IEEE Access
Multidisciplinary : Rapid Review : Open Access Journal

Received 5 March 2024, accepted 9 April 2024, date of publication 25 April 2024, date of current version 9 May 2024.

Digital Object Identifier 10.1109/ACCESS.2024.3393468

PERSPECTIVE

Sustainable Internet of Musical Things: Strategies to Account for Environmental and Social Sustainability in Network-Based Interactive Music Systems

RAUL MASU[1], NICOLÒ MERENDINO[2], ANTONIO RODÃ[2], AND LUCA TURCHET[3], (Senior Member, IEEE)
[1]Computational Media and Art, The Hong Kong University of Science and Technology (Guangzhou), Guangzhou 999077, China
[2]Department of Information Engineering, University of Padova, 35122 Padua, Italy
[3]Department of Information Engineering and Computer Science, University of Trento, 38122 Trento, Italy

Corresponding author: Nicolò Merendino (nicolo.merendino@unipd.it)

The work of Antonio Rodã and Luca Turchet was supported in part by Italian Ministry of University and Research, Programma Operativo Nazionale (PON) Scholarship, under Grant DOT1487343-5; and in part by Project DM 1061-2021 PON RI 2014-2020-React-EU.

ABSTRACT The use of internet-based and networking technology in computer music systems has greatly increased in the past few years. Such efforts fall in the remits of the emerging filed of the Internet of Musical Things (IoMusT), the extension of the Internet of Things paradigm to the musical domain. Given the increasing importance of connected devices in the musical domain, it is essential to reflect on the relationship between such systems and sustainability at the environmental and social levels. In this paper, we address this aspect from two perspectives: 1) how to design IoMusT systems in a sustainable way, and 2) how IoMusT systems can support sustainability. To this end, we relied on three lenses, combining literature from green IoT (lens 1), Sustainable HCI (lens 2), and the Sustainable Development Goals from the United Nations (lens 3). By combining these three lenses, we developed five strategies for a sustainable IoMusT, which are extensively presented and discussed providing critical reflections.

INDEX TERMS IoT, IoMusT, sustainability, SDG, HCI, green IoT.

I. INTRODUCTION

In the last decade, music technology researchers and practitioners have increasingly adopted network communication for developing new pieces of technology (see e.g., [126], [134]) or artistic inventions (see e.g., [56], [136]). Relying on the definition of the Internet of Things (IoT) [94] - which are devices, applications, and systems that are connected for communication purposes and data sharing - the lemma *Internet of Musical Things* (IoMusT) was introduced to identify IoT systems dedicated to music purposes [123]. Since its introduction, the IoMusT has become an independent field of study, which lies at the intersection of IoT, Human-Computer Interaction (HCI), and music technology, with dedicated venues[1] and an increasingly wide specific literature (e.g., [2], [8] - see Subsection II-A for a broader overview). As the IoMusT consolidates its importance as a specialized subfield of interactive technology research, we argue that it is essential to account for the ethical implications and the societal impact that such practice can have.

The IoMusT offers an ideal avenue for exploring the sustainability of IoT systems in general. Its technical requirements, such as low latency in data streaming, make it a fertile ground for analysis development. Moreover, the diverse facets within the realm of music provide a rich landscape for analyzing various aspects of an IoT

The associate editor coordinating the review of this manuscript and approving it for publication was Derek Abbott.

[1]https://internetofsounds.net/is2_2023/

system, a uniqueness rarely found in other IoT subcategories. Studying the IoMusT presents an exceptional opportunity to delve into the intricacies of sustainable IoT.

In this paper, we reflect upon *sustainability implications* of the IoMusT, a topic that has been largely overlooked thus far by the research community. While different conceptions and definitions of *sustainability* exist, a consensus supports that environmental, social, and economic sustainability are equally important [102], [108]. Thus, a sustainability reflection requires a comprehensive account of its various declinations. Since the beginning of the HCI debate on sustainability, this aspect is usually addressed in two ways: 1) how technology can be developed sustainably and 2) how technology can support sustainability [75]. Reasoning on this comprehensive account of the different forms of sustainability, in this paper, we aim to address the following research questions:

- RQ1: How can the IoMusT be developed in a sustainable way?
- RQ2: How can the IoMusT contribute to sustainability?

To answer those research questions, we devise three lenses derived from the literature:

- L1: sustainable IoT (lens 1);
- L2: Human-Computer Interaction (lens 2);
- L3: and Sustainable Development Goals defined by the United Nations (lens 3).

By looking at the IoMusT practice with these three lenses, we propose a model composed of five strategies that suggest how the development of an IoMusT system can intersect with the goal of moving towards sustainable development of technology. To complement each strategy, we provide examples that can facilitate contextualizing the categorization into specific projects. Most of the time, following a common practice in the IoMusT community, these examples are tailored around specific projects, users, or needs (see e.g. [32]). Therefore, the case studies described in this paper are analyzed by using a qualitative research methodology, an approach that is often adopted when dealing with ethical issues.

The core contribution of this research is a model that suggests how an IoMusT system can relate to sustainability in its different forms. The first two proposed strategies suggest how an IoMusT system can be developed in a sustainable way (RQ1), and the remaining three strategies outline how the IoMusT can contribute to promoting sustainability or rendering the world more sustainable (RQ2). We want to highlight that the IoMusT does not automatically imply those strategies, but that these strategies need to be pursued by following specific design and development intents. In this paper, we do not offer specific new practical solutions to address individual aspects of sustainability related to particular components of IoMusT system, instead we offer a model to connect individual instances to address sustainability from a comprehensive perspective. Such a perspective is crucial to truly address the sustainability issues, as the various aspects are interconnected, as highlighted in the United Nation goals for sustainable development and further stressed by recent HCI literature [55], [102], [108].

II. BACKGROUND

In this section, we will first outline relevant literature on the IoMusT field. Afterwards, we will present literature related to the three lenses: green and sustainable IoT (lens 1), Sustainable HCI (lens 2), and Sustainable Development Goals defined by the United Nation (lens 3).

The IoMusT presents a series of critical aspects in terms of system's performance that are particularly interesting to study when facing the topic of sustainability: indeed, IoMusT applications include a wide variety of requirements, ranging from low-speed information processing to streaming and processing of high-bandwidth data streams with stringent real-time requirements. Additionally, IoMusT is driven by artists, a type of professional that bases their practices on projects that are usually visionary and open to exploring the new possibilities that cutting-edge technologies offer. This makes the IoMusT a very populated source of case studies that fit with the relatively new topic of sustainability within the field of the IoT. To summarize, the IoMusT functions as a getaway that, in line with the holistic approach presented, allows our research to touch topics that are very specific and, therefore, challenging from a performance point of view, as well as topics that are more broadly applicable to the IoT in general.

A. THE INTERNET OF MUSICAL THINGS

The IoMusT is an emerging paradigm in computing that stems from the confluence of the IoT and music technology [123]. It belongs to the general field of the Internet of Sounds [124], which has recently received support by the IEEE with the creation of a dedicated Emerging Technology Initiative.[2] More specifically, the IoMusT refers to the networks of "Musical Things", which are smart objects serving a musical purpose. Such computerized systems embedded in physical objects are connected to local networks or the Internet, and can interact with each other and cooperate to reach common musical goals. The IoMusT technological infrastructure enables ecosystems of interoperable devices that connect musical stakeholders with each other providing novel interaction possibilities for different musical activities such as performance [11], composition [29] and pedagogy [2], both in co-located and remote settings. The IoMusT paradigm has the potential to impact a wide variety of stakeholders such as performers, composers, students, teachers, conductors, studio producers, live sound engineers, and audience members.

Different kinds of Musical Things have been developed by the IoMusT research community[3] both in industrial and academic settings [65], [137]. Noticeable examples in this space are the so-called smart musical instruments [120] and

[2]https://www.comsoc.org/about/committees/emerging-technologies-initiatives/internet-of-sounds

[3]See https://internetofsounds.net/

the musical haptic wearables for performers or audience members [127]. The development of such devices is rooted in embedded systems dedicated to low-latency audio processing tasks and equipped with connectivity capabilities [83], [126].

Moreover, the attention of researchers has focused on the development of several frameworks to connect Musical Things [33], [45], [81], [125], [130], as well as networked music performance system aiming at interconnecting geographically displaced musicians [18], [22], [24], [38], [61], [126]. In particular, recent years have witnessed an increasing use of 5G technologies in musical settings [23], [27], [39], [139].

B. SUSTAINABILITY IN IOT

The IoT debate on sustainability has primarily focused on environmental sustainability. In particular, a significant effort has been made to foster a green transition of IoT technology. Since IoT and networked computational systems have a heavy environmental footprint [15], researchers particularly focused on the massive production of such electronic devices. Over the years, researchers have analyzed the environmental impact of energy consumption of IoT, including improved energy consumption of data streaming [6] through efficient computing [91], the development of self-sustaining [110], and more efficient hardware [4]. Existing research has also investigated environmentally sustainable strategies related to specific components by studying, for example, how to reduce the impact of a single protocol such as Bluetooth [114], or how to schedule tasks in order to save energy [107].

Recently, Mahmoud and colleagues [1] proposed the idea of "Green IoT" (GToT). By systematically scrutinizing related works on sustainable IoT development, the authors identify "various efficient enablers, architectures, environmental impacts, technologies, energy models, and categories" to pursue green IoT development. This comprehensive text offers a valuable set of strategies addressing the different components of IoT systems. In this paper, we use the comprehensive model developed by Faisal and colleagues in their paper "Green IoT: An Investigation on Energy Saving Practices for 2020 and Beyond" [109] as the first lens in our model. Such a model comprises the following six items for a Green IoT transition:

- Hardware-Based
- Recycling-Based
- Software-Based
- Habitual-Based
- Awareness-Based
- Policy-Based

Hardware-Based Green IoT focuses on the reduction of e-waste, the carbon footprint of the "things", the traffic, and the energy consumption of the overall infrastructure. It does so by intervening in the development of the hardware components, such as the circuits and the casing of IoT devices.

Recycling-Based Green IoT proposes using recyclable material to produce devices in an IoT network, such as parts of smartphones that are no longer in use, thus reducing e-waste by recycling part of it.

Software-Based Green IoT references the efforts related to the development of high-efficiency software. An example that falls in this strategy is an orchestration in a Client-Server Model responsible for context evaluation of Servers [3].

Habitual-Based Green IoT highlights the habits we can adopt to decrease energy consumption in our daily activities. It includes practices such as tracking energy consumption in offices, homes, and industries through automation systems.

Awareness-Based Green IoT consists in the development of systems that create awareness in the population. It promotes activities such as providing individuals and groups with real-time feedback on their energy consumption and then advising about specific environmental aspects relying on real-time data collection and providing such information to the population.

Policy-Based Green IoT is an approach in which IoT systems promote sustainability-related policies such as smart garbage collection.

In addition to these six strategies, in our proposed model, we add "end-of-life" as a seventh IoT-related item. Literature focused on sustainable design has widely explored how the longevity of tools and devices is fundamental in terms of environmental impact, and (e-)waste is one of the most detrimental issues related to digital technology (i.e., [21], [26], [57], [58]). Within the IoT debate, this topic has been recently explored by Lechelt et al. [69] who specifically uses the term "end-of-life" and argued for the need for updating, recycling, and upcycling IoT devices.

