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Sound-driven Design through the lens of four applications for healthcare

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Abstract

Sound-driven design has roots in the history of Critical Alarms Lab (TU Delft) and emerged as a response to designers' need to tackle complex societal problems that cannot be solved by designing sounds only. In previous research, we discovered four different design approaches (designing THE, WITH, AGAINST sound FOR) and their corresponding problem (sonic, experiential, technical, and cultural) and solution (creative, integrative, mitigative, and purposeful) spaces. As such, we developed the ecologically-relevant TWAF framework to further understand the underlying mechanisms of sound-driven design. In this paper, we use the framework to demonstrate how different approaches are needed to holistically address complex issues when sound poses a societal threat or an opportunity for design especially in the healthcare context to improve the quality of the acoustic environment and listener experiences. With the case study in sound-driven design for healthcare, we demonstrated that sound-driven design shifts sound from being a by-product of the environment to an intentional, meaningful, and integrated experience enhancing well-being, sonic culture and quality of life.

CCS Concepts

• **Human-centered computing** → **Interaction design theory, concepts and paradigms**; • **Applied computing** → *Health care information systems*; **Sound and music computing**.

Keywords

sound-driven design, TWAF framework, noise mitigation, interaction design, sound design, participatory design, human-centered design; listening experiences, listeners

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1 Introduction

Sound design is a well established field with design theory and methodologies that addresses sound as a physical entity and aims to improve auditory comfort, sonic aesthetics and product function [13, 15, 26, 29, 31, 38]. Traditionally, the primary activity of sound design process is to work the sound or the source emitting the sound. This design approach works well for improving the quality of a single product and its functioning through sound. However, recently within the domain of design science and applications we have been observing an increase in complexity in the way design problems are articulated [5, 25]. This is no exception for the field of sound design if we consider biodiversity threatened by excessive levels of sound, chronic diseases caused by noise pollution, and hearing loss caused by inappropriate acoustic conditions.

These complex issues attributed to sound can represent deeply intertwined socio-technological and economical problems which cannot be solved by designing only better sounds. Hence, sound-driven design (SDD) has emerged in the mid 2010s as a response to addressing such complex sound-induced issues which require an in-depth understanding of the listeners' context and their culture, the role of sound in their daily interactions and experiences, products-services-systems emitting or facilitating the production of the sound and inherently the quality of sound and acoustic environments. As a result, sound-driven design [7] offers a holistic and multidisciplinary approach making the design process not only accessible by design professionals and stakeholders with diverse backgrounds but also inherently inclusive. In this paper, we will exemplify how sound-driven design approach can help respond to one design challenge observed in the context of healthcare (i.e., harmful consequences of excessive number of alarms) by presenting four different design strategies. Our main aim is to demonstrate with examples how sound-driven design outcomes vary as a result of the different interpretation of the same design challenge, and more in general to contribute to the understanding of the design projects tackling sound-induced issues, in order to provide more effective methodologies and improve processes.

1.1 From Sound design to Sound-driven design

Over the years, how engineers investigated the sound phenomena have evolved from defining auditory sensations through (psycho)acoustical measurements for mainly noise mitigation purposes [1, 2, 23, 49] to acknowledging sound as the property of a product to be engineered and its sonic experience to be shaped through human-centered approaches [24, 27, 31, 44]. This evolution is presented in

Figure 1. Thus, the field shifted the design space from reducing auditory discomfort to increasing and varying the product sound quality congruent with product experiences in a specific context [32]. Evaluation methods used to determine the cause of sound-induced harm often targeted one type of products (e.g., shavers, cars) and one type of product users. Thus, a direct relationship between the listener and the product sound would be observed and the root cause of the problem would be identified by listening tests and iterative prototyping. These approaches allowed society to enjoy better sounding products and acoustic environments (e.g., vacuum cleaners, coffee makers, car interiors and car engine sounds) in especially in private spaces.

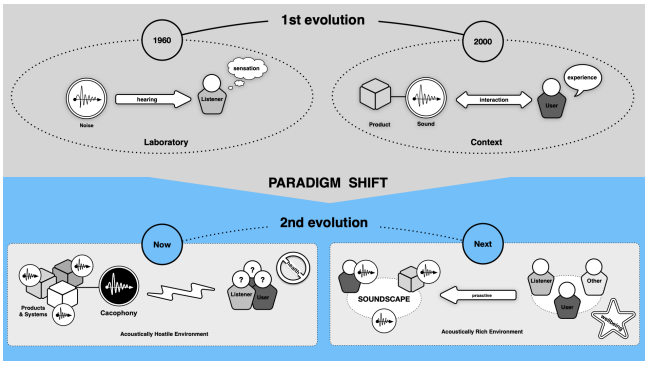

Figure 1: The two evolutions of the human-centered design for sounds and the paradigm shift towards a multi-listener and multi-source sound-driven design space.

Since the mid 2010s, the design space has changed due to the complexity of the issues caused by pervasive technologies and broken human-technology interactions. In general, excessive noise due to multiple sound sources in shared acoustic environments that contains multiple listeners pose socio-technological and even health associated design challenges. Thus the multiplicity of sound events and the plurality of users requires not only deconstructing the cacophony but also new solutions that would satisfy the needs and preferences of different listeners in the schizophonic world [28]. As the acoustic environments are becoming more complex and perhaps hostile, we could follow Findeli's approach "*one goal of design is to improve, or at least maintain the habitability of the world*" [14]. The goal of sound-driven design is then to offer better organised sound sources, if needed in the form of soundscapes, that support the wellbeing of its listeners and enhance sonic habitability of acoustic environments at large [6, 20, 21, 33, 48].

