Sustainable digital fabrication in NIME: Nine sustainability strategies for DMI production

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ABSTRACT

Sustainable NIME practices have gained significant attention in the past few years. This article further develops this perspective by proposing a set of strategies for sustainable digital fabrication processes, which is an important aspect of Digital Musical Instruments (DMIs) creation. We grounded our strategies on recent literature presented at NIME combined with state-of-the-art literature and policy on sustainable products. To start understanding how these strategies could be perceived and adopted by DMI makers, we run a workshop at iii (Instruments Inventors Initiative) - an incubator of musicians/makers. In the workshop we discussed some of these strategies in order to understand how they resonated with our participants. The article concludes by positioning our contributions within the broader context of research within the NIME community and related fields, offering a perspective on how these strategies might influence sustainable practices in DMI production.

Author Keywords

sustainability, digital fabrication, NIME, DMI

CCS Concepts

•**Applied computing** → **Performing arts;** •**Social and professional topics** → **Computing / technology policy;**

1. INTRODUCTION

In the evolving landscape of Digital Musical Instruments (DMIs) design, the intersection of Digital Fabrication (DF) and sustainability within the New Interfaces for Musical Expression (NIME) community emerged as a focal point for contemporary research. This paper delves into this intersection, offering a deep exploration of sustainable practices in digital fabrication within the realm of NIME.
This paper contributes to an ongoing debate within the NIME community on longevity [45], durability [35] and sustainability [34] - with a specific focus on digital fabrication -, by presenting a set of **strategies** that we developed based on previous experiences as well as on guidelines provided by institutions.

In order to address different moments of a DMI's life cycle (as analyzed in a recent paper on NIME sustainability [34]), the sustainability strategies focus on two main categories: **sustainability in production** and **avoiding disposal**, which are then articulated into a more specific set of actions. Overall the strategies are organized in a **two-dimensional model** 4. It is possible to cross the strategies proposed in relation to specific digital fabrication processes and technologies. After introducing the strategies, we will discuss a workshop that we organized among a community of instrument makers in order to start spreading them and collect feedback on their possible adoption.

At the end of the paper, we discuss the strategies and the workshop in the hope to contribute to the advancement of a sustainable NIME practice.

2. BACKGROUND

2.1 Sustainability and Longevity in NIME

In the past years, a discussion on **sustainability** in NIME has started. In 2020 NIME created an environmental committee (alongside other committees dealing with ethics and diversity) [1] and statement [2]). In 2021, a paper emerging from the work of that committee highlighted how sustain-

[1] `https://nime.org/committee/`
[2] `https://nime.org/environment/`

NIME'24, 4–6 September, Utrecht, The Netherlands.

ability has been generally overlooked in NIME [34]. Since then, researchers in the NIME community started to propose projects [38] and theoretical reflections [16] that explicitly aim at improving the sustainability of DMIs production. Accompanying the 2021 paper, the ECO.NIME wiki [3] - an online repository of resources to support a sustainable NIME practice - was launched.

Longevity is an important aspect of sustainability [33] as increasing the total hours a DMI is used lowers its environmental impact per hour. Additionally, increased longevity potentially reduces the need to make new DMIs [35]. In order to foster longevity, Calegario highlighted the importance of documentation [9], discussing the difficulties of replicating NIME projects and providing guidelines to produce replication-driven documentation. Bin also engaged with the issue and proposed five strategies to document NIME: Collaborative, Ongoing, Flexible, Openness, As complete as we can make it.

In NIME, the discussion on longevity points both to the existence of a problem and suggests possible ways to improve the status quo. Several authors pointed out that many projects presented during NIME conferences are used just a few times if not only once, before becoming debris also due to the pressure to deliver a large amount of output [41, 17]. This led to coin/use the locution "disposable instrument" [45].

Recent NIME papers discuss how to increase DMIs' longevity, for instance by 1) promoting the practice of developing modular and long-lasting instruments [8]; 2) proposing design solutions aimed at preventing breaking, allowing fixing, and open-sourcing the outcomes of the design process to support futures hacks and re-designs [38]; 3) inviting members of a community to explore different applications of a single DMI [20].

As the interest of the NIME community involves design and digital fabrication practices, it is worth looking at sustainability in digital fabrication from a broader perspective. For this reason, the following subsection includes several sustainable digital design practices deriving from non-NIME literature."