C. SUSTAINABILITY AND HCI

Researchers operating in the field of HCI widely investigated sustainability for almost two decades, to the point that in the current debate, the label Sustainable Human-Computer Interaction (SusHCI) exists to identify this subbranch of HCI. In an early paper commentary on sustainable interaction design, Blevis [13] focused on the possibilities for reducing waste. The author elaborated ten possible actions related to the residual components of technological artifacts on the environment, that range from *Disposing* them to *Active repair of misuse* the component to prolong the life-cycle. This type of reasoning echoes what we observed in relation to the end-of-life of IoT devices.

An important theoretical contribution to the debate on sustainable HCI is offered by Mankoff and colleagues [74], who evidenced two main perspectives on sustainability: *in* and *through* design. Whilst the first focuses on limiting the environmental impact of the production of a given artifact, the latter aims at promoting environmentally-friendly practices with persuasive strategies. Such a distinction was conceptualized within the frame of environment sustainability but has been applied to other forms of ethical reflection on digital technology. For instance, Bettega and colleagues used it to classify different types of digital commons [9], [10] (digital commons are tools maintained and used via commoning practices, community governance, and development). In this paper, we will use the in and through distinction as the second lens in our model.

In a paper that scrutinized the first "10 years of Sustainable HCI", Hansson et and colleagues [55] highlighted how the SusHCI discourse has primarily focused on individual resource consumption (e.g., aiming at decreasing individual impact or shifting individual choices toward more sustainable technology or behaviors). According to the authors, this approach tends to focus on supporting informed choice or via persuasive systems based on strategies such as gamification or feedback. A debate overly focused on persuasive systems has been openly critiqued by Dourish [37], who considers such an approach as an expression of neoliberal thinking as it tends to conceive environmental concerns merely in terms of personal (individualistic) moral choices. In continuity with these considerations, in the last few years, several authors (e.g., [9], [55], [67], [108], [111]) pointed out the very need of broadening the vision of sustainability by addressing the social system, supporting local communities, and social justice. Therefore, sustainability has started to be considered not only from the environmental perspective but also in relation to social issues [93] - such us inclusivity [62], local communities [46], labor [50], and economy [131]. This broadening of the perspective leads to looking for more comprehensive models, thus, following the recent call by [55] we direct our attention to the goals developed by the United Nation for sustainable development.

D. SUSTAINABILITY FOR THE UN

As we can observe in the recent evolution of the sustainable HCI debate, environmental sustainability needs to be coupled with social and economic forms of sustainability. The need to balance between sociology-economic and environmental sustainability represents also the underlying principle that grounds the 17 United Nations Sustainable Development Goals (SDGs).[4] For this reason, and because the UN represents the most relevant actor in international collaboration and policy, we decided to use the 17 goals as the third lens in our model.

1) No Poverty
2) Zero Hunger
3) Good health and wellbeing
4) Quality Education
5) Gender Equality
6) Clean water and sanctification
7) Affordable and clean energy
8) Decent work and economic growth
9) Industry innovation and infrastructure
10) Reduce inequality
11) Sustainable cities and communities
12) Responsible consumption and production
13) Climate action
14) Life below water
15) Life on land
16) Peace justice and strong institutions
17) Partnerships for the goals

[4]https://sdgs.un.org/

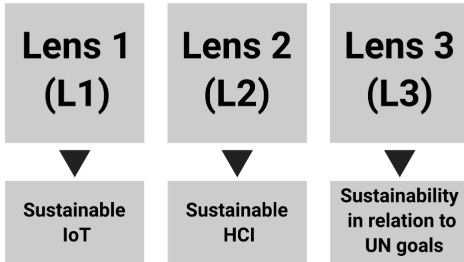

FIGURE 1. Overview of the three lenses we used to develop our inquiry.

III. METHODOLOGY TO DEVELOP OUR MODEL

By combining the three blocks of literature exposed above, we propose a comprehensive model to account for sustainability in the IoMusT. In this model, we used proposals for each of the compounds of literature as lenses. In particular, the three lenses (L1, L2, and L3) respectively correspond to three different levels in an inverse funnel that goes from IoMusT characteristics (L1), to relation with individual persons (L2), and finally to society (L3). Each lens specifically refers to a different corpus of research, namely the first lens refers to the Green IoT framework [109] with the addition of the end of life [69] element, the second lens is connected to the In and Through design distinction that characterised the beginning of HCI debate [75] and finally the last lens is derived by the SDGs. The three lenses can be schematized as follows:

- L1 $\rightarrow$ IoMusT characteristics: hardware, software, awareness, habitual, recycling, end of life (IoT-related literature)
- L2 $\rightarrow$ relation with individual persons: in design, through Design (HCI Literature)
- L3 $\rightarrow$ relation with society: SDGs (UN Policies)

The three lenses combined offer a perspective that allows for a holistic vision over the IoMusT. On the one hand, it is possible to zoom at different levels spanning from the embedded components of the tool to the relation with society and its overall impact. On the other hand, our model allows us to account for the three different types of sustainability (environmental - social - and economic) derived from the SDGs (see Figure 1). To reply to our research question we used the three lenses to define five strategies. To this end, we recursively clustered the items that populate the various lenses. Firstly, we coded them and then progressively harmonized the codes until we reached the five main strategies, which we present in the following section.

IV. THE FIVE STRATEGIES FOR IOMUST

By recursively connecting and clustering the various elements of each lens, we propose five strategies for a sustainable

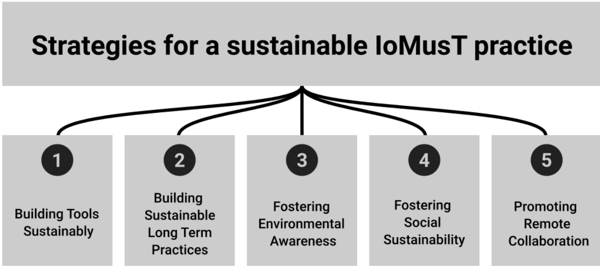

FIGURE 2. Diagram showing the 5 strategies identified.

IoMusT practice (see Figure 2) that account for such a holistic vision:

1) Building Tools Sustainably
2) Building Sustainable Long-Term Practices
3) Fostering Environmental Awareness
4) Fostering Social Sustainability
5) Promoting Remote Collaboration

Each of the strategies addresses a subset of items for each lens; the totality of the strategies covers the individual items of the three lenses combined. We will describe each strategy and analyze it in light of the three lenses. Additionally, examples for each strategy are provided.

A. FIRST STRATEGY: BUILDING TOOLS SUSTAINABLY

The first strategy we propose is related to the sustainable design and development of the Musical Things in the IoMusT. It primarily focuses on the environmental aspect of sustainability by trying to minimize the number of resources needed for a particular piece of technology. This first strategy partially overlaps with the purpose of the framework for the sustainable development of NIMEs (New Interfaces for Musical Expression) [79], which identifies a number of *resources* - material, consumable, process, storage, and transport - that should be considered and evaluated for their environmental impact at each stage of NIME research. We recommend using that model as an operational tool, we look here at how this strategy is related to the three lenses that we propose.

1) THE THREE LENSES FOR THE FIRST STRATEGY

From the perspective of the first lens (IoT characteristics), this strategy focuses on hardware, software, and recycling. Hardware includes both circuits and tangible interfaces. Sustainability, in this sense, could be achieved by using the minimum amount of components or relying on recycled material. Using recycled material is easier for interfaces (e.g., recycled PLA [5]) and in specific cases also for circuits (i.e., in the case of circuit bending [36]). While circuit bending is not widely adopted in IoMusT practices [77], more examples are emerging in the past few years (i.e., [42]). Regarding software, two main aspects of the IoMusT are particularly relevant concerning sustainability: streaming and machine learning as both these computing processes can be costly in terms of electricity consumption. These two elements must be carefully considered when designing and developing IoT systems for music performance. Concerning machine learning, in the last few years, there has been a skyrocketing interest in finding new algorithms that can analyze or generate music [63]. While this research is definitely interesting and valuable results have been reached, we also want to highlight that such expensive models are not always necessary. For instance, David Cope programmed an algorithmic system that could replicate the style of many composers mainly relying on Markov Chains more than three decades ago [76]. Concerning streaming, sending and receiving large amounts of information across the internet is not a negligible effort. While sending audio streams is often a necessity for acoustic performances (e.g., [51]), streaming also a video might not be a necessity [106]. Additionally, with electronic music performances, it is often not necessary to send audio, and control signals or MIDI notes are much less expensive in terms of computational power and, thus, electricity.

Albreem et al. [1] by combining research conducted by [98] and [138] proposed 5 specific ways to reduce the environmental impact of IoT technology in design: ‘‘1) Power-efficient hardware and software design techniques to reduce energy requirements in IoT-based applications. 2) Adoption of improved encryption and decryption techniques with minimal data path. 3) Refraining from continuous data transmission avoiding data redundancy. 4) Eco-friendly techniques in the manufacturing process of IoT devices. 5) IoT network powered by renewable energy sources as an alternative to conventional energy sources like fossil fuels’’. These five points could and should be directly applied to the IoMusT development.

From the perspective of the second lens, this first strategy is entirely in design, indeed, this strategy focuses on the core aspect of in design definition. As a matter of fact, it does not aim to change any behaviours in the future user but simply focuses on the development of the tools.

From the perspective of the third lens, this strategy contributes to SDG 7, and 8 (namely Affordable and clean energy and Climate action). Concerning SDG 7, it is true that the IoMusT cannot contribute to producing new energy, however, the attention paid to the optimization of the circuits contributes to reducing the energetic costs, thus contributing to reducing energy waste. Additionally, specific strategies to sourcing energy in a clean way can be developed. If we focus on the Things in the IoMusT such as instruments or wearables, these can be powered/(re)charged using clean sources such as solar energy. If we look at the network, especially in systems that need a central server to operate, relying on providers that power their machines using solar, wind, or other renewable sources to produce electricity is recommendable. Overall, this strategy contributes to reducing CO2 emissions; thus, it can be seen as a climate action that contributes to ‘‘combat climate change and its impacts’’.

2) FIRST STRATEGY RELATED EXAMPLES

As many actors in the field of the IoMusT build their own systems and equipment, here we outline a set of projects that

TABLE 1. Overview of the three lenses in the first strategy.