The historical account above presents a paradigm shift from being sound-centric to listener-centric in line with the shift from being object-focused to human-centered in more generic design approaches [19, 41]. This shift also means that object form follows the human condition and experience. For sound-driven design, experiences of sound is mediated by listening cultures and intentionality. Thus, exploring the listening dimension in design is key to understand the consequences of sound for reasons: First, to identify the roles of different listeners in shared acoustic environments and their intentionality with sound in the context of product / sound use [35, 39, 46, 47]. Secondly, to have common ground through the role of semantics in the communication of listening experiences in the design processes [7, 9, 45]. In summary, sound-driven design aims to broaden our notion of how to respond to listening experiences (sound-induced) that can have consequences beyond acoustic discomfort. As designers, we also have a responsibility to improve the quality of our 'sonic' lives and sound-driven design aims to support this effort. The practice of sound-driven design also evolved naturally following these trends in both acoustic and design worlds. Especially TU Delft has pioneered practised sound-driven design with both student projects and industrial partnerships (e.g., [37, 43]) but also at IRCAM ([42, 44]).

2 Designing THE, WITH, AGAINST sound FOR

Sound-driven design represents a shift from 'designing sound', as an object to be designed, towards 'designing for listening in complexity'. Thus, the approach is intrinsically human-focused and listener-centric. In earlier studies we have discovered evidence for listening experiences in sound-driven design through expert interviews [7] and a collaborative workshop involving such experts [8]. These studies provide us the theoretical understanding on how the practice of sound-driven design can be analysed and explored. Thus, our methodological considerations in this paper derives from our both theoretical studies and practical expertise in the field. The theoretical studies also allowed us to establish the field with the "semantic" evidence collected with the experts actively working in the field.

In our studies ([7, 8]), experts represented any professional who might have an interest in sound and its potential harm: sound designers, designers, acoustic engineers, and expert users. Interestingly, the interviews revealed that all experts had a common understanding of sound through which design communication could take place while experts used their own disciplinary knowledge and methods to conduct their sound-specific work. Moreover, engineers and sound designers connected on sound sources one aiming at systems and sources and the other at expressions and affective quality. Likewise, expert uses and human-centered designers connected on context and situationality one aiming at use and services and the other one at situational knowledge and methods of observation. More specifically,

- *sound designers* claimed to be the actual producers of sounds that enhance the expression of products, services, and systems and showed expertise on sound processing, from perception to verbalisation and acoustic production;
- *human-centered designers* oriented their listening culture for accumulating context-specific knowledge through usual design methods and aimed to conceptualise the experience driven by sound but not for producing sounds;
- *acoustic engineers* showed involvement in studying acoustics and vibrations and equated sounds to noise for improving the quality and functionality of products and systems, both at a mechanical, structural and at a management level for producing better sounds (i.e. acoustic comfort); and
- *expert users* focused on the role of sound in their workspace by reflecting on the effect of sound on wellbeing and its contribution to professional tasks and manifested possible

functional solutions without much focus on the acoustic quality of the sound.

Four strategies, are identified to position the experts' main role in sound-driven design: design THE, WITH, AGAINST sound FOR. The collaborative workshop [8] revealed more insights into the sound-driven design process further elaborating on the strategies used by different professionals to identify the design problem and the solution space. We found strong links between the strategy used (the, with, against, and for) and the type of professional (sound designers, designers, acoustic engineers, and expert users). Accordingly,

(1) Designing **THE sound** is ***sonic*** and ***creative***: *Sound designers* focus on a sonic problem (i.e., perceptual implications of listening) and use creativity (i.e., artistic experimentation and innovation) to offer aesthetic, expressive and sensory qualities of sound. The created sound is to evoke emotions and moods, and represent a unique sonic identity and convey information, functions and intentions.
(2) Designing **WITH sound** is ***experiential*** and ***integrative***: *Designers* focus on the integration problem of sound with other design elements (e.g., lighting, space, and materials) with the environment and context in order to create a cohesive and immersive experience. If sound is designed, it is used to create a more engaging (i.e., multisensorial) and remarkable experience (e.g., adventure) for the user. Listening experience is complementary to, and integrated in, the product experience.
(3) Designing **AGAINST sound** is ***technical*** and ***mitigative***: *Acoustic engineers* stand against sources and systems that produce unwanted or harmful sound. A technical problem (sources, mechanisms, physical configuration, regulations, systems, algorithms) is found in the physical, sensory, and functional aspects of noise, acoustics and vibrations. The design action aims at mitigating noise (i.e., unwanted sounds), thus increasing sound quality to create acoustic comfort in an environment.
(4) Designing **sound FOR** is ***cultural*** and ***purposeful***: *Expert users* seek for culturally relevant (e.g., values, beliefs, and practices) and meaningful sounds for a specific audience or community. Sound is used to tell stories, convey values and information and evoke emotions that are specific to a particular cultural context. The design action is to find purpose for the sounds to exist. Therefore, design process for the intervention encompassing sounds are inherently goal-oriented and context-dependent.

To summarise, sound-driven ***design problems*** can be sonic, experiential, technical, and cultural, while sound-driven ***design actions*** can be creative, integrative, mitigative and purposeful. The entire sound-driven design space can be seen in our **TWAF framework** in Figure 2, which also demonstrates how acoustic engineers and sound designers align themselves on the topics of (sound) source and its sonic expression (y-axis) and how expert users and human-centered designers align themselves on the topics of context of listening experiences (x-axis). Problem and design spaces form a ***sound driven-design strategy*** (e.g., sonic & creative) to address

