

# Embodying Sustainability: Paving Opportunities for NIME Research

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## Abstract

While sustainability has gained attention in NIME research, primarily focusing on instrument longevity and durability, the role musical interfaces play in promoting environmental awareness remains unexplored. This paper investigates how musical interfaces can foster sustainability through designing embodied experiences. We present a literature review that examines the integration of sustainability and embodiment in sonic interaction, in which we synthesize practical points on how sound, materials, data, and interactions can aesthetically support embodying sustainability. We further explore these concepts through a design case study. Our findings suggest that embodied musical experiences offer unique opportunities to cultivate environmental consciousness, contributing to a deeper understanding of sustainable musical interfaces relying on artistic expressions.

## Keywords

Embodiment, Sustainability, Environmental awareness, Aesthetics, Sustainability through design (StD)

## 1 Introduction

**Sustainability** has increasingly become a topic of interest in the NIME over the past few years [61], with authors focusing on different aspects primarily looking at different forms of longevity such as the longevity of instruments [27, 56, 60] and the durability aspects of fabricated devices [57, 58], sustainability and replicability of research [14, 88]. As within NIME embodied experiences have been increasingly deemed important [15, 33, 80], in this paper we propose a different lens and explore the overlap of sustainability and embodiment and how this overlap can be explored in NIME research.

This perspective explores the convergence of sustainability and embodiment within Human-Computer Interaction (HCI) <sup>1</sup> building on Blevis' original conception of Sustainable Interaction Design (SID) [10] and the subsequent development by Mankoff et al. [52], which emphasizes sustainability in design (addressing material lifecycle and environmental impact) and sustainability through design (promoting sustainable behaviors). In the latter - sustainability through design - one can be traced in many *artistic practices within HCI literature*. The outcome of such practices are often interactive installations [4], physicalizations [36], wearables [8], etc. Accordingly, natural elements, environmental data and diverse sustainability concerns are embodied in the performative behaviors of different artistic artifacts and many authors frequently mentioned *embodiment* to elaborate how themes on sustainability can be perceived and reflected through their artistic interventions [8, 40–42].

In this paper, we will zoom into the interactive sound and music aesthetics aspect of devices, and explore *what are the possibilities that music experiences have to foster sustainability via embodiment*.

To this end, we articulate our contribution in three parts:

- (1) A review of existing literature in the domains of New Interfaces for Musical Expression (NIME) and the work published within the ACM digital library to explore the integration of sustainability and embodiment in sonic and musical designs.
- (2) We proposed a reflection on how four aspects of musical interfaces - sound, materials, data, and interactions - can support sustainability in an embodied way.
- (3) Finally, to investigate these four aspects in practice, we implemented a design case study (reaching a conceptual design with sketches).

We conclude with a general discussion on how embodiment in music interface design can support sustainability, ultimately contributing to a more nuanced understanding of the interconnectedness of humans, nature, and technology.



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<sup>1</sup>Blevis' conception of sustainability can be arguably categorized as 'environmental sustainability' [10]; By embodiment we mainly refer to Dourish's framing that emphasizes how meaning is derived from our past sensorimotor practices and social contexts [23]

A note - in the rest of the paper we used the term musical interfaces (MI) to distinguish the concerned artifacts from the name of the venue (NIME).

## 2 Background

### 2.1 Sustainability in NIME

Sustainability in NIME has recently begun to gain momentum, with discussions focusing on multiple aspects, including environmental impact, the longevity of instruments and the preservation of knowledge. In 2021 Masu et al. systematically reviewed NIME proceedings in the context of environmental issues [55]. This literature review was contextualized based on prior debates on both physical impact (materials, fabrication) and data impact (computing resources), use and reuse of musical interfaces, and point towards a sustainability framework of NIME. Since then, the environmental issues of musical interfaces have become an ongoing discussion in the NIME community. In parallel, there is a debate on longevity that concerns the short lifespan of many projects presented in NIME [27, 56, 60]. In relation to this, several aspects have been considered, such as sustainable digital fabrication [57], FLOSS [58], documentation [9] and replicability [14, 88].

Overall, currently most discussions in NIME are mainly revolving around environmental impacts, longevity, and sustainability of devices. Few articles also discussed the importance of aesthetics as an “invitation” to reflect upon sustainability-related topics, showcasing aesthetic potentials in circuit bending [22], or highlighting the natural presence with instruments (e.g., [77]). In this paper, our aim is to expand and pave possible opportunities connecting the current sustainability discourse to embodiment and musical interactions, by drawing from recent practices within HCI, and a design case study.

### 2.2 StD and Embodiment

This paper sits at the intersection of the three areas of Sustainability, Embodiment, and Interactive Arts. As providing a comprehensive overview of all these is far beyond the scope of this work, we will focus this section on how these areas are connected. Starting from sustainability debate within the HCI debate, Blevis introduced a pivotal milestone with his Sustainable Interaction Design (SID) framework [10], which led to two key approaches to sustainability in interaction design in the latter works: sustainability in design (considering the material lifecycle and environmental impact of digital artifacts themselves); and sustainability through design (how digital interactions can promote sustainable behaviors and practices) [52].