L1	L2	L3
Hardware Software Recycling	In design	SDG 7 Affordable and clean energy SDG 13 Climate action

implicitly embrace the content of the first strategy. Firstly, the practice of circuit bending (that is, hacking existing electronics to change their behavior) may represent an interesting approach to reduce waste/material consumption related to digital musical instruments [42] as it fosters the repurposing of malfunctioning or obsolete electronic devices. With the recent development of networking capable programmable-circuit-boards (i.e., the ESP 32) that can be integrated into the hacking process, this approach can be adapted to IoMusT applications. An example is the case of Lorenzo Brutti who bent his guitar pedal using various boards (Arduino and similar tools) including an ESP 32 and connecting them to a local network for controlling purposes [5]; by combining commercial pedals with boards that are highly diffused, affordable and accessible, the Musical Thing designer provides a project that a wide number of other users can reproduce, fix or hack. The positive impact that such an approach can have on the practice of Musical Thing design has been discussed [59]. However, bent instruments tend to have a short lifespan [36]; as such, this approach cannot substitute the design of new tools. A few examples of novel Musical Things that implement this strategy exist. For instance, the *Knurl*, a networked musical device inspired by the cello, developed by Rafaele Andrade, is almost entirely built with recycled PLA (a sustainable material that can be employed in 3D printing), thus reducing the environmental cost related to the material design. Additionally, the instrument is designed considering energy consumption and is powered with solar panels, thus self-producing the energy necessary for the performances in a sustainable way.[6] Another interesting approach is offered by the experiments conducted by Haruya Takase and Shun Shiramatsu, in particular, the Smart Phones Orchestra,[7] uses smartphones owned by the audience to perform instead of using new hardware; in this case, users need to install on their own device a specifically designed application, avoiding the creation of new hardware and thus reducing its associated environmental impact. Another example is the redesign of the IoT-capable Chowndolo, which accounts for 1) minimizing waste of material and 2) designing the hardware to minimize the risk of breaking [87]. In this way, the environmental cost of the Musical Thing is drastically reduced. Finally, concerning streaming, as it has a great environmental cost [16], [35], we align with the recent recommendation suggested in the discourse on the Internet of Sounds [124]. Whenever it is possible, data messages rather than audio signals should be sent, and video should be streamed only when it is strictly necessary. OSC data communication protocol is well established [134], and while today's technology allows for relatively easy streaming of content such as video, this design choice needs to be carefully considered as it involves the streaming of way lighter amounts of data. Concerning energy consumption, it is also worth mentioning that the IoMusT has the huge advantage of providing musical interoperability without the need to travel. In this sense, many new solutions emerged during the recent COVID-19 pandemic. It is worth considering how these technologies can be adapted to long-term use for contrasting travel-related pollution. Relevant examples include L2Ork Tweeter [17], the Global Hyperorgan [56], and the many Algorave organized during the COVID-19 pandemic [103]. In those projects, where many artists and participants gathered together for musical events, the travel-related environmental footprint has been significantly reduced by hosting them on online platforms instead of physical venues.

[5] https://github.com/lbrutti/arduinoModPedal
[6] https://www.knurl-lab.in
[7] https://smartphoneorchestra.com/

B. SECOND STRATEGY: BUILDING SUSTAINABLE LONG TERM PRACTICES

The second strategy that we propose still focuses on building tools in a sustainable way. In this sense, it is similar to the first strategy. However, rather than focusing on the design and development phases, it concentrates on the long-term use of the technology, aiming at maximizing the life span, thus distributing the environmental cost of producing a specific new type of technology over a more extended period of time, eventually reducing waste. The problem of longevity has been discussed in the field of design for a few decades, in particular in relation to the lack of long-term interest that inevitably induces the production of a big amount of waste [129]. In the field of music technology, this issue is well known, especially in relation to the longevity of DMIs, to the point that Cannon and Favilla speak about *disposable instrument*. Moreover, Morreale et al. highlighted that the vast majority of DMIs presented at the NIME conference between 2010 and 2014 were used less than three times [89]. In this second strategy, we reflect upon how to promote long-term engagement using the three identified lenses.

1) THE THREE LENSES FOR THE SECOND STRATEGY

From the perspective of the first lens, this strategy is connected to hardware, software and recycling. Additionally, this lens looks at the issue of the end of life in the IoT which has recently been discussed by Lechelt [69]. The author argued that it is "compelling people to keep, reuse or recycle the object, or otherwise reimagine its use after its functional or performative 'death' ". We wish to expand this perspective and focus not only on the end of life of things, but also on postponing this end of life. Concerning hardware and software, we can recommend a number of solutions derived from open-source and open-hardware discourse. A recent EU report has highlighted how open-source solutions can prolong lifespan of hardware and prevent obsolescence [40]. As such, we can recommend publishing the specific IoMusT software in publicly available repositories and complement them with proper documentation. Concerning custom hardware, we propose that relying on open standards, open hardware and publishing customs schematics or design is precious to promote reparability, thus longevity. In the field of music technology, there is also a secondary benefit apart from reparability, which is hackability. Many communities of electronic musicians are not only interested in *using* specific tools but also in adapting them to their needs. This tendency can be traced back to early electronic music experimentation in the '60 and '70, notable examples being Gordon Mumma's *Pipehorn* [64]. Looking at a more mainstream scenario, such a tendency can be encountered, for instance, in the practice of most guitarists who often customize their guitar or their chains of effects [90]. It comes quite naturally to suggest that promoting hackability by providing documentation and open solutions will allow musicians to customize the tool to specific needs and thus increasing the use of specific technology. This strategy is also connected to the habitual green IoT strategy, as it fosters a different habit of using musical things, which fosters actively repairing the tool, not simply using them.

From the perspective of the second lens, this strategy combines an In and Through Design approach. Indeed, while developing things using open software and hardware can be seen as an In Design decision, facilitating hackability for customization aims at impacting the user's behaviors. Therefore, it can be also seen as a Thorough Design approach to sustainability.

From the perspective of the Sustainable Development Goals, this strategy fits with the aims of SDGs 8, 9, 11, and 12. Concerning innovation and infrastructure (SDG 9), this strategy is in line with the idea of a *resilient infrastructure*, which is supported by a continuous update of the tool facilitated by the access to the sources. This idea follows the model of open innovation, which, on the one hand, supports inclusivity by providing access to the resources of the tool while also aligning with economic development and growth [12], which is related to SGD 8. Additionally, prolonging the lifespan of the tools is a viable approach to promote responsible consumption and production (SDG 12), which is in itself connected to reducing waste and fostering responsibility in consumers/users (in this case musicians). Finally, concerning sustainable communities (SDG 11), this second strategy supports the development of communities of musicians and makers that synergically work together. A recent notable example of how this approach supports the development of strong community is offered by the Bela Platform [84], an open hardware for low latency real-time sound creation and manipulation largely used to develop DMIs [88]. The Elk Audio OS represents a similar open-source platform [126]. Additionally, facilitating reparability

TABLE 2. Overview of the three lenses in the second strategy.

L1	L2	L3
Hardware Software Recycling Habitual End of life	In design Though design	SDG 8 Decent work and economy growth SDG 9 Industry innovation and infrastructure SDG 11 Sustainable cities and communities SDG 12 Responsible consumption and production

supports the development of local communities facilitating the development of local experts capable of repairing or assisting musicians in hacking the system, which again is aligned with SDG 8 (Decent work and economic growth).

2) SECOND STRATEGY RELATED EXAMPLES

Concerning the second strategy, we propose a series of examples that show how practitioners in fields of the IoMusT embraced long-term practices and avoided, in this way, the disposal of usable resources. Relevant examples that specifically address longevity is offered by the Feral cello [34], which was explicitly designed with the intent to avoid the tendency of creating "disposable instruments" (using a terminology by Cannon and Favilla [20]). A few other examples in this sense exist (i.e., [43], [119]). The case of the T-Stick [73] is particularly relevant in this sense, as its longevity has been explicitly addressed for several years. By looking at this case, we can identify two main approaches 1) building research and cultural activities that promote and give continuity to the practices linked to the use of the instrument [48], and 2) updating the instrument and contrasting obsolescence [66], [92]. Concerning continuity of practice, the T-stick developers used it for new studies [133] and created ad-hoc commissions and workshops to help composers adopt the instrument [48]. Indeed, it is important here to stress that the early disposal of an instrument is not only dependent on technical aspects but often also derived from a lack of context to actually use it. From the technical point of view, the original instrument has also been updated [92]. An IoMusT approach can be particularly relevant to updating the instruments. Indeed, having the instrument connected to the internet can make it facilitate updates [99].

From a technical perspective, it is particularly relevant to consider software and hardware, and favoured as much a possible open solution. For instance, AirSticks 1.0 [60] relied on off-the-shelf virtual reality controllers "which were discontinued one year into the project", and thus needed to be updated. AirSticks 2.0 [119] combines sensor fusion of Inertial Measurement Units with low latency wireless data transmission over Bluetooth Low Energy.

In the music technology (research) community, we can observe a number of examples where the development of open hardware solutions induced the development of relatively big communities of DMI makers (e.g., [88]). Relying on such tools prevents obsolescence while also making the community stronger. This creates a virtuous loop that, in general, favors the overall sustainability of the tools [101]. In relation to IoMusT design and development, a recent publication pointed out a workflow that entirely relies on Free Software to design the connected devices [85].

C. THIRD STRATEGY: FOSTERING ENVIRONMENTAL AWARENESS

The third strategy we propose is related to the power that art in general, and music in particular, have to promote awareness over a specific issue, in the case of the third strategy, environmental awareness. Fostering awareness is useful in promoting a public discussion, eventually leading to individual behavioral and habitual changes or even policy development.

1) THE THREE LENSES FOR THE THIRD STRATEGY

This strategy relies on two components of the first lens, namely awareness and habitual-based IoT. Various forms of artistic creation have been used for a long time to promote ideas or shed light on specific issues. In the area of music, examples are countless, with examples including the long list of pop artists that composed songs against wars or violence (Beatles against the Vietnam war, U2 raising awareness on the Bloody Sunday events, 99 Posse on the police violence during the G8 protest in Genova), or Luigi Nono's *la Fabbrica Illuminata* that include noise from factories in support of workers protests. In all these examples, music is used as a medium to convey a message. The same approach can be used in IoMusT-based music performances. However, IoT devices, and digital media can also rely on direct representation of data related to a specific topic or event. In the field of music, this practice is usually referred to as sonification or musification [132]. Musification can be used to raise awareness over specific environmental issues on which it is possible to collect data, such as global warming or CO2 emission. The IoMusT can push this even forward by a musification of data collected in real time via sensors and streamed over the network. While raising awareness is already a step to promote better habits, specific solutions targeting it can be devised. For instance musification can be used to provide information about energy consumption, thus integrating it in daily life to promote habitual changes.

From the perspective of the second lens, both supporting awareness and habitual changes are related to sustainability through a Design approach. Indeed, these strategies can be achieved completely ignoring the environmental or social costs of producing or using a specific piece of music technology. Of course, we suggest combining this strategy with the previous two, but on a theoretical and formal level, these strategies are independent.

This strategy is connected to four SDGs: 6, 12, 14, 15. This strategy, indeed, can raise awareness on important aspects of environmental biodiversity such as life below water (SDG14) and life on land (SDG15). While music technology can hardly directly support biodiversity development, it can raise awareness of the current situation, sensitize the population, and eventually indirectly contribute to lifeform ecosystem sustainability. The same principle can be applied to awareness on water pollution (SDG6). Finally, when musification is applied to consumption habits, this strategy can promote responsible consumption of energy or other products (SDG12).

TABLE 3. Overview of the three lenses in the third strategy.

