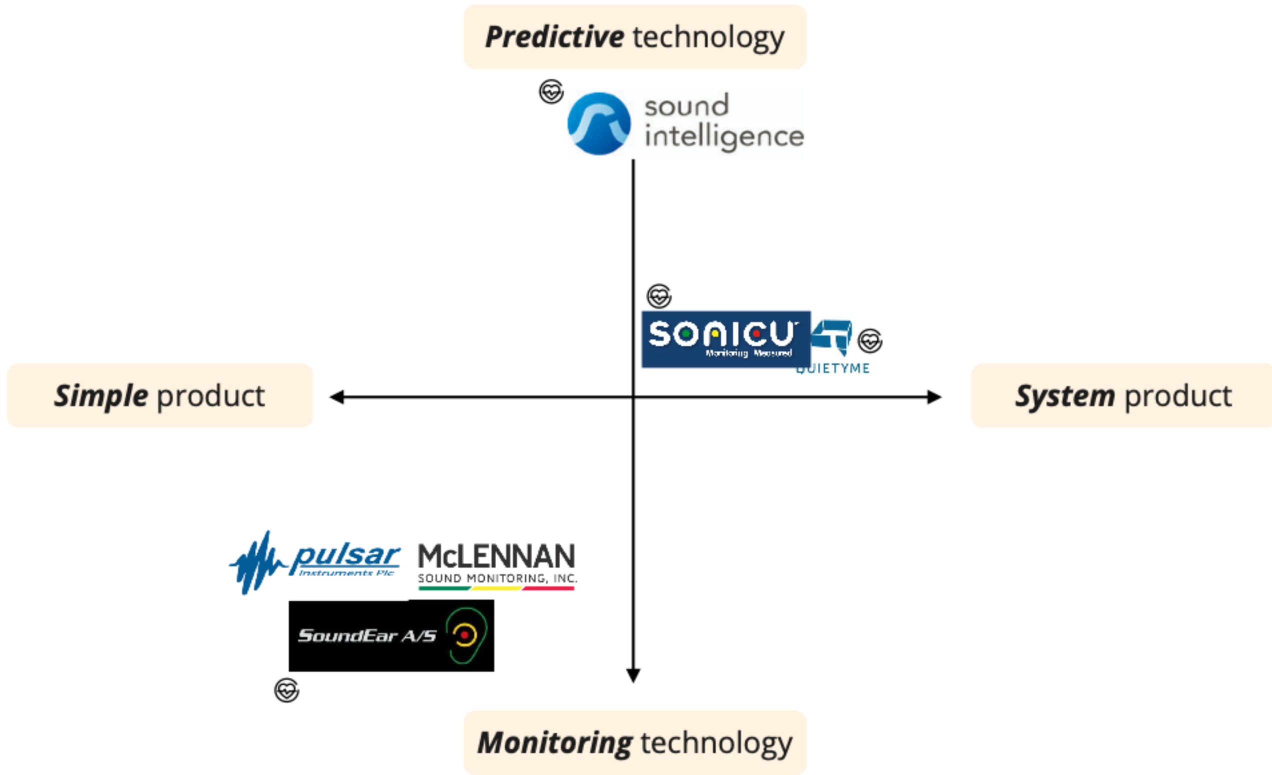
| Companies Name | | Application areas | Characteristics | Predictive sounds? | Specific for hospitals? | Country |
|---|---|---|---|---|---|---|
| SoundEar ★★★☆☆ |  | • Industry/Construction<br>• Mapping external noise<br>• Reducing hospital noise<br>• Minimizing hospital noise | • Reduces noise levels by making noise visual<br>• It helps everyone remember when to quiet down<br>• Improves the wellbeing of patients and staff (better sleep, faster recovery, less stress)<br>• Makes it easy to keep track of noise levels:<br>  ◦ Directly on the device in the room (patients, staff, visitors)<br>  ◦ In the software with noise measurements from each room displayed live (staff)<br>  ◦ Through automated noise reports sent to your email, e.g. one for each shift, for each day of the week or for each week (staff)<br>  ◦ In the software with the possibility of comparing and analyzing noise levels | | • Adult critical care unit\<br>• Operation theatre<br>• Neonatal intensive care unit | Gilleleje, Denmark |
| SONICU ★★★★☆ |  | • Healthcare<br>• Pharmaceutical<br>• Life sciences<br>• Food safety<br>• Animal health | Sonicu's wireless remote monitoring technology and cloud based management platform fully automate 24/7 monitoring, alarming, and reporting for virtually any monitoring application required. Companies choose Sonicu monitoring for complete operational visibility, superior protection and management of assets, and effortless compliance reporting.<br>SoniCloud, Sonicu's cloud based software platform, aggregates system-wide monitored data to a single dashboard, providing access to critical information from anywhere via phone, tablet, or PC, with real-time views of all departments and locations.<br><br>uses sound indicating meter (for a case study) | Cloud-based software capabilities with predictive algorithms for tailored alarming to reduce alarm fatigue and spot trends | • NICU<br>• ICU<br>• Critical Care Areas | Indiana (USA) |