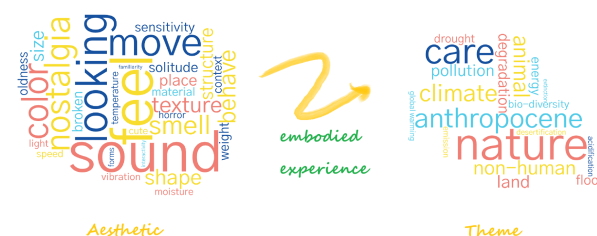
In the latter - sustainability through design - one can be traced in many *artistic practices within HCI literature*. The outcome of such practices are often *interactive installations* [4], *physicalizations* [36], *wearables* [8], etc. Consequently, natural elements, environmental data and diverse sustainability concerns are *embodied* in the performative behaviors of different artistic artifacts. These works often lead to performances, plays, provoking encounters, through which participants’ reflections on sustainability are facilitated through *embodied meaning-making process* [59]. Furthermore, many authors frequently mentioned embodiment to elaborate how sustainability themes can be perceived and reflected through their artistic interventions [8, 40–42] - as transforming “these conclusions into communicable formats that capture the public’s imagination” framed by Hohl [37, p. vii]. For instance, Jacobs et al. in their discussion on “a conversation

between trees” noted that one of the key ways of such artistic expression was in particular how the climate change data was “embodied in various material and sensory forms” [42, p133].

These examples show how embodiment can fruitfully support sustainability through design. We will develop design reflections to support this approach in NIME.

### 2.3 Themes and Aesthetics

Overall, a number of studies elaborate on how different aesthetic considerations can support embodied experiences in relations to different sustainability themes (we sketched this relationship in Figure 1). A number of *themes* have been tied to these sustainability approaches, such as promoting awareness on different ecological challenges; i.e., energy consumption [4], climate change [41] or carbon emission [36], etc. Other themes are more related to entangled relationships [6], which can be connected to emerging trends such as care ecology [81] and post-anthropocentrism [29].



**Figure 1: A diagram using common vocabularies to describe the relationship between aesthetics and themes in interactive artworks**

To realize a sensorial engagement and meaning-making, between these themes and the audience, different aesthetic elements are enacted as a context or space for (embodied) imagination or interpretation. The relationship between *aesthetics* and provoked experiences has been studied by HCI for many years, with the emergence of lemmas such as aesthetic interactions [63] rooted in pragmatist aesthetics [75]. In general, aesthetic elements could be embedded in diverse artistic ways: visual or auditory representations (of data), tactile interfaces (with certain materiality), temporal patterns, etc., and very critically the context rooted in past intellectual experiences, which makes the themes of concern not only sensational bodily but also thought-provoking [63]. DiSalvo’s adversarial design framework also examined how aesthetics could help artworks reveal hidden processes, expose relationships or create what he called ‘agonistic’ spaces, which can be arguably applied to environmental-political contexts [20]. Lastly, we want to quote Hallnäs and Redström’s point of view on computational things as a conclusive remark to close this paragraph - “aesthetics, as we understand it, is concerned with how material builds expressive things, that is, it is a logic of expressionals.” [34, p115].

In general, the remainder of this manuscript will constantly refer to how sustainability could be aesthetically or thematically embodied in musical interactions.

## 3 Embodiment, Sustainability and Musical Interfaces: an Overview on the Literature

Here we deep dive into existing examples of MIs that address sustainability with an embodied approach to provide some practical insight on how to further deepen this.

### 3.1 Reviewing Sustainability and Embodiment, in NIME

Here we provide an overview on Sustainability and Embodiment in NIME relying on existing literature reviews and integrating them. Practices on sustainable NIME have mainly focused on instrument longevity and documentation. The review by Masu et al. of the first 20 years of NIME literature [55] identified only 7 MIs that could potentially promote awareness on environmental concerns in the embodied way (through design) we discuss [31, 32, 50, 51, 66, 76, 77] - 6 of them are sonifications of environmental data. For instance, Suchánek presented a sound installation that sonifies soil moisture as a response to the drought issue [77], through which embodied meaning-making could help the audience bridge the auditory experience to sustainability concerns. However, the amount of these studies/works is not comparable to the current ethos on longevity or documentation. To update the results since that literature review, we further applied the same scheme to publications from 2021 to 2024<sup>2</sup>, yet still obtained only 2 more practical works involving sustainability in the embodied way (through design) we described above: ClimaSynth, a web-based application that encodes climate effect into sound synthesis to reflect issues of climate change [62]; and Ground Hum [2], an installation that incorporates waste elements as ‘performative materiality’ to question the problematic relationship with land under growth mania<sup>3</sup>. 6 other NIME papers incorporate natural elements as an aesthetic exploration to amuse audiences, without explicitly mentioning sustainability or involving any themes on environmental concerns [1, 13, 24, 83, 84, 86]. Apart from these, the trends are generally similar to the said literature review published 3 years ago [27, 56–58]. The practice of using musical interaction to embody themes and thus foster awareness on sustainability remains sporadic.

### 3.2 Reviewing Sustainability and Embodiment in ACM

To broaden our understanding of musical and sonic interfaces that support sustainability through design with embodiment, we performed a literature review focusing on the last 20 years of papers in the ACM database. The systematic search scheme we adopted can be found in Appendix A.

Our key search produced 1628 entries in the ACM digital library, we manually skimmed through all the abstract, to identify works that presented sonic artifacts that aim to foster sustainability in an embodied way.

This process does **not** aim to provide a systematic review of the state of the art on sustainability, as the selection process is subjective to our understanding of musical/sonic interfaces and biased toward embodied sustainability. By initially conducting a keyword search, we aimed at providing a solid overview of MIs where embodiment and sustainability converge. As such, we will briefly elaborate on the papers emerging from this process (26) that present technologies heavily relying on musical or sonic experiences, with extra attention to themes and aesthetics they manifest (details of venues in Appendix C).