L1	L2	L3
Awareness Habitual	Through design	SDG6 Clean water and sanctification SDG12 Responsible consumption and production SDG14 Life below water SDG15 Life on land

2) THIRD STRATEGY RELATED EXAMPLES

A number of artistic installations have used connected devices for creating musical experiences that try to direct the attention of the visitors or spectators to nature and environmental elements [122]. Examples include the Kites by Marije Baalman,[8] an art performance that creates music from the canvas of the kites developed with the aim of building a connection with natural elements; in the "wind instruments" performances, the audience is invited to attend an outdoor performance where the participants experience an audio-based augmentation of a natural phenomenon. Another IoMusT example developed with the aim of creating a connection with nature through the use of sound is the "Komorebi" by Matteo Marangoni and Dieter Van Doeren - a distributed sonic art performance that helps people to connect with nature via multiple connected sound-producing devices located in natural spaces.[9] More explicitly connected to the IoMusT, the "Ambient Birdhouse" [112] is an IoT device that helps persons discover birds and their sound in natural environments. Sharing the same endeavor, Suchanek [113] presented a set of networked devices that transform organic material (soil) into music (a choir). The purpose of the installation is to highlight the drought caused by climate change. Sound and music have been used also to highlight behaviours related to human energy consumption, for instance "Infodrops" [54] uses sound to enhance awareness of resource consumption.

D. FOURTH STRATEGY: FOSTERING SOCIAL SUSTAINABILITY

The fourth strategy we propose is to zoom out from environmental sustainability and focus on social sustainability and inclusivity. In the design discourse, social sustainability has been often referred to as the practice of developing projects targeting specific groups, rejecting the idea of "one solution fits it all", rather focusing on specific needs of marginalized communities or idiosyncratic characteristics of individuals [32]. This approach can include designing

[8] https://instrumentinventors.org/project/wind-instrument/
[9] https://matteomarangoni.com/Komorebi-page

music technology for persons with special needs, accounting for the economic accessibility of specific communities, and specifically aiming at these needs.

1) THE THREE LENSES FOR THE FOURTH STRATEGY

The first lens in our model is primarily derived from a model for an environmentally sustainable IoT. However, the habitual item belonging to this lens can be easily applied to other forms of sustainability. Indeed designing IoMusT applications for social justice and inclusivity has the potential to positively impact habits in everyday life of specific persons or groups.

From the perspective of the second lens, this strategy is primarily through design, as it promotes a form of social sustainability while in use. However, it is important to highlight how, in many cases, to account for specific needs properly, it is necessary to develop design processes that actively involve persons of communities [7], [32]. Therefore, these social sustainability characteristics end up being embedded in the design of a specific music system.

From the SDG goal perspective, the IoMusT can play a particularly important role for quality education (SDG4) and reduce inequality (SDG10). Indeed, a *Musical Thing* might be inexpensive, thus affordable by a wide variety of musicians belonging to different populations. Not expensive Musical Things range from a few sensors connected to an ESP 32 [72] to browser-based applications or apps that do not even require you to buy extra dedicated hardware [2]. For many decades, music technology researchers have developed tools, strategies, and systems that can support music education. Combining these solutions with Internet-based tools (e.g., the WebAudio API [28]) can lead to the development of systems that can be easily afforded and adopted worldwide with minimal costs supporting quality education. Another important point to stress is that the IoMusT can promote remote performances allowing geographically displaced musicians to play together [106]. This possibility can drastically reduce the costs of travelling, therefore promoting inclusivity. Another advantage of an Internet-based musical practice [105] is the possibility to easily share musical results, sounds, and samples [44], thus supporting accessibility.

As mentioned above, social sustainability is strongly related to inclusivity. Closely working with specific populations or individuals is particularly relevant for disabled people or people with special needs. A vast literature suggests how music can support a variety of different needs [70], and technology can successfully be integrated in music therapy [25], rehabilitation [78] or improving the life quality of disabled persons [96], including visually impaired persons [100]. The IoMusT can be particularly useful in these cases [118]. Indeed, recent research showed how disabled people benefit from the interaction with the entire ecology of multiple persons and multiple musical objects rather than from the individual interaction with one DMI [71], and

TABLE 4. Overview of the three lenses in the fourth strategy.

L1	L2	L3
Habitual	Through design In design	SDG3 Good health and wellbeing SDG4 Quality education SDG5 Gender equality SDG10 Reduce inequality

the IoMusT can facilitate collaborations among multiple musicians and networked ensembles of DMIs [121].

Finally, designing IoMusT systems targeting specific individuals, populations or communities can also promote a more inclusive experience in terms of gender (SDG5). Critical design literature well documented and analyzed how the design of digital tools and instruments is often based on a heteronormative vision. This risk is less diffuse in music technology, but research shows that the music technology debate is still majorly inhabited by male researchers [135]. Therefore, considering the design justice approach in the development of IoMusT is doubtlessly a practice to encourage.

2) FOURTH STRATEGY RELATED EXAMPLES

A vast variety of examples that use interactive technology for music purposes to facilitate social sustainability and inclusivity exist. Here we will present a brief overview.

The first subset of systems was designed to target disabled people or people with specific medical conditions. A comprehensive overview of musical systems for disabled people is available at [47]. We focus here on some IoMusT examples. For instance, Drake Music - a charity that focuses its endeavor on the development of crafted music technology for disabled people - developed a guide to play with iPad that can help people with disabilities in using networked music performances.[10] Another example is offered by Payne and colleagues, who developed Cyclops: an eye-controlled instrument specifically built for accessibility and flexible use [97]. Such projects can play a key role in allowing people with disability to play (or even pursue a career in) music.

In the next examples we point how Networked musical technology has also been used for rehabilitation. For instance, Tetley et al. [116] used an IoT system designed to provide feedback to percussionists and drummers to help people affected by strokes regain mobility and coordination. Furthermore, another system named "Bleow 58BPM" has been developed to help a singer in carrying on with her artistic career after a caryatid aneurysm [86].

Recently, IoMusT systems have also been developed to democratise access to music creation and allow persons with lower availability of budget to access a wider range of instruments; this is the case of a system that allows for controlling synthesisers via real-time hand tracking relying on a consumer-grade camera (thus inexpensive) [30].

[10] https://www.drakemusic.org/learning/resources-for-music-education/using-ipads-for-music/

TABLE 5. Overview of the three lenses in the fifth strategy.

L1	L2	L3
Habitual	Through design	SDG16 Peace justice and strong institutions SDG17 Partnerships for the goals

Similarly, networked sensors have been used to ease and potentially reduce costs of music education in preschoolers (e.g., [31], [80]).

E. FIFTH STRATEGY: PROMOTING REMOTE COLLABORATION

The fifth strategy we propose is intrinsically related to the networking capabilities of the IoMusT. Indeed, this last strategy is directly related to promoting remote collaboration and reinforcing networks among researchers, musicians, and institutions. This aspect is seldom considered as a valuable asset for sustainability as it allows practitioners in different parts of the world to collaborate sparing the pollution emitted by traveling. The well-being of networks of institutions is essential to promote a discourse on sustainability in all its forms. By supporting remote performances and remote collaboration, the IoMusT has the potential to reinforce networks among different institutions.

1) THE THREE LENSES FOR THE FIFTH STRATEGY

As we discussed for the previous strategy, the habitual strategy proposed for a sustainable IoT can be adapted to all those situations where an IoT system has the potential to positively impact the habits of specific persons or groups. This is the case: the IoMusT has the potential to foster and reinforce collaboration among institutions. This is a form of sustainability Through Design, as it promotes collaboration and partnerships through the use of the system.

This strategy is deeply connected, if not completely motivated by the last two Sustainable Development Goals (16 and 17). SDG 17 refers to the importance of developing partnerships to achieve other goals. The IoMusT, among the various forms of music technology, can be particularly useful to support and promote collaboration among practitioners, researchers, and musicians belonging to different regions as it provides a space to collaborate not only on project development but also in actual performative practice. We support that such collaboration can easily lead to the development of stronger institutions, which is identified as another goal (SDG16) to achieve sustainability by the UN.

2) FIFTH STRATEGY RELATED EXAMPLES

A wide variety of networked ensembles and collaborative experiences over the Internet have been developed. These collaborations among individuals can lead to or are an expression of institutional collaborations. For instance, Roberts et al. [104] developed a system for networked collaborative live coding and Harlow et al. [56] developed the Global Hyperorgan a platform for telematic musicking and research.

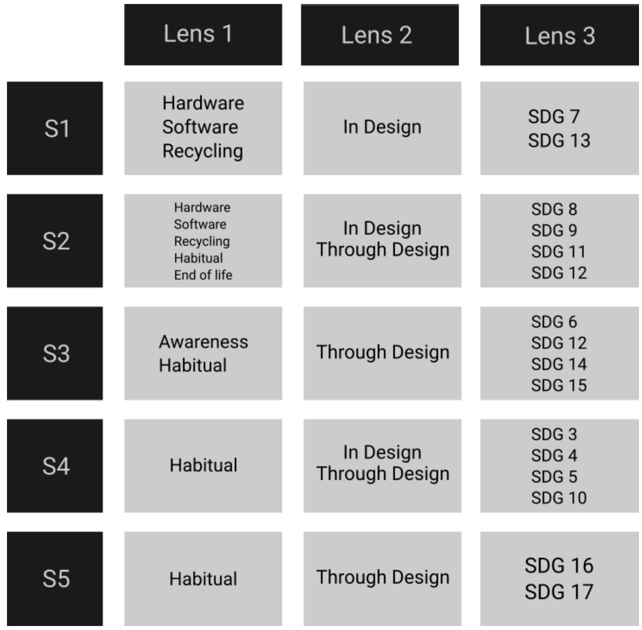

FIGURE 3. Overview of the strategies addressing the subsets of items included in the three lenses.

V. DISCUSSION

In this paper, we devised five strategies to endeavour the development of IoMusT projects that account for different forms of sustainability. We individually presented each strategy, framing it within the three lenses (IoT, HCI, and SDGs), and provided some practical examples. We now zoom out providing a discussion that connects them.

We also highlight that the five strategies are not automatically embedded in IoMusT practice, rather designers and developers should actively and willingly pursue them. The five strategies suggest a design space where IoMusT can be particularly fruitful in promoting sustainability in its different forms. For this reason, in the second part of this discussion, we point out some hints to put these strategies into practice.

In the next paragraph, we will firstly dissuss how the research presented is linked to the broader discoure on sustainability, then we will discuss how the strategies presented can take part in research fields connected to specific actions and practices.

A. IOMUST AND SUSTAINABILITY

In the introduction of this paper, we proposed two research questions related to the sustainable development of the IoMusT. The first two strategies represent a possible reply to the first research question, while the remaining three strategies address the second research question. We individually discuss the two RQs.

RQ1: How can IoMusT be developed in a sustainable way?