| QUIETYME ★★★★☆ |  | • Healthcare<br>• Hospitality<br>• Property management | We help healthcare industries sustain a Culture of Quiet with our smart technology and Success Manager. You'll see dramatic results in your patient satisfaction scores, patients experience, and increase your HCAHPS. | Doesn't seem to be algorithms predicting which type of noise accours | • **Patient room**<br>• **Nurses's station**<br>• **Common area's** | USA |
| NOISEAWARE<br>NoiseAware<br>★★☆☆☆ |  | • Residential areas | Which meant in the beginning, our goal was simple: prevent incidents at rental properties with noise monitoring technology. And that was a great start. Our smart sensors speak for themselves in how effective they are at preventing costly damage without sacrificing the privacy of guests. We recognize that now more than ever how important it is to be a good neighbor, not just in our own communities but in the world at large. For us, that means being tirelessly considerate, attentive, and compassionate towards our customers and providing tools that make it easier for everyone to be a good neighbor. | | No. Started as a sound monitoring system for noisy neighborhoods | USA |
| Biamp. Cambridge sound<br>biamp.<br>★★☆☆☆ |  | • Office/Open office<br>• Conference rooms<br>• Healthcare<br>• Legal<br>• Government&military<br>• Finance<br>• Retail<br>• Spa | Sound masking<br><br>By promoting patient rest and relaxation. Sound masking has been shown to have a measurable positive impact on responses to the HCAHPS survey question. Studies show that patients in rooms with sound masking find that it helps to shorten the time it takes to fall asleep and prevents unwanted noises from disrupting their sleep. | No, it's based on sound masking | | ? |