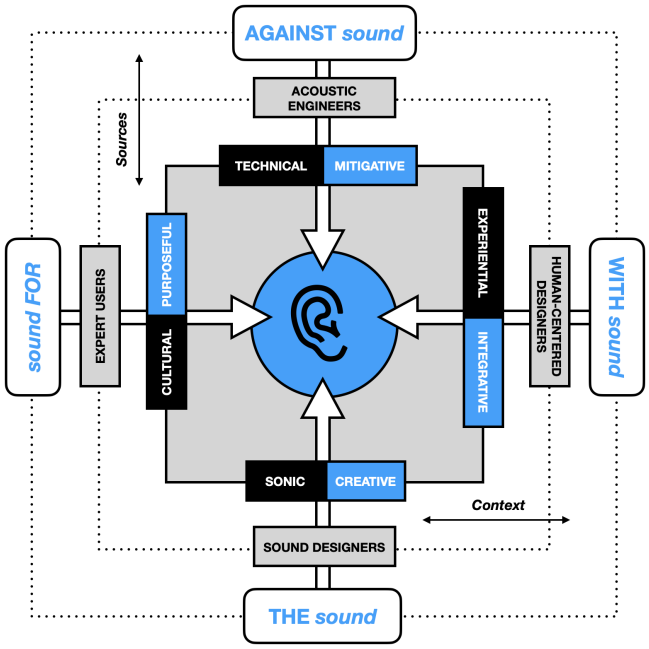

Figure 2: Underlying mechanisms for sound-driven design explained by the TWAF Framework: Designing [THE, WITH, AGAINST] sound [FOR].

listening in the heart of the sound-induced issues and opportunities. It is important to emphasise that both problem and design spaces can go beyond sound and therefore are sound-driven as the focus is on understanding and improving listening experiences and making 'sound' ecologically relevant and embedded in context. Sound-driven problems can be tackled with the lead of one expert or collaboratively involving experts at different stages of the design process. In sound-driven design, multi-disciplinarity may manifest itself as the following: Any human-focused and listener-centric approach will always involve expert users (i.e., listeners) in different phases of a design process (problem definition, conceptualisation, and evaluation); acoustic analysis will give evidence to the unwanted aspects of sound or confirm the improvement; created sounds or design interventions will need to be integrated in the journey of the user; and finally a desired listening experience is achieved.

3 Excessive alarms as design case for Sound-driven design

It has been widely acknowledged that excessive number of audible alarms are a major problem for the functioning of complex socio-technological environments problems manifesting itself especially in modern hospitals [10–12] but also in mission control rooms, or aircraft cockpits [16, 43]. The issue is linked to impacting operators regarding their wellbeing, physical health and productivity, which can have serious socio-economic consequences for the workforce. In Intensive Care Units (ICUs), the issue touches two types of listeners (i.e., ICU nurses and patients) and has been identified as "nurse alarm fatigue" and "patient anxiety" [4, 17, 18, 30, 36]. These studies

emphasise the need for design interventions to improve the quality of care provision and patient recovery.

To contextualise, medical alarms are part of a telemetric system connected to patient monitor (mainly, heart and respiratory rate, blood pressure, oxygen saturation, temperature) and life-support devices (e.g., mechanical ventilators, infusion pumps) which are designed to convey information regarding patient status to nurses and intensivists [3, 34, 40]. It is vital that nurses set alarm limits and respond to the alarm triggered by out-of-limit parameters. Over the years, the number of alarms have increased to a point that between 80% – 98% of alarms are considered non actionable [4] polluting the acoustic environment for both nurses and patients. While nurses might be unable to distinguish the actionable alarms, patients struggle with anxiety not knowing what these non-actionable alarms may represent (e.g., oxygen saturation sensor out of place alarm is not as critical as low-blood pressure alarm) due to lack of contextual knowledge. In general terms, the alarm issue goes beyond human factors (e.g., detectability, recognisability, actionability) and touches upon patient safety, burden on the workforce, and financial risks.

3.1 Method

The case of "excessive number of alarms in the ICU" is symptomatic of a complex socio-technological problem and therefore will be studied in this paper from the perspective of how sound-driven design responds to it with the support of four different strategies; i.e., designing THE, WITH, AGAINST sound FOR. We will follow the elements of the TWAF framework (Figure 2) developed to detail four different sound-driven design strategies to explain the problem space and present the solution space. As a result, we will demonstrate the diversity and commonality of the approaches used to address a sound-induced socio-technological issue. We are also interested in the collaborative aspect of the projects to discover how participatory were the designers' approaches.

We curated four design projects from prior work of The Critical Alarms Lab at the Faculty of Industrial Design Engineering (TU Delft, NL). The projects were part of MSc theses in MSc thesis (2x MSc Design for Interaction), Advanced Embodiment Design Course (MSc Integrated Product Design), and user-centered research project. All students had a background in product design and/or product engineering. Only one student had (electronic) music production skills gained outside of the academia. All projects were conducted in collaboration with the ICU Department of Erasmus Medical Center Rotterdam between 2017 and 2020. These projects can be seen in Figure 3. The projects selected were completed prior to the theoretical establishment of sound-driven design and its articulation in the design process. As such, we believe that these projects present an unbiased opportunity to apply the specific elements of the four strategies.

The projects were then evaluated by the authors on the bases of the parameters adhering to design problems and actions per strategy: sonic & creative for [THE], experiential & integrative for [WITH], technical & mitigative for [AGAINST], and cultural & purposeful for [FOR]. Based on our prior descriptions of the design elements of sound-driven design and the project descriptions, we ran a meta analysis comparing the projects with each other, developing common themes reflecting to what extend each strategy was

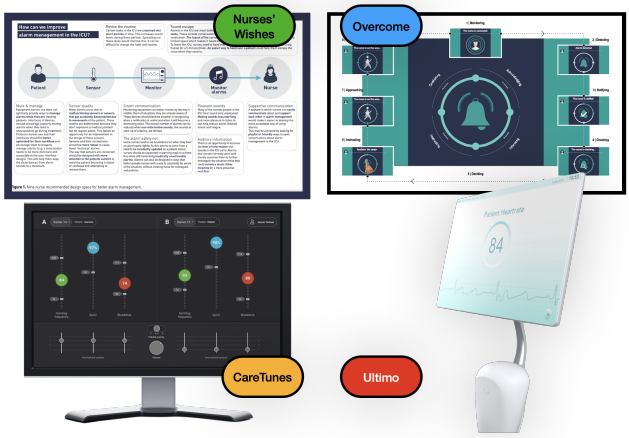

Figure 3: Selected sound-driven design projects from the archives of Critical Alarms Lab, TU Delft: CareTunes is a musical update for patient vitals [THE]; Overcome reduces patient anxiety by making alarms meaningful [WITH], Ultimo is a silent patient monitor [AGAINST], and Nurses' 9 wishes to improve alarm management [FOR].