**3.2.1 Main Sustainability Themes Covered in the Corpus.** Overall we identified works that can be categorized as installations [3, 26, 35, 44, 48, 49, 53, 64, 67, 68], audio artifacts [6, 12, 30, 38, 71, 72],

garments [46], sculptures [11, 19, 78], enrichments [43, 54, 87], web-based applications [17, 39], and performance [85]. All terms (except audio artifacts) are direct quotes from the original text in the literature, which are not mutually exclusive - for instance some authors used ‘installation’ that in essence represents ‘sonic sculpture’ [3], while others adopted the latter term [19]. Among these works, we found different themes spanning from nature [17, 44, 46, 64, 68, 78], climate [35, 53, 67], post-anthropocentrism perspectives [6, 38], energy [19, 30, 49, 72], pollution or emission (including air, water and noise pollution) [3, 11, 12, 39, 48, 85], animal well-being [43, 54, 87], and unique socio-materiality that promote sustainability [26, 71].

**3.2.2 Sound-Aesthetics.** We summarize an overview of *interaction and sound* design in relation to the themes presented above implemented in all the papers (N=26). The themes we discussed in the previous section were approached using different strategies - all of the works manifested at least one idea revolving around sound-aesthetics: 1) playing natural sounds or soundscapes, 2) making noise or glitches, 3) juxtaposing natural sounds and unpleasant sounds, 4) sonification of data or signals, 5) verbal dialogues for sound compositions, 6) musical interaction with animals, 7) sonic feedback triggered by everyday behaviors. We now briefly highlight some convergence over these sound-aesthetic strategies that support sustainability themes.

Most works that primarily rely on “*playing natural sounds or soundscapes*” [17, 44, 46, 64, 68] point out the problematic relationship with nature and thus seek an intimate connection - by reminding people of the poetic presence of distant nature. In terms of “*noise making*”, noise is used as an auditory representation of negative elements, such as broken media, or obsoleted technology, to foster reflections with impermanence of data and electronics obsolescence [26, 71]<sup>4</sup>. Furthermore, “*juxtaposing natural sounds with unpleasant sounds*” is used to highlight the negative impacts humans have made on the environment, such as marine acoustics versus oceanic noises [78, 85].

In terms of “*sonification*”, most works manifest various themes including nature, climate, energy, and pollution through data or signal meaning-making [3, 6, 11, 12, 19, 38, 39, 49, 53]<sup>5</sup>. Auditory experience could arguably help audiences better perceive the hidden and often unsustainable realities captured by data. Here in this category we also want to highlight how material signals could contribute to musical interaction and sustainability themes by introducing a post-anthropocentrism lens [6, 38]. For instance, In [6] the authors analyzed how care has become significant in their entanglements with the artifact made by Kombucha Scoby - a bio-digital device that can sonify the temporal signals of living organisms in a bottle. In this study, the material used as part of the installation becomes an agent for the active creation of melodies.

“*Verbal dialogues for sound compositions*” and “*musical interaction with animals*” are perhaps less common sound-aesthetic strategies for music communities but still interesting: dialogues are captured from social media for sound compositions [30, 67] - both works aim to contextualize discussions by directly engaging audiences verbally at the center of social debates on sustainability. There are also enrichment devices primarily intended to amuse animals, which can be played by animals directly [43, 54, 87].

<sup>2</sup>The search key terms are environment, ecology, carbon, footprint, sustainability, climate, pollution, conservation, biodiversity [55].

<sup>3</sup>Dorigatti and Masu also provided some interesting theoretical insights in relation to circuit bending as an aesthetic consideration for sustainability [22]

<sup>4</sup>Although sonification can practically produce noise when negative data emerges, we do not put them here.

<sup>5</sup>The sonification devices we presented here can be tangible (installation, audio artifacts, sonic sculpture) or intangible (web-based sonification)

Unsurprisingly, some SHCI concepts were adopted to foster sustainable everyday behaviors. “*Sonic feedback*”, originating from persuasive HCI [28], aims to respond meaningful sound effects to (un)sustainable behaviors, such as consuming energy (in)efficiently [48, 72].

**3.2.3 Four Aspects of MI Design to Connect Embodiment to Sustainability.** In this subsection, we provide some practical points focusing on common aspects of interactive music system design based on the results of the literature. These points are directly relevant to the sound-aesthetics and the expression of themes on sustainability.

*Sound and Interaction* are two aspects that are central in all the work, and their relevance can be considered self-evident. Using sounds or music to represent different meanings (either qualitative or quantitative) in relation to sustainability allows themes to be expressed intuitively. Overall sounds can be *pleasant* [17, 35, 43, 44, 46, 48, 54, 64, 68, 72, 78, 85, 87], *unpleasant* [26, 71, 72, 78, 85] or *neutral* [3, 6, 11, 12, 19, 30, 38, 39, 49, 53, 67, 68]. The philosophy of these MIs here is how audiences perceive and prefer sounds, and how their behaviors react to sounds accordingly toward a sustainable future. Several sound-aesthetic strategies discussed in the previous subsection rely on this. In addition to what these sounds can be, “*where to play with sounds*” has also been considered. We have witnessed MI that carefully chose the urban setting to bring back natural elements, and the community setting to evoke discussion [11, 17, 30, 64, 68].

Interactions here is porous - it can be centered on *human agents’ action* [12, 17, 19, 44, 46, 48, 64, 72, 78, 85], or simply led by *non-humans* [6, 38, 43, 54, 87], or autonomously reacting to the *environment* [3, 11, 26, 35, 39, 49, 53, 68] or *social context* [30, 67] without human intervention. With humans as the active agents of interaction, MIs commonly rely on a more tangible way to encourage encounters with nature, or sustainable actions that make a difference in reality. With non-humans as the agent, MIs could become a mediator fostering communication and wellbeing of non-humans, by amplifying their signals, co-performing with them, and amusing them. Environmental dynamics and social context can become rather more abstract agents through sonification or sound composition, with humans as almost audiences instead of performers.