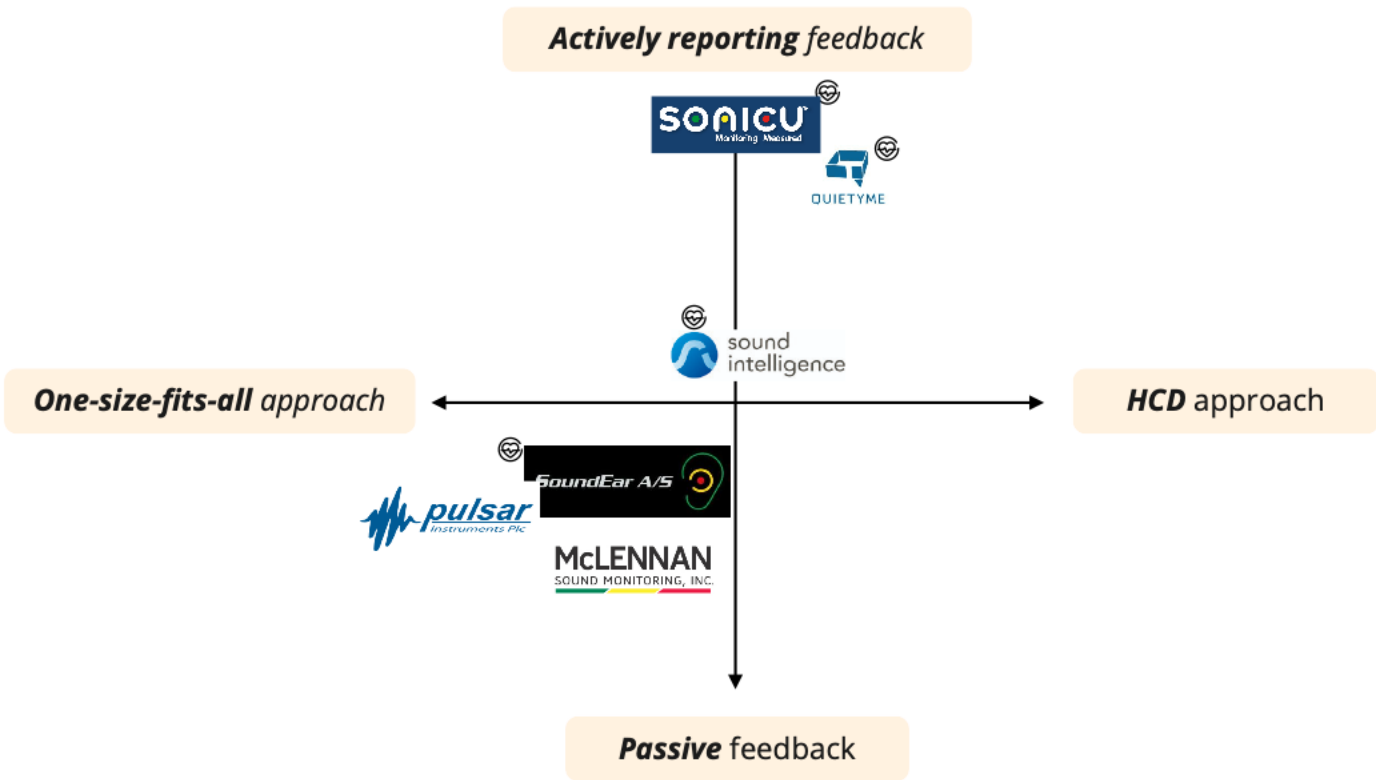
Current competitors

| Companies Name | | Application areas | Characteristics | Predictive sounds? | Specific for hospitals? | Country |
|---|---|---|---|---|---|---|
| McLENNAN ★★☆☆☆<br>McLENNAN SOUND MONITORING, INC. |  | General | • Continuous, 24 Hour Operation<br>• Dynamic, Super Bright LED Bar Graph Display<br>• Bar Graph Displays Green, Yellow, Red indicating Safe, caution, or serious volumes<br>• Large LED Numeric Display<br>• Computer-Built, Durable Metal Case<br>• True RMS Detection Technology<br>• Referenced to NIST Traceable Source<br>• Can Be Powered from an AC or DC Voltage Source<br>• Water, Corrosion, & Shock Resistant, Omni-Directional Electret Condenser Sound Sensor<br>• Either Remote or Local Sound Sensor Source Capability,<br>• Allowing Easy Management of Separate Areas<br>• Adjustable (61 – 122 dB) Excessive Sound Alarm<br>• Re-Range & Other Modification Possible<br>• Power Management, No Noise Uses No Power<br>• Monitoring Allows Noise Control | No, looks like a very simple sound monitoring product. Doesn't look to be connected in a system | No | Oregon (USA) |
| NTiAudio ★★★☆☆<br>NTi AUDIO |  | Environment (Residential areas) | **NoiseScout provides a comprehensive but easy-to-use 24/7 noise monitoring solution. Noise levels are recorded on-site by the XL2 Sound Level Meter and are available for remote monitoring and download. NoiseScout is aimed at both short term noise assessments and long term monitoring applications.** | No | No | |
| CLB Sound Intelligence<br>sound intelligence<br>★★★★☆<br>leader in health monitoring systems |  | • Agression detection<br>• Acoustic monitoring for healthcare<br>• Gunshot detection<br>• Breaking glass detection | Advanced Acoustic Monitoring by Sound Intelligence and CLB distinguishes which sounds warrant attention and which ones do not. This patented, state-of-the-art technology filters out irrelevant noises, reducing false alarms and improving operational efficiency. The Acoustic Monitoring System can also be set up to alert staff to specific sounds that indicate resident distress.<br><br>There is first generation, second generation and third generation<br><br>3rd generation uses cochleogram , sound is shown in the frequency axis similar to the way human year does.<br><br>The system analyses more than twelve different variables, it detects patterns and frequencies in it. | Yes, patented technology | Yes | Netherlands (Groningen University) |
| Pulsar ★★★★★<br>pulsar Instruments Plc |  | Hospitals | It's a sign noise sign rather a whole connected system.<br><br>For a more updated version, the system can also record and store | No, the technology looks a little simple | Yes, it can be implemented anywhere | |