used in practice by the designers. The authors collectively and in agreement rated each project on a scale of 1 - 5 (not at all - very). The results are shown in Figure 4. In the figure, we display the design solutions on the (Sound) Source axis (designing [THE] and [AGAINST] sound) and (Listener) Context axis (designing [WITH] sound [FOR]) It is fair to highlight that on the x-axis CareTunes offers a more sound oriented solution and Ultimo a more source oriented solution; likewise, on the y-axis Nurse's Wishes offers a listener oriented solutions and Overcome a context oriented solution
.

4 Sound-driven design projects

Sound-driven design has roots in the work of the Critical Alarms Lab. Since 2017, the lab specifically focuses on alarm and noise issues in healthcare. Below are four selected projects described on how the designers interpreted the problem and designed the solution. The descriptions are taken from the student or research reports available online and therefore are by default the design team's descriptions. Here is a short summary of how the projects addresses the excessive alarms issue: *CareTunes* transforms ICU alarms into a musical experience for stress-free patient monitoring focused on user experience and multi-sensory integration. *Overcome*, empowers patients with a digital interface that reduces alarm-induced anxiety emphasizing sound can provide meaningful feedback. *Ultimo*, smartly mutes unnecessary ICU alarms while maintaining critical awareness addressing alarm overload and system inefficiencies. *Nurses' Wishes* co-creates smarter, more intuitive alarms based on real nurse experiences centered on human values, professional

workflows, and social factors in alarm management. Below are the project descriptions provided by the designers themselves.

4.1 *CareTunes "working through harmony"*

Designer: Ir. Koen Bogers with a background in music production and interaction design.
Project type: MSc thesis for Design for Interaction Program at the Faculty of Industrial Design Engineering (TU Delft).
Problem interpretation: There is an overwhelming number of medical equipment alarms causing desensitization and nurse stress. Additionally, alarms provide low informational value and are often set too narrowly, causing unnecessary alerts. There are too many non-actionable alarms which create cacophony. Can these alarm sounds be more harmonious while being distinctive and part of the nurse workflows?
Approach: Iterative design approach using rapid prototyping and testing to gain insights and refine solutions. Prototypes serve as both exploratory tools to uncover key factors in sonifying patient data and communication tools to engage medical staff in discussions. By allowing healthcare professionals to experience the concept first hand, the process ensures more effective feedback and continuous improvement. This cycle of design, testing, and refinement helps develop a solution that aligns with the needs of ICU staff and patients.
Designed solution: To replace traditional alarms with a musical monitoring system, allowing nurses to track patient vitals from a distance through sonification of patient data. Nurses wear an earpiece that plays a continuous, pleasant musical stream, eliminating the disruptive noise of alarms while still conveying essential patient information. Nurses also use a visual display when needed for further support on correct information.
More info[1]: CareTunes was exhibited at Dutch Design Week in 2018 at the Embassy of Health Pavillion.

4.2 *Overcome "alarms that soothe"*

Designers: Ir. Salvo Cucinella with a background in user experience. **Project Type**: MSc thesis for Design for Interaction Program at the Faculty of Industrial Design Engineering (TU Delft).
Problem interpretation: Medical alarms cause stress and anxiety for patients due to their ambiguity and lack of control, potentially leading to delirium or PTSD. Non-actionable alarms and desensitisation delay nurses' responses, leaving patients exposed to distressing sounds for extended periods. How to restore the patients' perceived sense of safety when a medical alarm goes off and the nurse is unable to communicate with them?
Approach: Human-centered and research-driven process using context mapping technique to understand ICU patients' alarm experiences. This involved observations, interviews, and co-creation sessions with ICU nurses and former patients to gather deep user insights. The findings helped identify key phases, issues, and challenges in alarm interactions. Finally, the design was evaluated through Virtual Reality, demonstrating that users reduced anxiety. This iterative and evidence-based approach ensured the solution effectively addressed user needs.
Designed solution: A digital interface designed to help ICU patients understand medical alarms and receive visual feedback about nurses' responses. It follows a five-level strategy based on how nurses calm patients: acknowledging that an alarm has been received, informing patients about the alarm's meaning, instructing them on how to address false alarms, comforting them by providing estimated nurse arrival time, and distracting them to shift focus away from distressing alarm sounds. This structured approach reduces patient anxiety and improves communication between patients and nurses.
More info[2]: Overcome's approach to measure patient stress and anxiety has opened new research avenues to understand physiological markers for sound-induced stress (e.g., heart rate, respiratory rate).