In the previous analysis, we also revealed two other elements that proved to be particularly interesting in relation to embodiment and sustainability - *data and material*. Data is relevant as most MIs involve data processing as an integrated element, among which sonification is highly dependent on data. Data here are mostly *environmental data, or signals* (captured by sensors) [3, 6, 11, 12, 17, 19, 26, 35, 38, 39, 49, 53, 68, 72], and *social media feeds* [30, 67]. These environmental data or signals could provide an original statistical description of our environmental reality (often problematic), which can be mapped to sound and music to reveal this reality more intuitively. Social media feeds about environmental concerns are also viable for sound composition [30, 67].

Material can be another aspect found in most ‘tangible’ computing systems, for instance most installations or instruments<sup>6</sup> - in the previous subsection, we also highlighted some works relying on unique materiality [6, 38]. In our context of sustainability and embodiment, material with *unique cultural representations*

[6, 26, 38, 64, 78] or *physical qualities* [3, 12, 48, 49] could benefit MI design through its rich aesthetic expressiveness - such as the use of water to make sounds and visual patterns [3, 49]; or fragility of living elements in relation to empathy on non-humans [6]. Previously we also mentioned that repurposed hardware or exposed circuits could contribute to rich expressiveness [2, 22, 26].

In general, the four aspects are: sound, interaction, data and material. In Appendix B, we showcase how the 26 papers identified in the previous subsections are connected to these four aspects in terms of fostering embodied sustainability<sup>7</sup>. With these aspects, we do not intend to systematically exhaust all possibilities to tell “what practitioners should do”, instead the points we provide here are viable references for us to gain reflexive insights, and to inspire future works that seek to express sustainability themes in an embodied, artistic manner.

To obtain generative ideas from designing MIs that embody sustainability, we put the four aspects of reflexive considerations into practice, and devised a design activity that aims at brainstorming MI concepts through verbal and visual materials.

## 4 The Case Study

To practically investigate how to design MIs that could aesthetically embody sustainability themes, we engage in a design activity relying on a research through design approach [89] - a workshop to obtain generative ideas in forms of sketches.

Four design researchers (the authors of the paper - A1, A2, A3, A4) with experience in sustainable HCI and NIME took part in this design activity. The activity was documented through audio recording, photos and design diaries.

We examined this experience using a Reflection-on-Action [69], initiated by retrospectively looking at the material produced in the workshop, to identify issues or opportunities. This self-analytical approach is a method that enables researchers to understand the nuanced dynamics in decision-making processes that characterize design practice [47], and has been recently applied in other papers presented at NIME [16, 65].

### 4.1 Design Activities

Drawn from structured group ideation techniques<sup>8</sup> [73], we organized our design workshop in three main steps: 1) Initial Ideation that combined brainstorming, individual proposal and group discussion to define a theme; 2) Individual Ideation & Cross-Negotiation and 3) Collective Ideation.

**4.1.1 Initial Ideation.** As a first step, we defined a specific sustainability theme. Initially, each participant wrote different ideas on post-it notes (21 in total). We then discussed these ideas and iteratively clustered them into main thematic groups (Figure 2).

Following a group discussion, we agreed on a single theme for the upcoming design activities: **construction**. This theme was considered twofold, reflecting both the unsustainability of the “growth” obsession in a post-growth era [74], and the noisy, polluted soundscape of a construction site.

<sup>6</sup>Some papers only relied on sonic interaction to manifest sustainability themes. For instance, some papers use sensors (data) only to receive touch input, the sensor readings are deemed to be merely a technical solution; similarly some papers adopted plastic or metal (material) cases for their tangible installations as a common design decision. We decided not to include this information in the table

<sup>8</sup>We primarily referred to 6-3-5 method and gallery method as our design activity was conducted on a rather smaller scale, the two methods could support structured procedure suitable for small scale creativity. However we did not set strict time limits as it was deemed not necessary in our case.

<sup>6</sup>We acknowledge the importance of general SHCI considerations on degradable or compostable material, such as Alginate, Kombucha SCOBY, Chitosan, Cellulose, etc, as this aspect inevitably involves long-lasting concerns in relation to e-waste [7, 10]

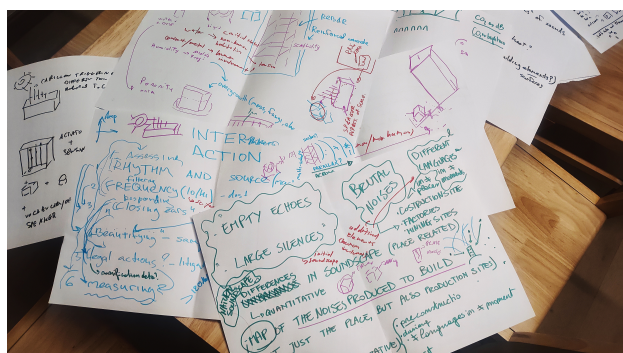




**Figure 2: Sustainability themes written by each participant**

**4.1.2 Individual Ideation & Cross-Negotiation .** In this activity, each of us chose one of the four aspects - data (A1), sound (A2), materiality (A3), interaction (A4) - to list ideas of aesthetic elements related to the main theme in relation to that specific aspect as (table 1 ). At this stage, the proposed elements did not adhere to any taxonomy, and remained open to modification in the subsequent discussion.