# C
Product analysis



# D
## Semi-structured interview

**INTERVIEW WITH NURSES**
Introductory script:
• Say something about yourself: Strategic design student from TU Delft. The interview is for my graduation project
• Explain the interview purpose and how the interviewee came to be selected: The purpose is to get a deeper insight in how nurses experience sound levels and how to help them to reduce them
• Assure anonymity and confidentiality, explain the interviewee that he/she may withdraw from the interview at any point (and make sure that the informed consent form is signed) I assure you that the interview is fully anonymous and confidential. To guarantee you this, I have a consent form for you and you may withdraw from the interview at any point.
• Explain that there are no right or wrong answers, you're interested in his/her opinions and personal experiences. During the interview there are no right or wrong answers. We are only interested in your opinion and personal experiences.
• Explain that he/she is free to interrupt at any time You can interrupt us at any time
• Ask permission to record: May we record the interview for writing a transcript? We will delete the files after the project.
• Do not mention anything about what you expect to find

**Themes 1(their current experience)**
In which unit are you currently working?
Which is your overall sound experience?
What do you think about the sound interactions you have with other colleagues while working?
Which is your opinion about these interactions, more precisely with nurses?
How do you think these interactions contribute to NICU soundscapes?

*Follow up question:*
*How important is sound in your life?*
*How important is sound in your working experience and daily routine?*
*Is it something, that for example, your are teached in your training?*