Strategy 1 addresses this question in the initial phase of designing an IoMusT, while Strategy 2 accounts for the longevity of the devices. This second aspect is fundamental

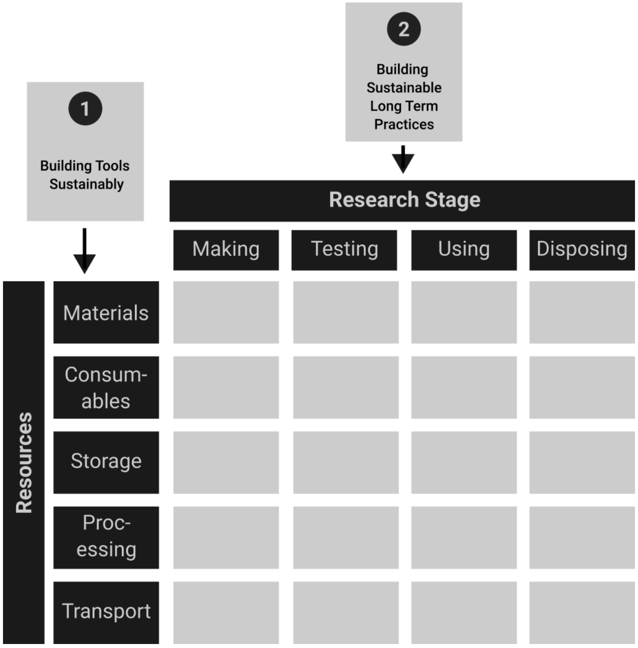

FIGURE 4. Diagram showing how strategies 1 and 2 complement the framework developed for a Sustainable NIME Practice.

especially if we consider the problem of e-waste. Many authors have identified longevity as a crucial element for sustainability [21], [26], [57], [58], [69]. These two strategies address sustainability primarily from an environmental perspective. However, they also touch on social aspects of sustainability; indeed by reducing costs and being reparable, an IoMusT device is also more affordable, thus inclusive. We argue that these two strategies should be applied in any IoMusT project. These two strategies complement the practical model developed for NIME research [79]. In this model, the authors propose two dimensions to account for sustainability *Resources* and *Research stage*. Our first strategy can be mapped to *Resources* while the second strategy can be mapped to *Research stages* trying to postpone the disposal (see Figure 4).

RQ2: How can IoMusT contribute to sustainability?

The IoMusT can support sustainability in different ways. Strategies 3, 4, and 5 propose three different ways to support three different types of sustainability by highlighting specific ways of using the IoMusT to foster different forms of sustainability. Strategies 3 and 4 tend to be mutually exclusive, while it is possible to combine them, it is quite uncommon, and to many extent not necessary. Strategy 5 relates to complex projects with multiple partners, as such it can be also intended as a meta strategy that can be combined with all the other four. To further detail, while these strategies are tailored to the IoMusT, their application can reach beyond this specific subdomain of IoT, offering valuable insights for other IoT fields. Industries where IoT capabilities are involved, such as agriculture [41] and industrial production [68] can employ the first and the second strategies to foster sustainable practices. The third

TABLE 6. Relevant related literature that can support the implementation of the strategies highlighted in this paper.

Strategy 1	IoT green development [1] NIME model [79] for an overview of the technologies for environmentally sustainable development
Strategy 2	FLOSS arguably represent the best model to prevent obsolescence and promote longevity[14]
Strategy 3	Fostering awareness needs a complex compound of design skills, we list here some relevant examples that can be used for developing such projects. [82, 117]
Strategy 4	The Design Justice framework represent the frontier approach to design for inclusivity and social sustainability [32]
Strategy 5	Many policies exist to support infrastructure collaborations and transnational cooperation (see for instance, [19, 115, 95, 52]). Accounting for these elements while developing IoMusT projects can foster this strategy.

strategy can take place in the wider debate on awareness on sustainability that emerged in several contexts [49], [53]. Lastly, the fourth and fifth strategies point to sustainable actions that are possible to experiment within other public service [128] related fields.

B. STRATEGIES INTO PRACTICE

As mentioned before, the five strategies are not automatically embedded in IoMusT practice; instead, designers and developers should actively and willingly pursue them. The five strategies suggest some space where the IoMusT can be particularly fruitful to promote sustainability in its different forms.

As summarised in Table 6, some relevant related literature can support the implementation of the strategies into specific actions and frameworks.

To further articulate, the practices presented by Albreem et al. [1] on sustainable development of IoT systems and the practices proposed by the NIME community in relation to sustainability [79] can help embrace the first strategy proposed in this research. Strategy two frames the goal of preventing the obsolescence of technology; As discussed by Blind et al. [14], the FLOSS movement arguably applies such a strategy by developing applications owned by communities and, therefore, not subject to the profit-oriented obsolescence of digital products.

Many researchers do propose actions related to the creation of awareness (strategy 3); community-based social marketing, for example, [82], includes a specific set of skills aimed to invite individuals to reflect on the topic of sustainability.

The Design Justice framework [32] embeds a variety of practices that help designers foster inclusivity and social sustainability, providing some practical applications of strategy 4.

Lastly, several research discuss possible applications of the 5th strategy proposed in this paper. [19], [52], [95], [115] by exploring the potential of infrastructure collaborations and transnational cooperation, guidelines to develop IoMusT projects aimed at promoting remote collaboration are provided.

VI. CONCLUSION AND FUTURE WORKS

In this research, we proposed five strategies to account for sustainability aspects in IoMusT projects. These strategies were realised by recursively combining item and instances coming form different corpus of literature and reflection that we used as lenses. Namly we combined literature from IoT (lens 1), HCI (lens 2), and the Sustainbale Development Goals (Lens 3). The five strategies that we propose strategies offer a model to connect individual instances to address sustainability from a comprehensive perspective. The first two strategies focus on how to design IoMusT systems in a sustainable way by deigning things minimising their impact (strategy 1), promoting reparability and longevity thus reducing e-waste and mitigating the costs (strategy 2). The remaining three strategies highlight how IoMusT can contribute to promote sustainability by fostering awareness on environmental issues or components (strategy 3), creating socially inclusive device (strategy 4), promote remote collaboration (strategy 5).

The main novelty of the work presented here is the holistic approach to sustainability that has never been attempted before in the music technology debate. As such it represents a first step toward a more sustainably aware IoMusT practice. It is hoped that this paper could spur further discussions on the topic of sustainability surrounding the emerging field of the IoMusT. While we understand that the examples we provided do not provide quantitative evaluation of the strategies, this is not the objective of this paper. On the contrary, we aimed at showing how the IoMusT can engage with the SDGs proposed by the UN, the HCI literature on Sustainability and the Green IoT development. Thus, it highlights possible preferential directions for the future development of musical IoT devices.

A. CHALLENGES

While our model outlines a possible design space which hints toward a design approach, it is necessary to develop more specific working protocols for the various strategies. In the previous section, we hinted at some possible references that can direct this work. However, it is necessary to further investigate each category to devise such practical protocols or frameworks. In a single paper, it would not be possible to analyze practical operational details at the granular level for each of these. This is the main limitation of this work, and we call for future research to investigate and analyze different cases.

In pair with the main challenge that emerges from the work presented, the need to design efficient communication and dissemination strategies that could help the IoMusT community to consider one or more of the topics explored when designing and carrying on a new project also needs to be considered in future research works.

Future research will probably need to explore how the practices mentioned in the present article can coexist with the artistic intention of a musician/performer to fully express their own message in a genuine way and, at the same time, make choices that are sustainable for the planet.

Lastly, we highlight that while the examples provided are accountable for sustainability, they are not readily amenable to quantitative analysis due to factors such as the abstract nature of awareness or the lack of comprehensive data collection and analysis. In light of this, we advocate for future research to apply our strategies in a series of specific case studies, thereby facilitating a deeper, more quantifiable understanding of their impact and effectiveness.

REFERENCES

[1] M. A. Albreem, A. M. Sheikh, M. H. Alsharif, M. Jusoh, and M. N. M. Yasin, "Green Internet of Things (GIoT): Applications, practices, awareness, and challenges," *IEEE Access*, vol. 9, pp. 38833–38858, 2021, doi: 10.1109/ACCESS.2021.3061697.

[2] C. Alexandraki, D. Akoumianakis, M. Kalochristianakis, P. Zervas, and E. Cambouropoulos, "MusiCoLab: Towards a modular architecture for collaborative music learning," in *Proc. Web Audio Conf.*, 2022.

[3] M. Alian, A. H. M. O. Abulila, L. Jindal, D. Kim, and N. S. Kim, "NCAP: Network-driven, packet context-aware power management for client-server architecture," in *Proc. IEEE Int. Symp. High Perform. Comput. Archit. (HPCA)*, Feb. 2017, pp. 25–36, doi: 10.1109/HPCA.2017.57.

[4] M. H. Alsharif, A. H. Kelechi, S. Kim, I. Khan, J. Kim, and J. H. Kim, "Notice of retraction: Enabling hardware green Internet of Things: A review of substantial issues," *IEEE Access*, early access, Jul. 5, 2019, doi: 10.1109/ACCESS.2019.2926800.

[5] I. Anderson, "Mechanical properties of specimens 3D printed with virgin and recycled polylactic acid," *3D Printing Additive Manuf.*, vol. 4, no. 2, pp. 110–115, Jun. 2017, doi: 10.1089/3dp.2016.0054.

[6] R. Arshad, S. Zahoor, M. A. Shah, A. Wahid, and H. Yu, "Green IoT: An investigation on energy saving practices for 2020 and beyond," *IEEE Access*, vol. 5, pp. 15667–15681, 2017, doi: 10.1109/ACCESS.2017.2686092.

[7] L. J. Bannon and P. Ehn, "Design: Design matters in participatory design," in *Routledge International Handbook of Participatory Design*. Evanston, IL, USA: Routledge, 2012, pp. 37–63.

[8] M. Benjamin and G. Aliénor, "Rapid prototyping of distributed musical things using Web technologies," in *Proc. 4th Int. Symp. Internet Sounds*, Oct. 2023, pp. 1–5, doi: 10.1109/ieeeconf59510.2023.10335368.

[9] M. Bettega, R. Masu, and M. Teli, "'It's like a GPS community tool': Tactics to foster digital commons through artifact ecology," in *Proc. Designing Interact. Syst. Conf.* New York, NY, USA: Association for Computing Machinery, Jun. 2021, pp. 1710–1725, doi: 10.1145/3461778.3462034.

[10] M. Bettega, R. Masu, N. B. Hansen, and M. Teli, "Off-the-shelf digital tools as a resource to nurture the commons," in *Proc. Participatory Design Conf.*, Aug. 2022, pp. 133–146.

[11] F. Bevilacqua, B. Matuszewski, G. Paine, and N. Schnell, "On designing, composing and performing networked collective interactions," *Organised Sound*, vol. 26, no. 3, pp. 333–339, Dec. 2021.

[12] F. Biermann, N. Kanie, and R. E. Kim, "Global governance by goal-setting: The novel approach of the UN sustainable development goals," *Current Opinion Environ. Sustainability*, vols. 26–27, pp. 26–31, Jun. 2017, doi: 10.1016/j.cosust.2017.01.010.

[13] E. Blevis, "Sustainable interaction design: Invention & disposal, renewal & reuse," in *Proc. SIGCHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, Apr. 2007, pp. 503–512, doi: 10.1145/1240624.1240705.

[14] K. Blind, M. Böhm, P. Grzegorzewska, A. Katz, S. Muto, S. Pätsch, and T. Schubert, "The impact of open source software and hardware on technological independence, competitiveness and innovation in the EU economy," Eur. Commission, Tech. Rep., 2021.

[15] D. Bol, G. de Streel, and D. Flandre, "Can we connect trillions of IoT sensors in a sustainable way? A technology/circuit perspective (invited)," in *Proc. IEEE SOI-3D-Subthreshold Microelectron. Technol. Unified Conf. (S3S)*, Oct. 2015, pp. 1–3, doi: 10.1109/S3S.2015.7333500.