2.2 NimeCraft and Digital Fabrication

Within the community of music instrument builders, designing and building tangible instruments and interfaces has always been a core aspect of artistic and research practices [1, 31]. Projects relying on digital fabrication to build DMIs such as the Chowndolo [38], the T-tree [8], and the Halldorophone [55] are easy to find. Additionally, Jorda highlighted the key role of digital fabrication and proposed the term "Digital Luthier" referring to the construction of tools that facilitate musicking with computers [25]. Recently, NIME community thoroughly studied the practices of building DMIs. For instance, Armitage et al. studied many digital lutherie practitioners, highlighting their needs and the tools they use. The authors coined the term "NIME-craft" to indicate the overlap of traditional crafting needed to shape tangible material with computing and coding skills [1].

People designing DMIs within NIME use different digital fabrication tools such as 3D printing, Laser Cutting, and CNC milling. For instance, the "Music Maker" platform [29] leverages **3D printers** to make woodwind and brass mouthpieces, and the project "TRAVIS II" relies on custom-made 3D printed elements to embed sensors into a violin [26]. "Chowndolo" [38] consistently uses **Laser cutting** to build the DMI's wooden body. This tool also allows for quick production of prototypes, as also shown by "Probatio 1.0" [10] toolkit. Finally, **CNC milling** - which allows producing objects based on 2D vector, graphics, or 3D models using 3 (or more) axis programmable robotic milling tools - has been adopted to fabricate electric guitars [28] locally.

Recently some studies have systematically scrutinized tools for digital fabrication within different organizational settings. For instance, Cavdir [11] provides a list of easily accessible digital fabrication techniques used to develop musical projects, mentioning both **in-house** and **rented means of production**. Additionally, Kontogeorgakopoulos [27] contextualized the process of designing and producing a DMI in a **fab lab** providing standard tools (3D printers, CNC machines, laser cutters, high-resolution milling machines for **circuit board** milling, electronics and microprocessors, and vinyl cutters) that have been used to build a fully functioning small orchestra.

In line with these papers, we systematically consider these techniques and we introduce a new perspective by considering how these tools can be used while accounting for sustainability.

3. NIME DIGITAL FABRICATION SUSTAINABILITY STRATEGIES

This section focuses on providing strategies to make the digital fabrication processes that characterize NIME more sustainable. In subsection 3.1 we outline **sustainability-related practices** derived from the design literature. In subsection 3.2 we present **nine strategies** derived from this design literature. Finally, in subsection 3.5, we will position the nine strategies into a **two-dimensional model** dimensional model connecting them to some digital fabrication processes commonly used in NIME (outlined in section 2.2).

3.1 Sustainability-related design practices

Literature on design, economics, and policies reflected on design practices that can be directly or indirectly related to sustainability.

The first design practice implicitly connected to sustainability - **robustness** of a product and the **optimization of the fabrication production** behind it - emerges from the literature on manufacturing. Norman emphasizes user-centered design for intuitive and durable products [47]. Similarly, Boothroyd, Dewhurst, and Knight focus on the principles of designing for ease of manufacturing [6], which inherently enhances product robustness. Additionally, Ashby and Jones [2] provide insights into the material selection, which is crucial for a product's durability and strength [46, 43].

Other design research works address the **logistic-related** properties of design. In the iconic book "Towards a New Architecture", Le Corbusier finds in the compact and foldable items on ocean-lines ships the principle of designing objects that are easier to store and transport [14]. More recently, Mather and Hal proposed the Design for Logistics (DFL) model to define a design practice that accounts for

[3] `https://eco.nime.org/`

logistics [36]. Lastly, IKEA has been studied by research focused on how logistics shaped the manner of designing objects and packaging [21].

Integrating **sustainable materials** is another critical aspect of contemporary design practices, addressed by several researchers [**?**, 22]: "Sustainable Materials, Processes, and Production" by Thompson serves as a comprehensive guide [53]. Furthermore, the EU Commission provides an extensive report on recycling materials and reducing waste production [4] .

The reflections on E-waste and early obsolescence of products raised by Chapman et.al, [12] propose a discussion focused on increasing the longevity of a product to prevent its disposal, which can be central in the transition toward sustainable development. Linking with Chapman's proposal, the importance of maintenance and **repairability** of electronic products has been acknowledged as a parameter to integrate into the product design process in many research works [52, 19, 59]. In line with this concept, initiatives such as the establishment of repair cafes around the world [42] have been mentioned in several research works related to sustainability. Several institutions' Political agendas have addressed sustainability. For example, the European Commission produced an extensive dossier to foster product durability and repairability in Europe [32]. Moreover, the French government proposed a "repairability index" [5] to evaluate the repairability of electronic products which account for: **documentation, disassembly, availability of spare parts, and price of spare parts**.