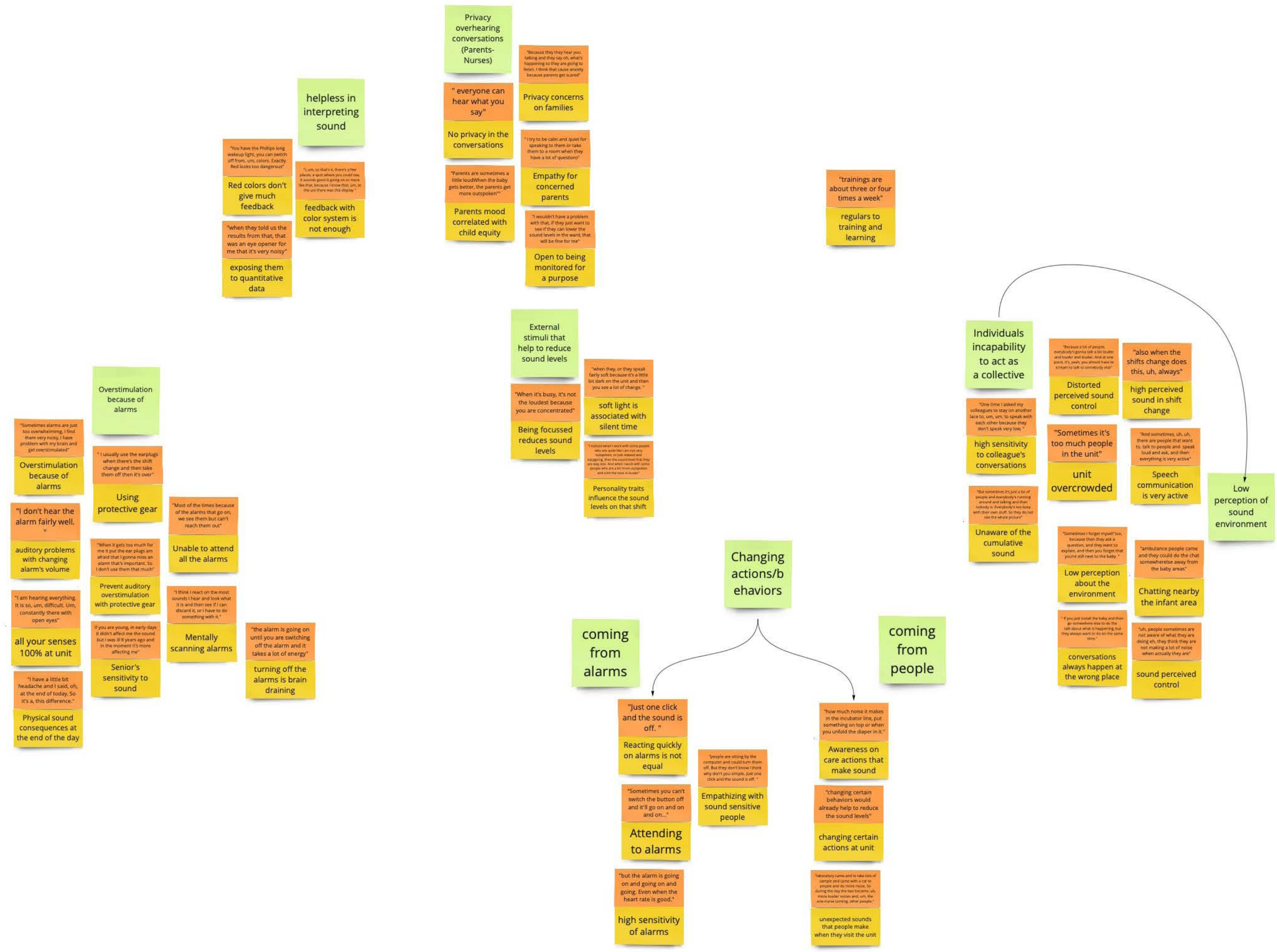
**Theme 2(soundscapes at NICU)**
Do you actively participate in the training offered between the shifts?
How are these training sessions? What do you usually do?
How do you experience this learning period?
What motivates you to take part in these training sessions?

*Follow up question:*
*Is it something you only see in your working hours?*
*How comfortable are you with e-learning?*
*Have you ever used  apps for learning new languages, for example? (Duolingo)*

**Theme 3 (trainings and technology)**
How is technology helping you to deal with sound? (For example the pager that you have in U4)
How would you feel if this technology would track your data, for example your voice?
What would you think if you had more training directly addressing the sound issue?



# E
## Data analysis



# F

## Semi-structure interviews(expert interviews)

**Interview guide - Irwin Reiss(Healthcare expert)-**
- How do you feel about this as a starting point?
- How much does the app support you in your daily work?
- Who else do you think should be involved? How extensive is the network of stakeholders that could benefit **from this implementation?**
- Among the multiple priorities that NICU has, is sound in the list?
- If the project would continue, who would have to approve, and what would they like to see?
- Is this platform in the innovative direction that the unit wants to take in the future?

**Interview guide - Alessandro Bozzon (AI expert)**
- When you talk about machine interactions, do you think this platform is an example?
- Which level of human-machine interaction does this solution employ?
- How would this platform respond to the current challenges of AI?
- How would AI enhance the functionality of this platform?
- Actually, the aim is that nurses have to interact the least with the platform(they have way more to worry about).