4.3 *Ultimo "silence with purpose"*

Designers: Ir. Nitin Gurram, Ir. Anna Gebala, Ir. Marek Torbus, Ir. Yuxiang Wang, Ir. Doris Boschma, Ir. David Schuit, Ir. Shaoyun Wang with varying backgrounds in engineering, user experience, usability and interface design, system design and algorithmics.
Project Type: Advanced Embodiment Design Course for MSc Program Integrated Product Design at the Faculty of Industrial Design Engineering (TU Delft).
Problem interpretation: Over 70–90% of audible alarms in the ICU are non-actionable, causing unnecessary disruptions in nurse workflows. These alarms also create cacophony in the acoustic environment and therefore are unwanted. Nurses must manually toggle "private mode" at night to dim screens and reduce alarms, but monitors remain fully active during the day, disturbing patients' recovery and causing anxiety. Visitors often fixate on the monitors, leading to stress and distraction from patient care.
Approach: Engineering approach with human-centered (considering the needs of multiple listeners), iterative, and systems-oriented design process, focusing on user needs, testing multiple solutions though prototyping, and integrating smart technology (IoT based multi-device connectability) to create an optimal ICU experience.
Designed solution: The technological solution mutes alarms and hides unnecessary visuals by detecting room occupancy using Bluetooth beacons and a ceiling-mounted camera. A PC processes this data to differentiate between clinicians and visitors, adjusting the patient monitor accordingly. This system creates a quieter, patient-friendly ICU while ensuring essential monitoring for medical staff.
More info[3]: Ultimo is a Core77 design award winner. The concept of Ultimo is now part of the Smart and Silent (SASICU) project funded by EU Innovative Health Initiative Joint Undertaking IHI JU) No 1011328080.

4.4 *Nurses' wishes "designed by nurses for nurses"*

Designers: ICU nurses (Erasmus MC) with the lead of Ir. Rosel van den Berg, Dr. Froukje Sleeswijk-Visser and Dr. Elif Özcan with backgrounds in human-centered design, design for interaction and sound design.
Project Type: Design research based on context analysis and co-creation between Erasmus MC and TU Delft.
Problem interpretation: According to the nurses: There is mistrust in the system due to non-actionable auditory alarms; Many alarms are patient/nurse induced and are misleading; Poor sensory technology due to disconnections or malfunctions and failure to recognize nurses' ongoing procedures. Incomplete auditory information from patient monitors lack a holistic view of patient status, forcing nurses to rely on visual confirmation; personal preferences in alarm management lead to inconsistency in alarm responses. What are the contextual factors, daily life activities and emotions of nurses and their coping strategies with sound and noise in general that can provide insights into future design directions that fit within nurses' workflow?
Approach: A qualitative, human-centered and holistic approach combining observations, sensitization techniques, and semi-structured interviews

[1] https://www.youtube.com/watch?v=gRjQ8rWvZAo, https://zenodo.org/records/5113511
[2] https://delftdesignlabs.org/projects/overcome-reducing-icu-patients-anxiety-through-medical-alarms-feedback-provision/
[3] https://designawards.core77.com/health-wellness/86989/Ultimo.html, https://www.sasicu.eu/about-sasicu

to understand ICU nurses' experiences with medical alarms. Researchers conducted two direct observations in an ICU to prepare for interviews, followed by seven in-depth interviews with nurses of varying experience levels. To enhance awareness of clinical sounds, nurses used sensitization booklets and audio recorders to document and reflect on significant sound events before the interviews. Semi-structured interviews in the ICU setting allowed for real-time co-creation for future alarm experiences and alarm management challenges.

Designed solution: Nine strategies were co-created under four intervention domains for improved alarm management.

Human-Sensitive Technologies | 1. Improve alarm interfaces to allow easier acknowledgment and muting; 2. Enhance sensor design to reduce non-actionable alarms and improve patient comfort; 3. Reduce the number and volume of non-informative alarms using AI and smarter technology.

Sound Design | 4. Make alarm sounds more informative to help nurses interpret urgency without needing visual confirmation; 5. Design less startling and more pleasant alarms to reduce stress and alarm fatigue.

Alarm Culture | 6. Standardize alarm management to balance individual nurse preferences and minimize unnecessary alarms; 7. Foster open communication among nurses to collaboratively optimize alarm settings and reduce conflicts.

ICU Setup and Workflow | 8. Create quiet spaces or easy ways for nurses to take short breaks from noise; 9. Distribute tasks more evenly throughout shifts to prevent sound overload during peak hours.

More info[4]: These recommendations by nurses have been taken into account by the management of Erasmus MC by establishing alarm task forces, changing the layout of the ICUs and being part of consortiums with industrial and academic partners.

5 Results

Considering the rating scales and the project descriptions provided by the design teams, we will discuss commonalities and distinctions to highlight how each project aligns with different sound-driven design strategies while sharing a common goal of improving the ICU acoustic environment. We will also reflect on the participatory aspect of sound-driven design as the TWAF framework in Figure 2 suggest a holistic and collaborative approach. Below are our main findings across project ratings and thematic meta analysis.

5.1 Project ratings

Our ratings strongly suggested that each project used a specific sound-driven design strategy with the highest scores. These scores can be found in the radar plot in Figure 4. *CareTunes* scored the highest (5 points) on **Sonic & Creative** followed by Experiential & Integrative (4 points) and lowest (2 points) on Technical & Mitigative as it integrates well into the nurse experience and is less about technical noise reduction and more about crafting a meaningful and pleasant auditory experience. *Overcome* scored the highest (5 points) on **Experiential & Integrative** followed by Cultural & Purposeful (4 points) and lowest (3 points) on Sonic & Creative and Technical & Mitigative as it enhances patient interaction with sound in a meaningful way. It also has strong purpose-driven elements but is less about sound creation or technical noise mitigation. *Ultimo* is scored highest on **Technical & Mitigative** and lowest (2 points) on Sonic & Creative leveraging engineering solutions to reduce noise