After these individual ideas were presented, we recursively commented and discussed them in pairs (we repeated this three times to have all the pairing combinations) to generate early design sketches. In this process, we developed a negotiation between different aesthetic elements to mediate intrinsic ideas and the specificity of each aspect. Some more defined design ideas were conceptualized and brought to the next level of discussion (Figure 3).

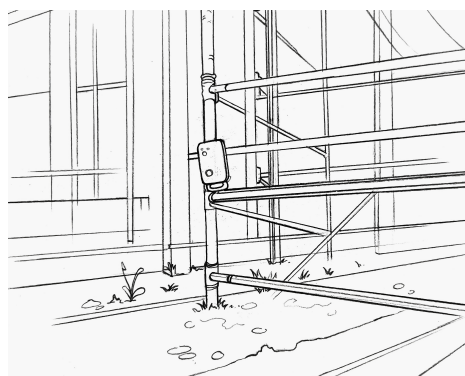


**Figure 3: Quick sketches and notes from the workshop**

**4.1.3 Collective Ideation.** After cross-negotiating ideas, we collectively developed a series of conceptual designs by selecting, integrating, and refining the ideas previously discussed. These designs did not necessarily need to adopt all previous ideas we generated, instead they only considered the most relevant or helpful ones. In some cases, the final conceptual design had already taken a clear shape during the earlier phase, while in others it emerged during this final collective discussion. In total we produced 5 main *conceptual designs*, and we present 3 most relevant ones due to the length limits of this paper.

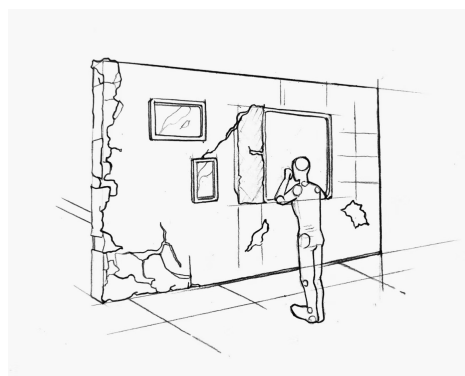
- (1) **Imbued Echoes:** a large-scale interactive soundscape that reacts to the audience via proximity sensors near construction elements. The space is decorated with scattered construction artifacts. When audiences get closer / further to the artifacts, different sounds would be triggered (voices

of workers, sounds of wandering animals, everyday conversation of dwellers), leading to a parallax, location-based perspective to sound story of a given construction artifact (Figure 4).



**Figure 4: The Sketch of Imbued Echoes, completed after the workshop based on the collective ideation**

- (2) **Sonic Itinerary:** a sonic sculpture that reacts with environmental sound when the audience puts ears against a wall structure and triggers sensors. Such environmental sounds correspond to different periods of the place, such as construction noise, natural sounds of rain, wind, or birdsong, and the sound of crowds passing by. In this way, the sonic history of the place is presented in an immersive way, which can be augmented with vibration-based tactile feedback. The soundscape can be deployed in different scenarios: 1) in situ performance specific to unfinished abandoned buildings; 2) any empty room that allows devices to be integrated inside the wall; 3) a scaffolding structure that can be deployed on stage (Figure 5).

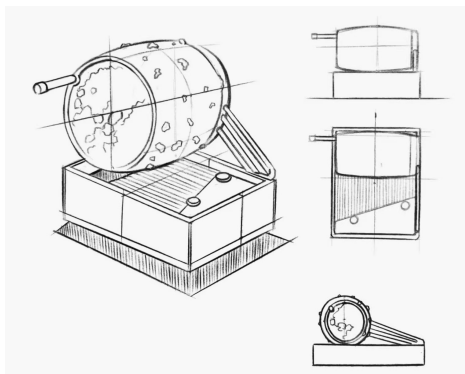


**Figure 5: The Sketch of Sonic Itinerary, completed after the workshop based on the collective ideation**

- (3) Noisy Carillon: a musical installation in the form of a music box made of concrete and metal. It resembles brutalist architecture, and the musical texture is inspired by the same metallic picks commonly found in other music boxes. Likewise, the sound is triggered by turning the crank as a metaphor for a concrete mixer. However, the rolling component can be filled with gravel, water and other materials, which creates noise by the collision of different materials, leading to a confrontation between noise and music (Figure 6).

**Table 1: Categorization of aesthetic elements in sound, material, data, and interaction from the workshop**

Aspect	Aesthetic Elements
<b>Sound</b>	Empty echoes Sound of dripping water Large silences Spatial differences in soundscape (natural space, construction site, community, etc.) Moments of soundscape (before, during, and after construction) Noises, languages, natural sounds around constructions
<b>Material</b>	Construction scaffolding Construction scraps Concrete powder Liquid concrete Solid concrete Broken concrete Betoniera (spinning wheel) Water
<b>Data</b>	Spatial division of urban space Animal distribution Construction distribution Construction history Amounts of wall/construction/anything built Pollution data of construction (air, water, soil) Emission data
<b>Interaction</b>	How sound is heard (perception and sensemaking of rhythm or source) Sound filtering/processing (propagation across distance, medium) How people respond to sound (audience/musician's performative behavior through experience) Beautifying sound (e.g., industrial music using sampled noises) Context transition (noises embodied in acoustic-cultural-legal-scientific contexts) Quantitative ways to process and demonstrate sonic data (e.g., data visualization) 'Being there,' from Heidegger's conception (unique stage/space/location for performance)

**Figure 6: The Sketch of Noisy Carillon, completed after the workshop based on the collective ideation**

In the next subsection, we would reflectively examine all these phases, by which we hope to identify opportunities or weaknesses from our practices to support a more tailored workflow that helps bridge embodiment to sustainability in the MI design.