Can this platform potentially humanize this human-machine/technology interaction?

**Interview guide - Dave Murray(Sound expert)**
- **How would this platform respond to the current challenges of machine listening?**
- Clustering and localizing the sound
- Which are the challenges in terms of accuracy?
- To the challenge to make people aware of their sound environment?
- What do you think about the constellation as a sound representation?
- Does this product respond to the privacy issues that we will have in the future regarding voice recording?

**Interview guide - Lieke (Therapist expert)**
- How would this platform support your clinical work?
- How do you imagine such an implementation in your daily care?
- How would this interface help you understand the sound environment at NICU?



# G

## Evaluation plan

The valuation plan was written following the method of Product Evaluation from Delft Design Guide

**Step 1: Describe the aim of the product concept evaluation**
Type of evaluation: impact evaluation
The aim of the test is to evaluate the different aspects of the design goal, therefore an evaluation goal is stated:
- Evaluation goal: checking the effect that this platform has on the nurse and exploring how their awareness/ understanding changes regarding sound at the NICU.
- Design goal: I want to strengthen the sound understanding of nurses at NICU while supporting them to take action regarding sound issues

**Step 2: determine what type of evaluation you want to conduct**
For the interface that was designed, the type of evaluation that suits best is to let the user interact and explore the interface and use questionnaires to test the effect. Since the goal of the product is to see the effect that it has on them and in their knowledge, there is going to be a before and after questionnaire.

**Step 3: create the appropriate concept representation**
The concept that the nurses will test will be the interface prototyped in Figma.

**Step 4: search for respondents and invite them**
4.1 Description of the respondents
The prototype is going to be tested with nurses working at NICU in one of the four units, all levels of seniority. In order to recruit nurses more easily, I'll go to the room where they meet for lunch and coffee breaks. The time frame will be between 12am-4am, so that it is between lunch break and shift overlap.

**Step 5: conduct the user evaluation**
5.1 Description of the testing environment
The testing environment will be at the hospital. Firstly, because it is an environment that the nurses are familiar with, and secondly, they have to make little effort to conduct the test (no setting up video calls or taking their free time out of the hospital).

5.2 Aspects of the product that need to be evaluated
The goal of evaluating the design with the nurses was to evaluate how relevant the concept was for the nurses, so testing desirability rather than usability. The aspects of the product that would be evaluated are extracted from the design goal. The keywords are used as the main fundamentals that would be tested in the user evaluation.

Design goal: I want to strengthen the sound understanding of nurses at NICU while supporting them to take action regarding sound issues.
Aspects to evaluate: impact, understanding, confidence and actionability

5.3 Questions I want to ask them
- Before testing

Goal: test their level of aware understandability of sound in the NICU environment
- I'm confident in knowing the sound levels at NICU
- I'm knowledgeable regarding the sound sources at NICU
- I'm confident in taking action to reduce certain sound sources at NICU
- I'm aware about the sound levels at the NICU

- Preparation for the test

Goal: give them tasks just to give them an opportunity to explore and interact with the interface. Give them a chance to interact with it and understand the product.

| Aspect to evaluate | | Type of test | Statements |
|---|---|---|---|
| IMPACT | Understanding | Before/after test to measure the impact that explore the interface has on the nurses | I'm knowledgeable regarding the sound sources at NICU |
| | Confidence | | I'm confident in knowing the sound levels at NICU |
| | Actionability | | I'm confident in taking action to reduce certain sound sources at NICU |
| | Awareness | | I'm aware about the sound levels at the NICU |
| | | | |
| Expectations | | After questionnaire | -I would define the level of awareness that this product brings as...<br>-If you had to define only one sound characteristic that you would like the interface, which would be? |
| Environment related | | | -This product would speak for the sound quality at the NICU<br>-This platform would support me in understanding the sound sources |
| Work related | | | -This platform would support my well being<br>-This platform would cover my sound related needs<br>-This platform would ease my clinical work |

- What information do you understand at first glance?
- How clear is the function of the constellation for you?
- How much information do you obtain from the constellation?