Furthermore, concerning the discussions on the longevity of digital devices, institutional reports point out that open hardware, **free/libre, and open source software (FLOSS)** can play a significant role [6]. These initiatives are a source of tools that individuals and communities can freely employ to develop DMIs and electronic device manufacture without being dependent on proprietary software owned by private companies and, therefore, potentially inaccessible [56, 48]. In recent years, open-source applications have reached a level of maturity that allows designers to rely on them to carry out their practices. From Computer-Aided Design (CAD) [39] to music production [44], through microcontroller programming [60], researchers and professionals can develop devices using tools developed and maintained by creative communities.

3.2 Nine strategies to increase DMI and digital fabrication sustainability

In this subsection, we will present a set of **nine strategies** that formalize several design approaches we derived from the literature outlined in section x These strategies are meant to provide a general plan of action that can guide instrument designers in making sustainable choices. The strategies focus on two main phases of DMI's lifecycle (as analyzed in a recent paper on NIME sustainability [34]): **making sustainably** and **avoiding disposal** (see 1).

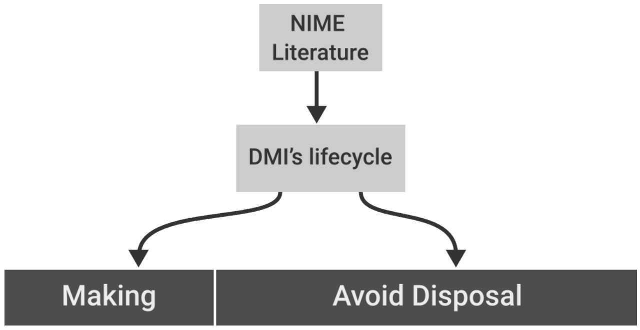

Figure 1: Diagram showing the rationale behind the focus on the two phases of a DMI lifecycle

3.3 Making sustainably

We outline here the rationale for the creation of **the three strategies related to the making phase** 2 of a DMI lifecycle and how we derive them from the literature on design presented above:

- **1) Optimize Fabrication processes** indicates those actions that reduce the environmental impact of fabricating DMI by choosing more efficient fabrication techniques and optimizing the process. This strategy is derived from the literature on **production** [43, 2].

- **2) Optimize logistics** points to the good practice of making DMIs that are easy to transport and store so that they do not require a massive infrastructure when not in use. This strategy is derived by **logistic-related properties** of a product [36]

- **3) Rely on recycled or sustainable Materials** target the choice of environmentally friendly raw materials to produce DMI's. This strategy is derived by **sustainable materials literature and policies** [**?**, 22].

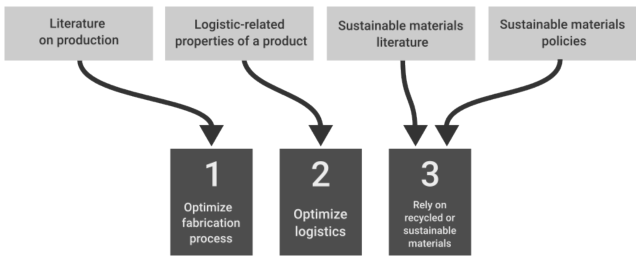

Figure 2: Diagram showing the rationale behind the Making related strategies

3.4 Avoid disposal

We outline here the rationale for the creation of the **six strategies related to avoiding or delaying the disposal** phase of a DMI life-cycle. Most of these strategies are related to **repairability** and are derived from the French repairability index, in addition, we include a strategy derived from **robustness** (to minimize breaking) and one on **FLOSS** for digital fabrication 3.