## 4.2 Reflection-on-Action

In this conclusive section, we report our self-reflection on the design activity and connect it to the relevant literature.

**4.2.1 Embodiment and Boundary Making.** In this design activity, we primarily intended to conceptualize experiences that reproduced and amplified the sustainability issue concerned through

sounds or music. All of our final design concepts aim to enact embodied experiences - such as bodily exploration, and embodied meaning-making.

Early in the negotiation, we only focused on making individual ideas from different aspects compatible and did not consider how to enact the embodiment of audiences. As negotiations progressed, we realized that our theme on sustainability is relatively niche for musical expression and may require a proper context to support our expression. Thus we reckoned it was not a good idea to glue different individual ideas like "Frankenstein's monster" - something cobbled together from various parts in a haphazard, pieced-together manner, instead we had to synthesize these ideas as a whole to reach a self-consistent state.

With this in mind, at the end of collective ideation, our activity led to some key designs that essentially involved a series of boundary objects for creating meaningful embodiment for audiences. For instance, one of the early concepts was an experience that could allow audiences to *feel* how construction has an impact on the acoustic ecology of a physical space. This direction originated from individual ideas in Table 1, especially moments and spatial differences in a soundscape, and led to the final concepts of Sonic Itinerary (SI) and Imbued Echoes (IE). To amplify the felt auditory experience, we decided to emphasize audiences' bodily involvement in situ as a way to connect their bodies to the material reality of this space - in the case of SI, it's 'pressing ears against the wall'; as for IE it's 'exploring the soundscape' and 'getting closer/further to the construction artifacts'. This embodied experience relied on many aspects of considerations to enact - such as material (wall for SI; artifacts for IE),

soundscape dynamics (temporal dynamic for SI; spatial dynamic for IE), force & location (touch readings for SI; proximity readings for IE), and audience subjectivity ('being there'/presence for both concepts). Thus, our practice suggested a necessary layer of boundary-making among designers to enact audience embodiment: In both cases, to synthesize all aspects towards a mutual expression, we derived one object that could help transmit and transform meanings from different aspects to the others in a meaningful way - taking SI as an example, the wall represented construction debris, captured touch input, made sounds inside, and required pressing ears to listen. This helped us, as creators, express our theme of construction impact all together via only one object and one action, which met our expectation to amplify the concerned issue, by concentrating the theme on one singular outcome.

Since our conceptual design method does not allow us to validate the conceptualized artifacts in reality, we chose to focus primarily on our own experiences as practitioners who engaged with this design activity. The said examples showcased what could be fundamental to designing MIs that can aesthetically embody sustainability - a boundary object that helps connect complex meanings through different perspectives each artist holds, thus to establish a conversational space for audiences.

In Noisy Carillon, we conceptualized the 'rolling component' as a structure that potentially involved multifold meanings to interpret - from material, sonic, and behavioral representation of noisy construction to musical representation of something beautiful. We hoped the player could relate the performance to themes of construction mania and its negative acoustic impact, by simultaneously triggering music (from picks of the music box), noise (from concrete materials inside the component) and experiencing an interaction similar to operating a construction machine. In the future, we will build this artifact to examine the experience and solidify our understanding on this layer of boundary-making between audiences and artists.

**4.2.2 Sustainability as Themes and Aesthetics, in MI Design.** As pointed out in the background, aesthetics can be connected to different themes [20, 34, 63], we look at these two aspects within our design case to further elaborate on this relationship.

In the initial *themes* ideation, we identify an interesting dynamic that could be found among many related works - an inconsistent framing on what sustainability could be and could involve. Different ontological scopes such as 'social sustainability' as a broad concept (and one pillar of the Triple Bottom Line framework [25]) have emerged in contrast to 'construction noise'. This inconsistency of scope is a manifestation of how diverse the understanding on sustainability can and has been, as an umbrella term in artistic practice. Our design after initial ideation mainly revolved around environmental themes, which could have fortunately made the process smoother, as sonic aesthetics can be derived and ideated easier from themes such as construction, non-humans, land, etc. than social inclusion or economy. In light of our experience, we support that it would be advisable to anchor such views of sustainability at the center of ecological domain, with additional complementation on recent post-anthropocentric, socio-environmental trends [70].

We also found exploring the derived *aesthetic elements* - that could implicitly embody the theme "construction", such as "sound of dripping water", "empty echoes", "spatial division (of urban soundscape)", "construction scraps" - fascinating. Here through a

practical lens, we witnessed the feasibility and designers' aspiration to aesthetically embody sustainability in MI design. Perhaps the most sensible tension that occurred in our practice emerged when each designer began ideating these aesthetics with respect to data, sound, materiality and interactions. While presenting his ideas about interactions, Kuzmin commented that it is difficult to imagine what an artwork can be without explicitly referring to the sound we could have; similarly Masu initially ideated interactive sonic experiences instead of just sound textures and effects and felt that at least sound and interactions should have some level of priority. These reflections from our practice suggest a hierarchical relationship between the various aspects where sound-interaction aesthetics should be considered together with more weight over the other two in practice.

Lastly, we observed a tacit convergence on how we approached "theme" and "aesthetic" - in our case we all tried to avoid conceptualizing MIs that only sonified how much particles had been emitted to the air during construction, even if this could be a rather straightforward way to tell audiences what the issue was. Instead, we all preferred those rather ambiguous yet entangled experiences that required audiences to appreciate "what's in it". Some previous works also relied on more aesthetic representations of fragile materials, nature, land, exposed circuits to support a subtle expression on some broad themes like the human-nature relationship [2, 6, 44, 64].