[16] M. Brennan and K. Devine, "The cost of music," *Popular Music*, vol. 39, no. 1, pp. 43–65, Feb. 2020.

[17] I. Bukvic, ''Latency-, sync-, and bandwidth-agnostic tightly-timed telematic and crowdsourced musicking made possible using L2Ork tweeter,'' in *Proc. NIME*, 2022. [Online]. Available: https://nime.pubpub.org/pub/h9u2ynt0
[18] J.-P. Cáceres and C. Chafe, ''JackTrip: Under the hood of an engine for network audio,'' *J. New Music Res.*, vol. 39, no. 3, pp. 183–187, Sep. 2010.
[19] Y. Caloghirou, N. S. Vonortas, and S. Ioannides, *European Collaboration in Research and Development: Bus. Strategy and Public Policy*. Ann Arbor, MI, USA: Edwards, 2004.
[20] J. Cannon and S. Favilla, ''The investment of play: Expression and affordances in digital musical instrument design,'' in *Proc. ICMC*, 2012.
[21] S. Carlsson, A. Mallalieu, L. Almefelt, and J. Malmqvist, ''Design for longevity—A framework to support the designing of a product's optimal lifetime,'' *Proc. Design Soc.*, vol. 1, pp. 1003–1012, Aug. 2021.
[22] A. Carôt and C. Werner, ''Distributed network music workshop with soundjack,'' in *Proc. 25th Tonmeistertagung*, Leipzig, Germany, 2008.
[23] A. Carôt, M. Dohler, S. Saunders, F. Sardis, R. Cornock, and N. Uniyal, ''The world's first interactive 5G music concert: Professional quality networked music over a commodity network infrastructure,'' in *Proc. Sound Music Comput. Conf.*, Jun. 2020, pp. 407–412.
[24] A. Carot, C. Hoene, H. Busse, and C. Kuhr, ''Results of the fast-music project—Five contributions to the domain of distributed music,'' *IEEE Access*, vol. 8, pp. 47925–47951, 2020.
[25] *Music Therapy*, Early Intervent Center, Cardiac Rehabil. Center, Phys. Fitness Center, 2013.
[26] J. Chapman, *Emotionally Durable Design: Objects, Experiences and Empathy*. Evanston, IL, USA: Routledge, 2012.
[27] F. Cheli and S. Giordano, ''Service parameters identification for adaptive networked music performance,'' in *Proc. Global Inf. Infrastruct. Netw. Symp. (GIIS)*, Sep. 2022, pp. 94–98.
[28] H. Choi, ''AudioWorklet: The future of web audio,'' in *Proc. ICMC*, 2018.
[29] I. Clester and J. Freeman, ''Composing the network with streams,'' in *Proc. Audio Mostly Conf.*, Sep. 2021, pp. 196–199.
[30] D. Cocchiara and L. Turchet, ''Democratizing access to collaborative music making over the network using air instruments,'' in *Proc. AudioMostly*, Sep. 2022, pp. 211–218.
[31] C. Core, A. Conci, A. D. Angeli, R. Masu, and F. Morreale, ''Designing a musical playground in the kindergarten,'' in *Proc. Electron. Workshops Comput.*, Jul. 2017, pp. 1–12.
[32] S. Costanza-Chock, *Design Justice: Community-Led Practices to Build the Worlds We Need*. Cambridge, MA, USA: MIT Press, 2020.
[33] R. B. Dannenberg, ''Scalable and easy-to-use NIME networking,'' in *Proc. NIME*, 2022.
[34] T. Davis, ''The feral cello: A philosophically informed approach to an actuated instrument,'' in *Proc. Int. Conf. New Interface Musical Expression*. Copenhagen, Denmark: Aalborg University Copenhagen, 2017, pp. 279–282. [Online]. Available: http://www.nime.org/proceedings/2017/nime2017paper0053.pdf
[35] K. Devine, *Decomposed: The Political Ecology of Music*. Cambridge, MA, USA: MIT Press, 2019.
[36] E. Dorigatti and R. Masu, ''Circuit bending and environmental sustainability: Current situation and steps forward,'' in *Proc. NIME*, Jun. 2022, doi: 10.21428/92fbeb44.18502d1d.
[37] P. Dourish, ''HCI and environmental sustainability: The politics of design and the design of politics,'' in *Proc. 8th ACM Conf. Designing Interact. Syst.*, Aug. 2010, pp. 1–10, doi: 10.1145/1858171.1858173.
[38] C. Drioli, C. Allocchio, and N. Buso, ''Networked performances and natural interaction via LOLA: Low latency high quality A/V streaming system,'' in *Proc. Int. Conf. Inf. Technol. Perform. Arts, Media Access, Entertain.* Cham, Switzerland: Springer, 2013, pp. 240–250.
[39] J. Drre, N. Werner, S. Hminen, O. Lindfors, J. Koistinen, M. Saarenmaa, and R. Hupke, ''In-depth latency and reliability analysis of a networked music performance over public 5G infrastructure,'' in *Audio Engineering Society Convention 153*. Audio Engineering Society, 2022.
[40] *The Impact of Open Source Software and Hardware on Technological Independence, Competitiveness and Innovation in the EU Economy: Final Study Report*, Eur. Commission. Directorate Gen. for Commun. Netw., Content Technol., 2021, doi: 10.2759/430161.
[41] M. S. Farooq, S. Riaz, A. Abid, T. Umer, and Y. B. Zikria, ''Role of IoT technology in agriculture: A systematic literature review,'' *Electronics*, vol. 9, no. 2, p. 319, Feb. 2020.
[42] A. M. Fernandez and F. Iazzetta, ''Circuit bending and diy culture,'' in *Keep it Simple, Make it Fast*, 2015, pp. 17–28.
[43] R. Fiebrink and L. Sonami, ''Reflections on eight years of instrument creation with machine learning,'' in *Proc. Int. Conf. New Interface Musical Expression*, R. Michon and F. Schroeder, Eds. Birmingham, U.K.: Birmingham City University, Jul. 2020, pp. 237–242. [Online]. Available: https://www.nime.org/proceedings/2020/nime2020paper45.pdf
[44] E. Fonseca, J. P. Puig, X. Favory, F. F. Corbera, D. Bogdanov, A. Ferraro, S. Oramas, A. Porter, and X. Serra, ''Freesound datasets: A platform for the creation of open audio datasets,'' in *Proc. 18th ISMIR Conf.*, Suzhou, China, X. Hu, S. J. Cunningham, D. Turnbull, and Z. Duan, Eds., 2017, pp. 486–493.
[45] A. Fraietta, O. Bown, S. Ferguson, S. Gillespie, and L. Bray, ''Rapid composition for networked devices: HappyBrackets,'' *Comput. Music J.*, vol. 43, nos. 2–3, pp. 89–108, Jun. 2020.
[46] J. Fredericks, G. A. Caldwell, and M. Tomitsch, ''Middle-out design: Collaborative community engagement in urban HCI,'' in *Proc. 28th Austral. Conf. Comput.-Hum. Interact.* New York, NY, USA: Association for Computing Machinery, 2016, pp. 200–204, doi: 10.1145/3010915.3010997.
[47] E. Frid, ''Accessible digital musical instruments—A review of musical interfaces in inclusive music practice,'' *Multimodal Technol. Interact.*, vol. 3, no. 3, p. 57, Jul. 2019.
[48] T. Fukuda, E. Meneses, T. West, and M. M. Wanderley, ''The T-stick music creation project: An approach to building a creative community around a DMI,'' in *Proc. NIME*, Shanghai, China, 2021. [Online]. Available: https://nime.pubpub.org/pub/7c4qdj4u
[49] I. H. Garbie, ''Sustainability awareness in industrial organizations,'' *Proc. CIRP*, vol. 26, pp. 64–69, Jan. 2015.
[50] M. Glöss, M. McGregor, and B. Brown, ''Designing for labour: Uber and the on-demand mobile workforce,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2016, pp. 1632–1643, doi: 10.1145/2858036.2858476.
[51] H. M. Gomes, J. Read, A. Bifet, J. P. Barddal, and J. Gama, ''Machine learning for streaming data: State of the art, challenges, and opportunities,'' *ACM SIGKDD Explor. Newslett.*, vol. 21, no. 2, pp. 6–22, Nov. 2019, doi: 10.1145/3373464.3373470.
[52] K. Hainsch, K. Löffler, T. Burandt, H. Auer, P. C. del Granado, P. Pisciella, and S. Zwickl-Bernhard, ''Energy transition scenarios: What policies, societal attitudes, and technology developments will realize the EU green deal?'' *Energy*, vol. 239, Jan. 2022, Art. no. 122067.
[53] S. Hamid, M. T. Ijab, H. Sulaiman, R. Md. Anwar, and A. A. Norman, ''Social media for environmental sustainability awareness in higher education,'' *Int. J. Sustainability Higher Educ.*, vol. 18, no. 4, pp. 474–491, May 2017.
[54] J. Hammerschmidt, R. Tunnermann, and T. Hermann, ''InfoDrops: Sonification for enhanced awareness of resource consumption in the shower,'' in *Proc. ICAD*. Georgia Institute of Technology, 2013.
[55] L. Å. E. J. Hansson, T. Cerratto Pargman, and D. S. Pargman, ''A decade of sustainable HCI: Connecting SHCI to the sustainable development goals,'' in *Proc. CHI Conf. Hum. Factors Comput. Syst.* Yokohama, Japan, May 2021, pp. 1–19, doi: 10.1145/3411764.3445069.
[56] R. Harlow, M. Petersson, R. Ek, F. Visi, and S. Östersjö, ''Global hyperorgan: A platform for telematic musicking and research,'' in *Proc. NIME*, 2021.
[57] K. M. Hasling and U. Ræbild, ''Sustainability cards: Design for longevity,'' in *PLATE: Product Lifetimes And The Environment*. Amsterdam, The Netherlands: IOS Press, 2017, pp. 166–170.
[58] M. Hebrok, ''Design for longevity: Taking both the material and social aspects of product-life into account,'' *J. Des. Res.*, vol. 12, no. 3, p. 204, 2014.
[59] G. Hertz and J. Parikka, ''Zombie media: Circuit bending media archaeology into an art method,'' *Leonardo*, vol. 45, no. 5, pp. 424–430, Oct. 2012.
[60] A. Ilsar, G. Kenning, S. Trolland, and C. Frame, ''Inclusive improvisation: Exploring the line between listening and playing music,'' *ACM Trans. Accessible Comput.*, vol. 15, no. 2, pp. 1–21, May 2022, doi: 10.1145/3506856.
[61] *Jamkazam*. [Online]. Available: https://jamkazam.com/
[62] M. Jasim, P. Khaloo, S. Wadhwa, A. X. Zhang, A. Sarvghad, and N. Mahyar, ''CommunityClick: Capturing and reporting community feedback from town Halls to improve inclusivity,'' *Proc. ACM Human-Computer Interact.*, vol. 4, no. 3, pp. 1–32, Jan. 2021, doi: 10.1145/3432912.

[63] S. Ji, J. Luo, and X. Yang, "A comprehensive survey on deep music generation: Multi-level representations, algorithms, evaluations, and future directions," 2020, *arXiv:2011.06801*.

[64] T. Johnson, "The voice of new music by Tom Johnson," *Learning*, 1973.