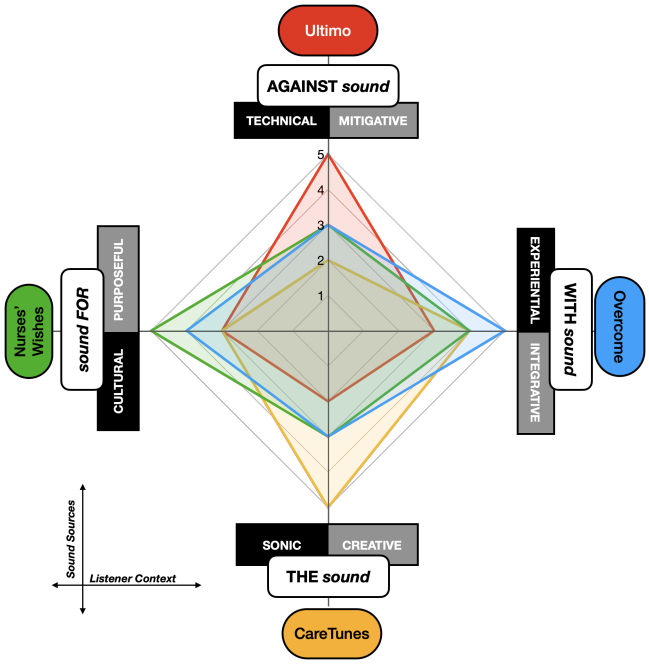

Figure 4: Radar chart representing the ratings on a scale of 1 - 5 (not at all - very) per design project given on four sound-driven design strategies (designing THE sound is Sonic & Creative, design WITH sound is Experiential & Integrative, designing AGAINST sound is Technical & Mitigative, designing sound FOR is Cultural & Purposeful). The placement of the strategies is based on the TWAF framework and projects that scored the highest on a certain strategy is placed closest to the strategy. The x-axis represents the Listener Context and y-axis represent the Sound Sources.

pollution in the ICU having some experiential aspects but not emphasising creativity or cultural significance. *Nurses' Wishes* scored the highest (5 points) on **Cultural & Purposeful** followed by Experiential & Integrative (4 points) and lowest (3 points) on Technical & Mitigative ad Sonic & Creative as it uses human-centered research to co-create purposeful and context-aware alarm solutions. While it integrates sound into nurses' workflows, it is less focused on artistic creativity or purely technical noise mitigation. Therefore, in the figure, we placed the projects where the strategies are mentioned as they are exemplary of the strategies. The figure also shows that all projects used all the strategies in a balanced way, except for Sonic & Creative.

The results show that sound-driven design operates on multiple strategies. However, designing new sounds requires deep expertise in sound composition which many designers (in broad sense) may lack. The majority of projects focus on functional, technical, or integrative solutions, rather than purely expressive or artistic sound design. Sound is often treated as a problem to solve (noise mitigation, usability, communication) rather than as a creative medium to explore artistic or emotional experiences.

[4]https://healthmanagement.org/c/icu/issuearticle/nine-nurse-recommended-design-strategies-to-improve-alarm-management-in-the-icu-a-qualitative-study.

5.2 Thematic meta analysis

Upon studying the project descriptions and assessing them with the elements of the TWAF Framework, we offer a meta analysis of some major themes that we found by systematically examining and categorizing commonly occurring patterns in project descriptions, descriptions of the strategies, descriptions of the problem interpretation, and descriptions of the design solutions. We also categorised the methods used and the technology mentioned. Furthermore, we looked into the level of participation and the background of participators in the project descriptions.

We observed **three commonalities** in the design space across the projects which tackled an alarm-related problem through iterative and research-guided design process with human-centered approach:

1. All projects emphasize listener-centric focus, detailing how sound affects nurses, patients, and medical staff. They use qualitative research methods like observations, interviews, and co-creation to ensure solutions align with real-world needs.

2. Each project addresses issues with medical alarms, whether it is their stress-inducing properties, inefficiency, or lack of contextual awareness. The goal is to improve how alarms are perceived, used, and integrated into medical workflows.

3. Prototyping, testing, and refinement are key in all projects, ensuring solutions are user-informed and adjusted based on feedback. Some projects use Virtual Reality (VR), Internet of Things (IoT), or Artificial Intelligence (AI), while others rely on co-creation workshops and qualitative insights.

We also observed **three key differences** across the projects considering the rating scales with respect to different design problems (Sonic vs. Experiential vs. Technical vs. Cultural) with varied sound design approaches and different levels of technology integration with regards to technological complexity.

1. Approach to design problem: *CareTunes* (Designing THE Sound) applies a Sonic & Creative strategy to create new soundscapes through musical alarms. *Overcome* (Designing WITH Sound) applies a Experiential & Integrative strategy to enhance patient experience through interactive alarm interpretation. *Ultimo* (Designing AGAINST Sound) applies a Technical & Mitigative strategy to reduce unwanted alarms through engineering solutions. *Nurses' Wishes* (Designing Sound FOR) applies a Cultural & Purposeful strategy to adapt alarm design to nurses' needs via co-creation.

2. Sound design strategy: *CareTunes* alters soundscapes entirely, turning alarms into continuous musical feedback. *Overcome* improves sonic interaction, giving visual support and structured alarm responses. *Ultimo* eliminates unnecessary sound, muting alarms via sensor-based automation. *Nurses' Wishes* optimizes existing alarms by making them more informative, standardized, and manageable.

3. Technology integration: *Ultimo* uses smart sensors and IoT for automated alarm management (high-tech integration). *CareTunes* relies on sound synthesis and wearable tech (moderate-tech). *Overcome* incorporates VR simulations for observing and measuring experience-driven improvements (moderate-tech). *Nurses' Wishes* is more qualitative, using co-creation and sound documentation rather than new tech (low-tech).

In Table 1, we present to what extent expert users (i.e., listeners namely, ICU nurses and staff) took part in the process by detailing their participation level, key methods used, and depth of stakeholder involvement. Below we will discuss the findings from this table.

Stakeholders participation: We looked into which stakeholders were involved in the projects and identified that ICU nurses, ICU staff, designers, former patients, engineers, usability experts, and (sound) design researchers as co-creators of the solutions. For *CareTunes*, ICU nurses, designers, engineers provided feedback on musical alarm systems, helped refine prototypes. For *Overcome*, ICU nurses, former patients shared experiences of alarm distress, participated in co-creation workshops. For *Ultimo*, engineers, usability experts, ICU staff helped refine AI-based alarm suppression system, tested usability. For *Nurses' Wishes*, ICU nurses, researchers in sound design led, and participated in, co-creation sessions, documented personal experiences with alarms.