## 5 Ontology of Sustainability and Visions on Human-Object Relationship

As we saw, the sustainability discourse in the NIME community has a strong association with Blevis' SID - the overall reduction of the environmental footprint in making and using phases. In this section, we discuss some implications of current trend in the NIME community and how it can be connected to embodying sustainability, especially in a context of post-anthropocentrism.

Recent debate has largely elaborated on how MIs are inscribed with culture and knowledge [18], and these aspects are often considered to be embodied in the instrument itself. Interestingly, musical or sonic artworks presented in other computing venues (non-NIME) have shown the effectiveness of connecting embodiment to sustainability in a performative manner [3, 6, 11, 12, 17, 19, 26, 30, 35, 38, 39, 43, 44, 46, 48, 49, 53, 54, 64, 67, 68, 71, 72, 78, 85, 87]. As such, it is surprising that we did not find more papers within NIME relying on these inscribed properties of musical devices in relation to sustainability issues [2, 31, 32, 50, 51, 62, 66, 76, 77]. A few recent studies from NIME actively incorporated natural elements into sonic aesthetics through interaction, although sustainability is not explicitly involved as a theme. 4 of these works are sound applications reactive to natural environments via sensor readings [1, 24, 83, 84] - this is, in fact, a common approach in SHCI artworks fostering human-nature connection [45]. These evidence imply possibly underestimated avenues for exploring sustainability within NIME research - through a more practical and expressive way with embodiment, especially in terms of mediating human, nature, and non-human relationships.

However, here it should be noted that a recent post-anthropocentrism lens furthered the debate on technological interventions in relation to nature [82] - some practices use natural elements merely to amuse humans, while other practices seek less intrusive ways to serve both sides [6, 43, 44, 46, 87]<sup>9</sup>. Although drawing a

<sup>9</sup>The effectiveness of technology that mediates sustainability issues is also discussed in Disalvo's work [21]

clear line between what is intrusive and what is not goes beyond the scope of this paper, we do hope to highlight this tension as it risks to cause unexpected ethical issues for practices that aim to embody sustainability. This can be exceptionally critical for the MIs with a strong involvement of non-humans, or those deployed in a nature setting. We suggest a necessity to clearly assess the impact of such practice on non-humans and in situ surroundings.

Since post-anthropocentrism has become a trend in SHCI, there has been increasingly more literature offering alternative values, ethics, and considerations to the sustainability debate, which is deemed relevant to “socio-environmental sustainability” in Scuri et al.’s reflections with SHCI [70]. This trend mirrors Thorpe’s call for eco-logical musicking [79], in which the author explored co-authorship with ecology. Building upon these, we also want to suggest that there’s a necessity to explore alternative relationships between players, instruments, audiences, and the merged roles they play. In essence, this is to question “those (human) who have more power” [5] and thus empower the non-human actors to rebalance the unsustainable relationship.

## 6 Conclusion

Overall we reckon embodiment could be an unique leverage point fostering sustainability “through” the design and use of musical interfaces, which complement the “in design” approach that has been explored more in NIME.

In this paper, we conducted a literature review to synthesize common themes and sound-aesthetic strategies in relation to sustainability. Practical points in relation to data, material, sound and interaction aspects of musical device design were derived, and a case study was presented, showcasing how practitioners could turn aesthetics into themes of sustainability. We conceptualized 3 embodied sonic experiences that intended to aesthetically attune the noisy, anthropocentric, construction-obsessed reality. We then discussed our main idea - embodiment to foster sustainability - connecting it to recent visions of post-anthropocentric design.

We believe that one of the key benefits of linking embodiment to sustainability is paving a practical way to explore sustainability within NIME research. From an epistemic point of view, the practices of connecting embodiment to sustainability complement the conceptual scope of “sustainable musical interface” beyond the widely explored topics of longevity or documentation. While this approach is not completely new in NIME research (e.g., [77]), this paper offers a systematized reflection by imagining what MIs can do as culturally charged objects. We hope that these ontological expansions would motivate both researchers and organizations to pave new, and especially artistic avenues on sustainability research in NIME.

## 7 Ethical Standards

This paper is aligned with the ethical standard on NIME. No participants were involved, nor any animal or vegetal specimens. This work also aims to contribute to the discussion over a sustainable NIME, which is one of the point touched in the conference ethical code. As none of the author is native speaker we used GPT based AI to improve our writing.

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## A Appendix A

In our review on musical or sonic interfaces that support StD, we adopted similar key terms used in Masu et al.'s literature review [55] on environmental sustainability of NIME - these key terms are sustainability, ecology, environment, carbon, climate, pollution, conservation, biodiversity, with 3 additional adjective deviations we add: sustainable, ecological, environmental. The complete search scheme is given below, which relied on the advanced search of the ACM database to look for relevant titles, publication titles, author keywords, and abstracts. After identifying 1628 papers, we examine all the papers by reading their titles and abstracts. Papers that did not present any musical or sonic interfaces or did not involve any sustainability/environmental

themes will be excluded. Below is the search syntax we used, and the address can be found [here](#).