[65] D. Keller, C. Gomes, and L. Aliel, "The handy metaphor: Bimanual, touchless interaction for the Internet of Musical Things," *J. New Music Res.*, vol. 48, no. 4, pp. 385–396, Aug. 2019.

[66] L. Kirby, P. Buser, and M. M. Wanderley, "Introducing the t-tree: Using multiple t-sticks for performance and installation," in *Proc. Int. Conf. New Interface Musical Expression*, Jun. 2022.

[67] B. Knowles, O. Bates, and M. Håkansson, "This changes sustainable HCI," in *Proc. CHI Conf. Hum. Factors Comput. Syst.* Montreal, QC, Canada, Apr. 2018, pp. 1–12, doi: 10.1145/3173574.3174045.

[68] A. S. Kumar and E. Iyer, "An industrial IoT in engineering and manufacturing industriesbenefits and challenges," *Int. J. Mech. Prod. Eng. Res. Dvelopment*, vol. 9, no. 2, pp. 151–160, 2019.

[69] S. Lechelt, K. Gorkovenko, L. L. Soares, C. Speed, J. K. Thorp, and M. Stead, "Designing for the end of life of IoT objects," in *Proc. Companion Publication ACM Designing Interact. Syst. Conf.* New York, NY, USA: Association for Computing Machinery, Jul. 2020, pp. 417–420, doi: 10.1145/3393914.3395918.

[70] A. Lubet, *Music, Disability, and Society*. Temple Univ. Press, 2011.

[71] A. Lucas, J. Harrison, F. Schroeder, and M. Ortiz, "Cross-pollinating ecological perspectives in ADMI design and evaluation," in *Proc. NIME*, Shanghai, China, 2021. [Online]. Available: https://nime.pubpub.org/pub/d72sylsq

[72] A. Maier, A. Sharp, and Y. Vagapov, "Comparative analysis and practical implementation of the ESP32 microcontroller module for the Internet of Things," in *Proc. Internet Technol. Appl. (ITA)*, Sep. 2017, pp. 143–148.

[73] J. Malloch and M. M. Wanderley, "The T-stick: From musical interface to musical instrument," in *Proc. 7th Int. Conf. New Interface Musical Expression*, 2007, pp. 66–69. [Online]. Available: http://www.nime.org/proceedings/2007/nime2007066.pdf

[74] J. Mankoff, "HCI and sustainability: A tale of two motivations," *Interactions*, vol. 19, no. 3, pp. 16–19, May 2012, doi: 10.1145/2168931.2168937.

[75] J. C. Mankoff, E. Blevis, A. Borning, B. Friedman, S. R. Fussell, J. Hasbrouck, A. Woodruff, and P. Sengers, "Environmental sustainability and interaction," in *Proc. Extended Abstr. Hum. Factors Comput. Syst.*, 2007, pp. 2121–2124.

[76] V. Manzo, "Algorithmic composition: Implementations in western tonal art music, video games, and other music technologies," in *Teaching Electronic Music*. Evanston, IL, USA: Routledge, 2021, pp. 103–119.

[77] A. T. Marasco, E. Berdahl, and J. Allison. (Jun. 2019). *Benditi/O: A System for Networked Performance of Circuit-Bent Devices*. [Online]. Available: https://zenodo.org/record/3672982

[78] A. Maratos, C. Gold, X. Wang, and M. Crawford, "Music therapy for depression," in *Cochrane Database of Systematic Reviews*, 2008.

[79] R. Masu, A. P. Melbye, J. W. Sullivan, and A. R. Jensenius, "Nime and the environment: Toward a more sustainable NIME practice," in *New Interfaces for Musical Expression*, 2021.

[80] R. Masu, A. Conci, C. Core, A. De Angeli, and F. Morreale, "RobinFlock: A polyphonic algorithmic composer for interactive scenarios with children," in *Proc. 14th Sound Music Comput. Conf.*, Espoo, Finland, 2017, pp. 125–132.

[81] B. Matuszewski, "A web-based framework for distributed music system research and creation," *J. Audio Eng. Soc.*, vol. 68, no. 10, pp. 717–726, Dec. 2020.

[82] D. McKenzie-Mohr, "Fostering sustainable behavior through community-based social marketing," *Amer. Psychologist*, vol. 55, no. 5, pp. 531–537, 2000.

[83] A. McPherson and V. Zappi, "An environment for submillisecond-latency audio and sensor processing on BeagleBone black," in *Audio Engineering Society Convention 138*. Audio Engineering Society, 2015. [Online]. Available: http://www.aes.org/e-lib/browse.cfm?elib=17755

[84] A. McPherson, "Bela: An embedded platform for low-latency feedback control of sound," *J. Acoust. Soc. Amer.*, vol. 141, no. 5, p. 3618–3618, May 2017.

[85] N. Merendino and A. Rodà, "Defining an open source CAD workflow for experimental music and media arts," in *Proc. 10th Int. Conf. Digit. Interact. Arts*, Oct. 2021, pp. 1–6.

[86] N. Merendino, A. Rodà, and R. Masu, "'Below 58 BPM,' involving real-time monitoring and self-medication practices in music performance through IoT technology," *Frontiers Comput. Sci.*, vol. 6, Feb. 2024, Art. no. 1187933.

[87] N. Merendino, G. Lepri, A. Rod, and R. Masu, "Redesigning the Chowndolo: A reflection-on-action analysis to identify sustainable strategies for NIMEs design," in *Proc. Int. Conf. New Interface Musical Expression*, 2023.

[88] F. Morreale, G. Moro, A. Chamberlain, S. Benford, and A. P. McPherson, "Building a maker community around an open hardware platform," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, May 2017, pp. 6948–6959.

[89] F. Morreale and A. McPherson, "Design for longevity: Ongoing use of instruments from nime 2010-14," in *Proc. Int. Conf. New Interface Musical Expression*. Copenhagen, Denmark: Aalborg University Copenhagen, 2010, pp. 192–197. [Online]. Available: http://www.nime.org/proceedings/2017/nime2017paper0036.pdf

[90] J. Mulholland and P. Webb, "Social embedding, artisanal markets and cultural fields: Quality, value and marketing in the cases of new wave custom motorcycles and boutique guitar pedals," in *The Artisan Brand*. Ann Arbor, MI, USA: Edwards, 2022, pp. 42–61.

[91] M. Muniswamaiah, T. Agerwala, and C. C. Tappert, "Green computing for Internet of Things," in *Proc. 7th IEEE Int. Conf. Cyber Secur. Cloud Comput. (CSCloud)/6th IEEE Int. Conf. Edge Comput. Scalable Cloud (EdgeCom)*, Aug. 2020, pp. 182–185, doi: 10.1109/CSCloud-EdgeCom49738.2020.00039.

[92] A. Nieva, J. Wang, J. Malloch, and M. Wanderley, "The t-stick: Maintaining a 12 year-old digital musical instrument," in *Proc. Int. Conf. New Interface Musical Expression*, T. M. L. Dahl, and D. Bowman, Eds. Blacksburg, VI, USA: Virginia Tech, Jun. 2018, pp. 198–199.

[93] S. Oh, "From an ecodesign guide to a sustainable design guide: Complementing social aspects of sustainable product design guidelines," *Arch. Des. Res.*, vol. 30, no. 2, pp. 47–64, May 2017.

[94] K. K. Patel, S. M. Patel, and P. Scholar, "Internet of Things-IoT: Definition, characteristics, architecture, enabling technologies, application & future challenges," *Int. J. Eng. Sci. Comput.*, vol. 6, no. 5, pp. 1–12, 2016.

[95] I. Pătru-Stupariu and A. Nita, "Impacts of the European landscape convention on interdisciplinary and transdisciplinary research," *Landscape Ecol.*, vol. 37, no. 5, pp. 1211–1225, May 2022.

[96] M. Pavlicevic, *Music Therapy in Context: Music, Meaning and Relationship*. Jessica Kingsley Publishers, 1997.

[97] W. C. Payne, A. Paradiso, and S. Kane, "Cyclops: Designing an eye-controlled instrument for accessibility and flexible use," in *Proc. Int. Conf. New Interface Musical Expression*, R. Michon and F. Schroeder, Eds. Birmingham, U.K.: Birmingham City University, Jul. 2020, pp. 576–580. [Online]. Available: https://www.nime.org/proceedings/2020/nime2020paper112.pdf

[98] P. Pazowski et al., "Green computing: Latest practices and technologies for ICT sustainability," in *Proc. Manag. Intellectual Capital Innov. Sustain. Inclusive Soc., Joint Int. Conf.*, Bari, Italy, 2015, pp. 1853–1860.

[99] L.-A. Phan and T. Kim, "Breaking down the compatibility problem in smart homes: A dynamically updatable gateway platform," *Sensors*, vol. 20, no. 10, p. 2783, May 2020.

[100] A. Pino and L. Viladot, "Teaching–learning resources and supports in the music classroom: Key aspects for the inclusion of visually impaired students," *Brit. J. Vis. Impairment*, vol. 37, no. 1, pp. 17–28, Jan. 2019.

[101] G. Poderi, "Sustaining platforms as commons: Perspectives on participation, infrastructure, and governance," *CoDesign*, vol. 15, no. 3, pp. 243–255, Jul. 2019.

[102] B. Purvis, Y. Mao, and D. Robinson, "Three pillars of sustainability: In search of conceptual origins," *Sustainability Sci.*, vol. 14, no. 3, pp. 681–695, May 2019.

[103] C. Roberts, "A new user interface for collaborative remote music performance," Ph.D. dissertation, Worcester Polytech. Inst., 2022.

[104] C. Roberts, J. Allison, D. Holmes, B. Taylor, M. Wright, and J. Kuchera-Morin, "Educational design of live coding environments for the browser," *J. Music, Technol. Educ.*, vol. 9, no. 1, pp. 95–116, May 2016.

[105] A. Roda and S. Canazza, "Virtual performance, actual gesture: A web 2.0 system for expressive performance of music contents," in *Proc. 2nd Conf. Hum. Syst. Interact.*, May 2009, pp. 474–480, doi: 10.1109/HSI.2009.5091025.

[106] C. Rottondi, C. Chafe, C. Allocchio, and A. Sarti, "An overview on networked music performance technologies," *IEEE Access*, vol. 4, pp. 8823–8843, 2016.

[107] A. Sabovic, A. K. Sultania, and J. Famaey, "Demonstration of an energy-aware task scheduler for battery-less IoT devices," in *Proc. 19th ACM Conf. Embedded Networked Sensor Syst.* New York, NY, USA: Association for Computing Machinery, Nov. 2021, pp. 586–587, doi: 10.1145/3485730.3493358.

[108] S. Scuri, M. Ferreira, N. Jardim Nunes, V. Nisi, and C. Mulligan, "Hitting the triple bottom line: Widening the HCI approach to sustainability," in *Proc. CHI Conf. Hum. Factors Comput. Syst.*, Apr. 2022, pp. 1–19.

[109] F. K. Shaikh, S. Zeadally, and E. Exposito, "Enabling technologies for green Internet of Things," *IEEE Syst. J.*, vol. 11, no. 2, pp. 983–994, Jun. 2017, doi: 10.1109/JSYST.2015.2415194.