User / listener involvement: Each project engaged participants (i.e., users / listeners) at different stages of the design process (namely, problem exploration, co-creation and ideation, prototyping and testing, and iteration and refinement). Participation level (i.e., involvement in participation) ranged between medium (*CareTunes and Ultimo*) to high *Overcome* and very high (*Nurses' Wishes*).

Tools and methods: The tools and methods for participation varied depending on whether the focus was on exploring needs, designing solutions, or testing ideas:

For *problem exploration*, context mapping, interviews, and observations were used. For example, nurses and patients documented their experiences using sensitization booklets and audio recorders (*Overcome* and *Nurses' Wishes*).

For *co-creation and ideation*, workshops, storytelling, and collaborative prototyping were used. For example, former ICU patients and nurses helped shape alarm communication strategies via co-creation sessions (*Overcome*).

For *prototyping and testing*, rapid prototyping, virtual reality (VR) testing, and sound samples were used. For example, nurses wore earpieces to experience musical alarms and provide feedback on sound variations (*CareTunes*).

For *iteration and refinement*, usability testing, user feedback loops, and field studies were used. For example, engineers worked with hospital staff to refine AI-driven alarm suppression based on ICU workflow (*Ultimo*).

6 Discussion

The sound-driven design projects we shared in this paper responded to a real-life context with actual problems nurses and patients experience on a daily bases. Reflecting on the impact of these projects, ICUs at Erasmus MC have become very quiet over time as a real culture change took place at the nurse, technologist and management level reducing unwanted sounds especially alarms and speech. Now the real challenge is to provide positive sounds and soundscapes [22]. These projects exemplify that hospitals can become more **human-centered, efficient, and less stressful** environments, benefitting both patients and healthcare professionals through sound-driven design.

Table 1: Participatory aspects of sound-driven design according to the expert user involvement

Project	Participation Level	Key Methods Used	Depth of User Involvement
CareTunes (THE Sound)	**Medium** – Focused on testing sound experience.	Sound samples, Listening sessions	Nurses provided feedback on musical alarms, but design choices were largely guided by designers.
Overcome (WITH Sound)	**High** – Co-creation with patients & nurses.	Sensitization booklets, Context mapping, VR simulation	Patients & nurses shaped the alarm experience, influencing both problem framing & solutions.
Ultimo (AGAINST Sound)	**Medium** – Engineering-led, but feedback-driven.	AI training, Hospital field studies, Usability testing	ICU staff helped refine AI-based system, but the solution was heavily tech-driven.
Nurses' Wishes (Sound FOR)	**Very High** – Nurses led the design process.	Audio diaries, Co-creation workshops, ICU-based interviews	Nurses defined problems, co-created solutions, and set priorities for alarm management.

6.1 How are sound-driven design strategies used in the case study?

Among the four projects, the ***Experiential & Integrative*** strategy is the most commonly used by designers. This is evident in projects like *Overcome* (designing WITH sound) and *Nurses' Wishes* (designing sound FOR), both of which emphasize user experience, interaction, and integrating sound with other elements in the environment to improve communication and well-being. Even *Ultimo* (designing AGAINST sound, a more technical solution) and *CareTunes* (designing THE sound, a musically creative solution) have considered users' needs and the result of their listening experiences at certain stages of the design process. Design professionals frequently approach sound as part of a larger experience, rather than an isolated element.

The ***Sonic & Creative*** strategy is the least commonly used by design professionals, with only one project—*CareTunes* (designing THE sound)—truly fitting this category. Designing entirely new sonic objects requires deep expertise in sound composition, music, and auditory aesthetics, which many designers do not specialize in. The majority of projects focused on functional, technically advanced, or integrative solutions, rather than purely expressive or artistic sound design. Sound is often treated as a problem to solve (noise mitigation, usability, information design) rather than as a creative medium to explore artistic or emotional experiences. While creative sound design is valuable, it is often overlooked in favour of practical, experience-driven, and technical solutions**.** Expanding the role of sound beyond function—into emotional expression, identity, and creativity—could bring new opportunities for cases that can afford musicality and sonic creativity.

The ***Technical & Mitigative*** strategy is used in projects that focus on reducing, controlling, or eliminating unwanted sound through engineering and system-based solutions such as *Ultimo* (designing AGAINST sound) and to a certain extent in *Nurses' Wishes* (designing sound FOR) proposing technical alarm reduction strategies, such as AI-driven smarter alarms and sensor improvements to reduce false alerts. Although technical, these solutions are still user-focused (hence, human centered-technology for smart technology, automation, and algorithms) ensuring that noise mitigation improves nurse workflows and patient well-being. Moreover, they tackle sensory experiences by removing unnecessary alarms and reduce sensory overload. If sound-driven design expands beyond mitigation and problem-solving, it could reshape how we experience sound in everyday life.

The ***Cultural & Purposeful*** strategy is used in projects that seek to make sound meaningful within a cultural, social, or professional context such as *Nurses' Wishes* (designing sound FOR) which explores how nurses experience alarms in their daily workflow, identifying cultural factors (mistrust in alarm systems, personal alarm preferences) and goal-driven solutions (standardizing alarm management, promoting teamwork in adjusting alarms). Nurses actively shaped the solutions in ensuring the interventions fit their workflow and needs. *CareTunes*, while primarily ***Sonic & Creative***, also has a cultural impact—it redefines how nurses interact with patient monitoring through continuous musical feedback instead of disruptive alarms, shifting the alarm culture in ICUs. Rather than focusing purely on technology, these projects seek to make sound more meaningful, trusted, and aligned with human experience, hence can have even low-technological outcomes.