- After testing

Ask about the level of awareness or confidence gained

- I'm confident in knowing the sound levels at NICU
- I'm knowledgeable regarding the sound sources at NICU
- I'm confident in taking action to reduce certain sound sources at NICU
- I'm aware about the sound levels at the NICU

Test the desirability regarding the product: the expectations that user has from it and how it would change their environment and their work.

- I would define the level of awareness that this product brings as...
- This platform would support my well being
- This product would speak for my sound quality at the NICU
- This platform would support me in understanding the sound sources
- This platform would cover my sound related needs
- This platform would ease my workload
- If you had to define only one sound characteristic that you would like the interface, which would be?

**Step 6: Analyse the results and present the results concisely**



# I

## Evaluation II: results

**Part A)Pre-test & post-test**

| Before | Q1: I'm confident in knowing the sound levels at NICU | Q2: I'm aware about the sound levels at the NICU | Q3: I'm knowledgeable regarding the sound sources at NICU | Q4: I'm knowledgeable regarding the sound sources at NICU |
|---|---|---|---|---|
| | 4 | 4 | 5 | 4 |
| | 3 | 2 | 2 | 4 |
| | 4 | 5 | 5 | 5 |
| | 2 | 3 | 4 | 5 |
| | 3 | 4 | 3 | 4 |
| | 3 | 4 | 3 | 4 |

| Before test | Min. | Max. | Mean | Median | Std. deviation |
|---|---|---|---|---|---|
| I'm confident in knowing the sound levels at NICU | 2 | 4 | 3,41 | 3 | 0,7527 |
| I'm aware about the sound levels at the NICU | 2 | 5 | 3,67 | 4 | 1,0327 |
| I'm knowledgeable regarding the sound sources at NICU | 2 | 5 | 3,67 | 3,5 | 1,211 |
| I'm confident in taking action to reduce certain sound sources at NICU | 4 | 5 | 4,33 | 4 | 0,5163 |

| After | Q1: I'm confident in knowing the sound levels at NICU | Q2: I'm aware about the sound levels at the NICU | Q3: I'm knowledgeable regarding the sound sources at NICU | Q4: I'm knowledgeable regarding the sound sources at NICU |
|---|---|---|---|---|
| | 3 | 4 | 5 | 4 |
| | 4 | 4 | 5 | 5 |
| | 4 | 4 | 5 | 3 |
| | 4 | 4 | 5 | 4 |
| | 3 | 3 | 5 | 4 |
| | 3 | 3 | 4 | 4 |

| After test | Min. | Max. | Mean | Median | Std. deviation |
|---|---|---|---|---|---|
| I'm confident in knowing the sound levels at NICU | 3 | 4 | 3,50 | 3,5 | 0,5477 |
| I'm aware about the sound levels at the NICU | 3 | 4 | 3,67 | 4 | 0,5163 |
| I'm knowledgeable regarding the sound sources at NICU | 4 | 5 | 4,83 | 5 | 0,4082 |
| I'm confident in taking action to reduce certain sound sources at NICU | 3 | 5 | 4 | 4 | 0,6324 |

**Part b) After test questionnaire**

| Product evaluation test | | | | | |
|---|---|---|---|---|---|
| I would define the level of information that this product brings as... | This platform would support my well being | This platform would support me in understanding the sound sources | This product would speak for my sound quality at the NICU | This platform would cover my sound related needs | This platform would ease my clinical work |
| 4 | 4 | 5 | 4 | 3 | 4 |
| 5 | 4 | 4 | 3 | 2 | 2 |
| 4 | 4 | 5 | 5 | 4 | 3 |
| 4 | 4 | 4 | 4 | 3 | 3 |
| 4 | 4 | 4 | 4 | 3 | 4 |
| 4 | 3 | 4 | 4 | 3 | 2 |
| 4,17 | 3,83 | 4,33 | 4,00 | 3,00 | 3,00 |