**The syntax:** ContentGroupTitle:(("conservation" OR "biodiversity" OR "pollution" OR "environment" OR "environmental" OR "climate" OR "carbon" OR "footprint" OR "sustainability" OR "sustainable" OR "ecological" OR "ecology") OR Abstract:(("conservation" OR "biodiversity" OR "pollution" OR "environment" OR "environmental" OR "climate" OR "carbon" OR "footprint" OR "sustainability" OR "sustainable" OR "ecological" OR "ecology") OR Keyword:(("conservation" OR "biodiversity" OR "pollution" OR "environment" OR "environmental" OR "climate" OR "carbon" OR "footprint" OR "sustainability" OR "sustainable" OR "ecological" OR "ecology") OR Title:(("conservation" OR "biodiversity" OR "pollution" OR "environment" OR "environmental" OR "climate" OR "carbon" OR "footprint" OR "sustainability" OR "sustainable" OR "ecological" OR "ecology")) AND ContentGroupTitle:(("music" OR "musical" OR "sound" OR "sonic") OR Title:(("music" OR "musical" OR "sound" OR "sonic") OR Abstract:(("music" OR "musical" OR "sound" OR "sonic") OR Keyword:(("music" OR "musical" OR "sound" OR "sonic"))

Note that by “musical or sonic interfaces”, we mean technologies that rely heavily on musical or sonic interfaces to achieve their design objectives. By ‘sustainability’ we mainly refer to Blevis’ initial framing in the previous work [10, 52], which can be arguably categorized as ‘environmental sustainability’. In HCI this commonly encompasses diverse themes such as human-nature connection, ecological degradation, environmental pollution, energy consumption, carbon emission, etc., which has been reflected in our search key terms. We acknowledge that sustainability can be a broad topic and we are not able to exhaust all subtopics under this umbrella term; yet other relevant subtopics such as societal resilience or economic sustainability could be either too niche or unlikely to be involved in most artistic practices, thus we decided not to consider these in our context.

## B Appendix B

All details from the 26 papers that aesthetically foster sustainability, connected with the four aspects, see Table 2 and Table 3.

## C Appendix C

Here we provide all venue and year details of 26 identified papers from the ACM database and 9 papers from NIME in Table 4.

**Table 2: Aesthetic elements of sound and interaction from the literature**

<b>Interaction<sup>a</sup></b>	<p><b>Human agents making sounds:</b> moving/wandering [17], touching [19, 78], pressing ear (to listen) [64], breathing [12, 48], audio-visual performance [85], everyday sustainable behaviors [72], playing audio to non-humans [46], shouting to mountain forest [44];</p> <p><b>Non-human agents making sounds:</b> playing [43, 54, 87], microphysiological response [6, 38];</p> <p><b>Sonic artifacts as agents making sounds:</b> revealing environmental dynamics [3, 11, 26, 35, 39, 49, 53, 68], contextualizing sustainability discourses [30, 67]</p>
<b>Sound<sup>b</sup></b>	<p><b>Pleasant sounds:</b> ocean waves [68], Neighborhood sound record [68], water [35], sound of oxygen bubbles [48], marine environment [85], animal sounds from forest [78], wetland [64], state park [17], forest [44, 46], echo of human voice [44], applause sounds [72], music and sound favoured by animals [43, 54, 87];</p> <p><b>Unpleasant sounds:</b> sounds of screams, saws, coins, gunshots, explosions, personal media chips, mining machinery, and axes [78], noise [26, 71, 85], broken music [72];</p> <p><b>Neutral sounds:</b> verbal dialogues [30, 67], digitally synthesized sounds [3, 6, 11, 12, 19, 38, 39, 49, 53, 68];</p> <p><b>Performance stage:</b> nature [44, 46], urban [64, 68], campus [17], communities [30], square [11], zoo [43, 54, 87]</p>

<sup>a</sup> all 26 papers included<sup>b</sup> all 26 papers included**Table 3: Aesthetic elements of data and material from the literature**

<b>Data<sup>c</sup></b>	<p><b>Environmental data or signals:</b> CO2 concentration/levels [11, 12], vessel parameters and estimated emissions [39], contaminant concentrations [3], electricity consumption [19, 49], environment's light intensity [26], weather condition [53], energy consumption [72], light level through living organisms [6], bio-electrical signal [38], wind speed [68], solar radiation [68], underwater hydrophone signal [68], GPS location [17], reservoirs and snowpack data [35], cloud and precipitation data [35];</p> <p><b>Social media feeds:</b> [30, 67]</p>
<b>Material<sup>d</sup></b>	<p><b>Material with unique cultural representations:</b> repurposed electronics [26], plants as natural elements [38, 64], fragility of living material (Kombucha Scoby) [6], golden filaments as mineral elements [78];</p> <p><b>Material with unique physical qualities:</b> water [3, 49], mirrored acrylic and condensed vapour [12], algae to absorb CO2 [48]</p>

<sup>c</sup> 16 papers included<sup>d</sup> 10 papers included**Table 4: Venue and year of all papers**

Venues	Literature	Years	Literature
NIME	[2, 31, 32, 50, 51, 62, 66, 76, 77]	2024	[6, 17, 19, 39, 48, 54, 62, 67, 71]
AM	[17, 19, 39, 72]	2023	[53, 72, 78]
CHI EA	[35, 49, 64]	2022	[2]
SA Art Gallery	[46, 48, 53]	2021	[3, 12, 26, 38, 87]
ARTECH	[26, 78]	2020	[43, 51, 77]
CHI	[30, 43]	2019	[49]
C & C	[3, 85]	2017	[35, 85]
MM	[38, 44]	2016	[50, 66]
NordiCHI	[11, 71]	2015	[30, 64]
TEI	[6, 87]	2013	[44]
ACI	[54]	2011	[76]
ACM Comput. Graph. Interact. Tech.	[67]	2010	[11]
AHs	[12]	2009	[46]
SAME	[68]	2008	[68]
		2004	[31]
		2003	[32]