[110] M. Shirvanimoghaddam, K. Shirvanimoghaddam, M. M. Abolhasani, M. Farhangi, V. Z. Barsari, H. Liu, M. Dohler, and M. Naebe, "Towards a green and self-powered Internet of Things using piezoelectric energy harvesting," *IEEE Access*, vol. 7, pp. 94533–94556, 2019, doi: 10.1109/ACCESS.2019.2928523.

[111] M. S. Silberman, L. Nathan, B. Knowles, R. Bendor, A. Clear, M. Håkansson, T. Dillahunt, and J. Mankoff, "Next steps for sustainable HCI," *Interactions*, vol. 21, no. 5, pp. 66–69, Sep. 2014, doi: 10.1145/2651820.

[112] A. Soro, M. Brereton, T. Dema, J. L. Oliver, M. Z. Chai, and A. M. H. Ambe, "The ambient birdhouse: An IoT device to discover birds and engage with nature," in *Proc. CHI Conf. Hum. Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, Apr. 2018, pp. 1–13, doi: 10.1145/3173574.3173971.

[113] J. Suchnek, "Soil choir v.1.3—Soil moisture sonification installation," in *Proc. Int. Conf. New Interface Musical Expression*, U.K. Birmingham, Birmingham City University, Jul. 2020, pp. 617–618. [Online]. Available: https://www.nime.org/proceedings/2020/nime2020paper121.pdf

[114] A. K. Sultania and J. Famaey, "Energy-aware battery-less Bluetooth low energy device prototype powered by ambient light," in *Proc. 19th ACM Conf. Embedded Networked Sensor Syst.* New York, NY, USA: Association for Computing Machinery, Nov. 2021, pp. 584–585, doi: 10.1145/3485730.3493357.

[115] K. Suzuki, *Policy Logics and Institutions of European Space Collaboration*. Evanston, IL, USA: Routledge, 2017.

[116] J. W. Tetley, S. Holland, S. Caton, G. Donaldson, T. Georgiou, F. Visi, and R. C. Stockley, "Using rhythm for rehabilitation: The acceptability of a novel haptic cueing device in extended stroke rehabilitation," *J. Enabling Technol.*, vol. 16, no. 4, pp. 290–301, Nov. 2022.

[117] D. Thor and P. Karlsudd, "Teaching and fostering an active environmental awareness design, validation and planning for action-oriented environmental education," *Sustainability*, vol. 12, no. 8, p. 3209, Apr. 2020.

[118] J. Timoney, A. Yaseen, and D. Mcevoy, "The potential role of Internet of Musical Things in therapeutic applications," in *Proc. 10th Workshop Ubiquitous Music*, 2020.

[119] S. Trolland, A. Ilsar, C. Frame, J. McCormack, and E. Wilson, "AirSticks 2.0: Instrument design for expressive gestural interaction," in *Proc. NIME*, Jun. 2022, doi: 10.21428/92fbeb44.c400bdc2.

[120] L. Turchet, "Smart musical instruments: Vision, design principles, and future directions," *IEEE Access*, vol. 7, pp. 8944–8963, 2019.

[121] L. Turchet, D. Baker, and T. Stockman, "Musical haptic wearables for synchronisation of visually-impaired performers: A co-design approach," in *Proc. ACM Int. Conf. Interact. Media Experiences*, Jun. 2021, pp. 20–27.

[122] L. Turchet and J. Hueller, "Promoting awareness on sustainable behavior through an ar-based art gallery," in *Proc. Int. Conf. Augmented Reality, Virtual Reality Comput. Graph.* Cham, Switzerland: Springer, 2020, pp. 53–65.

[123] L. Turchet, C. Fischione, G. Essl, D. Keller, and M. Barthet, "Internet of Musical Things: Vision and challenges," *IEEE Access*, vol. 6, pp. 61994–62017, 2018.

[124] L. Turchet, M. Lagrange, C. Rottondi, G. Fazekas, N. Peters, J. Østergaard, F. Font, T. Bäckström, and C. Fischione, "The Internet of Sounds: Convergent trends, insights and future directions," *IEEE Internet Things J.*, 2023, doi: 10.1109/JIOT.2023.3253602.

[125] L. Turchet and F. Antoniazzi, "Semantic web of musical things: Achieving interoperability in the Internet of Musical Things," *J. Web Semantics*, vol. 75, Jan. 2023, Art. no. 100758.

[126] L. Turchet and C. Fischione, "Elk audio OS: An open source operating system for the Internet of Musical Things," *ACM Trans. Internet Things*, vol. 2, no. 2, pp. 1–18, May 2021.

[127] L. Turchet, T. West, and M. M. Wanderley, "Touching the audience: Musical haptic wearables for augmented and participatory live music performances," *Pers. Ubiquitous Comput.*, vol. 25, no. 4, pp. 749–769, 2021.

[128] O. Velsberg, U. H. Westergren, and K. Jonsson, "Exploring smartness in public sector innovation–creating smart public services with the Internet of Things," *Eur. J. Inf. Syst.*, vol. 29, no. 4, pp. 350–368, Jul. 2020.

[129] C. Vezzoli and E. Manzini, *Design for Environmental Sustainability*. Cham, Switzerland: Springer, 2008.

[130] R. Vieira, D. C. Muchaluat-Saade, and F. L. Schiavoni, "Sunflower: An interactive artistic environment based on IoMusT concepts," in *Proc. ACM Int. Conf. Interact. Media Experiences*, Jun. 2022, pp. 245–248.

[131] V. Vlachokyriakos, C. Crivellaro, P. Wright, E. Karamagioli, E.-R. Staiou, D. Gouscos, R. Thorpe, A. Krüger, J. Schöning, M. Jones, S. Lawson, and P. Olivier, "HCI, solidarity movements and the solidarity economy," in *Proc. CHI Conf. Human Factors Comput. Syst.* New York, NY, USA: Association for Computing Machinery, May 2017, pp. 3126–3137, doi: 10.1145/3025453.3025490.

[132] B. N. Walker and M. A. Nees, "Theory of sonification," in *The Sonification Handbook*, vol. 1, 2011, pp. 9–39.

[133] T. J. West, M. Wanderley, and B. Caramiaux, "Making mappings: Examining the design process," in *Proc. Int. Conf. New Interface Musical Expression*, R. Michon and F. Schroeder, Eds. Birmingham, U.K.: Birmingham City University, Jul. 2020, pp. 291–296. [Online]. Available: https://www.nime.org/proceedings/2020/nime2020paper55.pdf

[134] M. Wright, "Open sound control: An enabling technology for musical networking," *Organised Sound*, vol. 10, no. 3, pp. 193–200, Dec. 2005, doi: 10.1017/s1355771805000932.

[135] A. Xamb, "Who are the women authors in nimeimproving gender balance in nime research," in *Proc. Int. Conf. New Interface Musical Expression*. Blacksburg, VI, USA: Virginia Tech, Jun. 2018, pp. 174–177. [Online]. Available: http://www.nime.org/proceedings/2018/nime2018paper0037.pdf

[136] A. Xambó and G. Roma, "Performing audiences: Composition strategies for network music using mobile phones," Birmingham City Univ., Tech. Rep., 2020.

[137] A. Yaseen, S. Chakraborty, and J. Timoney, "A cooperative and interactive gesture-based drumming interface with application to the Internet of Musical Things," in *Proc. Int. Conf. Hum.-Comput. Interact.* Cham, Switzerland: Springer, 2022, pp. 85–92.

[138] C. Zhu, V. C. M. Leung, L. Shu, and E. C.-H. Ngai, "Green Internet of Things for smart world," *IEEE Access*, vol. 3, pp. 2151–2162, 2015, doi: 10.1109/ACCESS.2015.2497312.

[139] L. Turchet and P. Casari, "Latency and reliability analysis of a 5G-enabled internet of musical things system," *IEEE Internet Things J.*, vol. 11, no. 1, pp. 1228–1240, 2024, doi: 10.1109/JIOT.2023.3288818.

RAUL MASU received the Diploma (bachelor's and master's levels) degree in music from the Conservatory of Music of Treno and the Ph.D. degree in digital media from the Faculty of Science and Technology, Nova University of Lisbon. He is currently an Assistant Professor with the Computational Media and Art, The Hong Kong University of Science and Technology (Guangzhou). He is particularly active in the new interfaces for musical expression (NIME) community, he is one of the initiators of the NIME Eco Wiki, a repository to support a sustainable practice for music technology design. He conducted research in Italy, Portugal, Thailand, and China. He has published around 50 articles in the field of music technology and human–computer interaction in venues, such as CHI, TEI, DIS, NIME, Organised Sound, and Audiomostly.

NICOLÒ MERENDINO received the M.A. degree in systems design from ISIA, Rome, in 2013. He is also known as "Chi ha ucciso Il Conte?" and an UI/UX Designer specialized in the development of interfaces for experimental music and media arts. With a focus on open source software and digital fabrication, he brings a unique approach to GUI and TUI design, combining technology and artistic expression. He has since worked extensively in the field of systems design. He has contributed his expertise to renowned organizations, such as STEIM and The Waag Society in Amsterdam and conducting research as a Ph.D. Student and a Researcher with the University of Padova. His innovative designs and passion for TUI continue to shape the future of interface design and interactive experiences.

ANTONIO RODÃ was born in 1971. He received the degree in violin from the Conservatory of Padova, in 1994, the master's degree in electronic engineering from the University of Padova, in 1996, the Ph.D. degree in audiovisual studies from the University of Udine, in 2007, and the degree in composition from the Conservatory of Verona, in 2009. Since 1997, he has been working with "Centro di Sonologia Computazionale," Padova. He is currently an Associate Professor with the Department of Information Engineering, University of Padova, and he is responsible for the courses of data and algorithms and sound design and music technologies. He has participated in 13 national and international research projects and is the author or coauthor of more than 150 papers on national and international journals and peer-reviewed conferences. His main research interests include models for expressiveness in music, multimedia systems, interactive multimodal learning environments, preservation, and restoration of audio documents.

LUCA TURCHET (Senior Member, IEEE) received the master's degree (summa cum laude) in computer science from the University of Verona, in 2006, the degrees in classical guitar and in composition from the Music Conservatory of Verona, in 2007 and 2009, respectively, the Ph.D. degree in media technology from Aalborg University Copenhagen, in 2013, and the degree in electronic music from the Royal College of Music of Stockholm, in 2015. He is currently an Associate Professor with the Department of Information Engineering and Computer Science, University of Trento, Italy. His scientific, artistic, and entrepreneurial research has been supported by numerous grants from different funding agencies, including European Commission, European Institute of Innovation and Technology, European Space Agency, Italian Ministry of Foreign Affairs, and the Danish Research Council. He is the Co-Founder of the Music-Tech Company Elk. He is also the Chair of the IEEE Emerging Technology Initiative on the Internet of Sounds and the Founding President of the Internet of Sounds Research Network. He serves as an Associate Editor for IEEE ACCESS and the *Journal of the Audio Engineering Society* and has been a Guest Editor for *IEEE Communications Magazine*, the *Personal and Ubiquitous Computing* journal, the *Journal of the Audio Engineering Society*, *Frontiers in VR*, and *Digital Creativity*.

Open Access funding provided by 'Università degli Studi di Padova' within the CRUI CARE Agreement