In our use cases, we observed more focus on mitigation than creation suggesting that artistic (aesthetic and musical) approaches to alarms are less explored compared to noise control strategies. Most projects (e.g., Ultimo, Overcome) remove or suppress unwanted sound rather than designing new, targeted soundscapes. Designing new sonic creations for sound composition, music, and auditory aesthetics is a specific field that requires an acquired skill by designers which in the use cases we described was lacking in many of the experts except for one. Hence, designing the sounds did not emerge as a major theme. Moreover, society often treats issues with sound as a problem to solve (noise mitigation, usability, communication) rather than as a creative medium to explore artistic or emotional experiences. Technical & Mitigative strategy dominates the solutions provided, but can lack emotional depth as a strategy. Future projects could blend Technical & Mitigative with Experiential & Integrative approaches to make hospitals more humanised and emotionally less taxing. More opportunities exist to integrate positive soundscapes into hospital settings to improve well-being applying creative, integrative and purposeful aspect for sound-driven design [22].

6.2 To what extent sound-driven design is participatory?

All four projects incorporated participatory design to varying degrees, involving different stakeholders and using diverse methods. Stronger participation was observed for *Overcome* and *Nurses' Wishes*, directly involving end-users in ideation. Whereas *Ultimo* and *CareTunes* were more designer/engineering-driven, but still included user feedback in testing. The role of participation changed

based on the goal of the project. Exploratory projects (*Overcome*, *Nurses' Wishes*) used ethnographic methods (observations, diaries, journey mapping) to uncover needs. Projects that have high technological component (*Ultimo*) used feedback loops (usability testing, field studies) but had less co-creation. ICU nurses were the most consistently involved stakeholders. All projects consulted nurses, but *Nurses' Wishes* uniquely empowered them as co-designers rather than just feedback providers. Technology-oriented projects lacked deep participatory engagement. *Ultimo* relied more on engineers designing for users, whereas Overcome focused on co-design with users. Future projects could merge technical and participatory approaches better by involving users earlier in the process.

7 Conclusions

Our study provided strong support that sound-driven design is listener-centric and multi-disciplinary. We have discovered more explicit focus on listening experiences refining how sound is interacted with, and embedded in real-world settings. The study also provided clearer differentiation of the functional, emotional, and communicative roles of "**sound as an object**" vs. "**sound as an experience**" in real-world design projects. Human-centered research (i.e., observations, interviews, co-creation, iterative prototyping and evaluation cycle, and user feedback and testing) reinforced the importance of making sound-driven design solutions ecologically relevant and therefore best fit for listening experiences in specific context and situations.

The four categories (Sonic & Creative; Experiential & Integrative; Technical & Mitigative; Cultural & Purposeful) act as guiding principles for how sound can shape design solutions. Multidisciplinary collaboration is crucial not only to bring experts together, but to ensure sound interventions are meaningful, functional, and ecologically embedded. Further studies should investigate how collaboration takes place in different stages of a sound-driven design process and observe how sonic, experiential, technical and cultural problems are analysed (e.g., tools and methods) and articulated (i.e., semantic ordering) and creative, integrative, mitigative and purposeful solutions are developed (e.g., tools and methods to build, test, and evaluate).

While the participatory aspect of all projects were high, participation mostly included interactions between designer / engineer and expert users. In order to make a real impact, sound-driven design could benefit from involving as many stakeholders as possible making the design process both participatory and collaborative considering the complex nature of socio-technological design problems. By doing so, design teams can include not only expert 'listeners' or 'sound users' who are directly involved in context but also stakeholders that have influence in the 'listening' context (e.g., policy makers, industrial partners, managers, and scientists). As a result, collectively, societally-relevant and environmentally-responsible solutions can be developed that embed sound-inclusive products / services / systems supported by advanced technologies.

To conclude, **sound-driven design** is a **human-centered, multidisciplinary approach** that focuses on **culturally sensitive and ecologically-relevant listening experiences** as a core aspect of the design process. Hence the project outcomes may vary in terms of their (sonic) embodiment whether the focus was on sound, product, system or the combinations. The resulting design can then take different forms such as better sounding alarms to sonification (musical information system), graphical user interfaces triggered by sounds to AI-supported technical systems to suppress sounds, and finally from cultural tokens and workflows to sound-sensitive guidelines and policies.

Overall, sound-driven design approach recognizes that sounds, sound sources, sonic environments and unwanted sounds (i.e., noise) can be:

- Designed as an expressive, informative, and emotional medium;
- Integrated into a broader experience with other design elements (light, visuals, haptics) to create an immersive and stress-free experience;
- Mitigated or managed at the source and system to enhance acoustic comfort and usability;
- Shaped by cultural and professional / human values underlying real-world practices, and workflows.

7.1 Sound-driven design beyond healthcare

Sound and noise are pervasive elements of our lives. With the case study in sound-driven design for healthcare, we demonstrated sound is not only heard but also understood, felt, and purposefully utilized to enhance human interactions with environments, products, and systems. Whether in hospitals or broader society, **sound-driven design shifts sound from being a by-product of the environment to an intentional, meaningful, and integrated experience enhancing well-being, sonic culture and quality of life**. Thus, the approach can be used for shaping public spaces (outdoors, urban areas, transportation, and workspaces) for better listening, reducing noise pollution while enhancing intentional sonic interactions. For people with hearing impairments, neurodiverse conditions, or sensory sensitivities, sound-driven design can create more intuitive, non-intrusive ways of interacting with environments. Beyond function, sound-driven design can strengthen cultural identity and emotional engagement (e.g., soundscapes in museums, artful experiences, or city-wide sonic explorations) as part of cultural storytelling. Instead of fighting against noise, society can demand for better listening experiences in urban planning, education, and even shape policy-making contributing to sustainable acoustic environments.

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