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[4] `https://www.eea.europa.eu/publications/the-case-for-increasing-recycling`
[5] `https://technical-regulation-information-system.ec.europa.eu/en/notification/24323https://repair.eu/news/the-french-repair-index-challenges-and-opportunities/`
[6] `https://commission.europa.eu/about-european-commission/departments-and-executive-agencies/digital-services/open-source-software-strategy_en`

- **4) Document** strategy is based on the principle of creating a comprehensive set of outcomes that allow other people to understand a DMI in every one of its parts. This strategy is derived from the **documentation** parameter of the **French repairability Index**

- **5) Rely on Modularity** sets the goal of creating instruments that are expandible, upgradeable, and fixable by easily adding, removing, or replacing their components. This strategy is derived from the **documentation** parameter of the **French repairability Index**

- **6) Rely on standard and snteroperability** relate to a DMI's property of operating well into (ideally) any context without requiring custom-made parts, protocols, and infrastructures. This strategy is derived from the **availability of spare parts** parameter of the **French repairability Index**

- **7) Consider affordability of reparation** points to the need for using components that are economically accessible by most people and communities. This strategy is derived from the **price of spare parts** parameter of the **French repairability Index**

- **8) Optimize and account for durability** suggests designing instruments that are not fragile and weak to environment-related factors. This strategy is derived from **design literature on robustness** [43, 2]

- **9) Rely on FLOSS for fabrication** strategy is based on the adoption of Free/Libre Open Source software to generate the files needed to operate the machines. This strategy is derived from the **literature on obsolescence [52, 19, 59] and the EU report on free/libre, and open source software (FLOSS).**

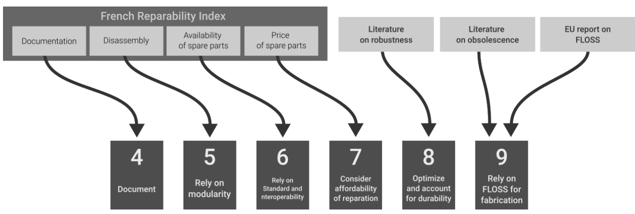

Figure 3: Diagram showing the rationale behind the avoid disposing of related strategies

In order to focus on the fabrication process and the materials used, we have omitted a discussion on the transport activities listed in the Masu et al.'s [34] "NIME Sustainability Framework". We believe that transport requires a separate discussion connected to the context in which a DMI is possibly designed, produced, and used.

3.5 A 2-dimensional model for sustainable digital fabrication

The nine strategies we propose point to some insights that instrument makers can (and should) follow to make their outcomes more sustainable. To support people in shifting from general strategies to operative actions, we created a **two-dimensional model for sustainable digital fabrication** (figure X) where the nine strategies are mapped/intersected with specific digital fabrication processes and technologies. The strategies are placed in the X axis of the model, while the Y axis is populated by specific digital fabrication technologies.

Each intersection between the strategies and the digital fabrication technologies is meant to be filled with more operative tools, such as tutorials or specific suggestions. We propose such a format with the intention of fostering a systematic approach to place/read the specific suggestions on how to enact the strategies proposed above. To facilitate this process we complemented this paper with a number of tutorials that we published in the NIME ECO wiki.

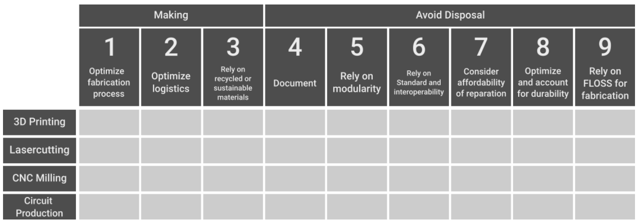

Figure 4: Visualization of the two-dimensional model

4. THE III WORKSHOP

To disseminate the strategies (and the tutorials in the Wiki) and get feedback from a community of practitioners, we organized an in-person workshop at iii (Instruments Inventors Initiative) - an artist-run community platform focused on the digital creation of musical devices. This workshop was part of a broader collaboration around sustainable digital fabrication between some authors of this paper and iii and was publicly promoted under the name of "Designing Durable Instruments and Installations (ECO NIME)" [7] Following iii usual settings for events, the workshop was organized as an instructional activity where the participants learn content offered by an instructor.

The strategies, as presented in this paper, were used as guidelines to define the content of the workshop and were shown briefly to the participants.
Since we could not cover all the strategies and the wiki content in a one-day workshop, a few weeks before the workshop, we sent participants a questionnaire to identify which digital fabrication technologies they found more interesting and tailored the workshop accordingly. During the workshop, we used each of these digital fabrication technologies to showcase the strategies within different scenery of use. Within this overall structure, we collected feedback via discussions and a final questionnaire.

The **workshop** consisted of a 4-hour session and was attended by 11 participants. The participants were art and design students (7), researchers (2), and professional artists (2). The participants were primarily females (6), and the group was also composed of male participants (4) and one (1) non-bi person. The participants were primarily young adults (approximately 20-30), with only one person above 35. The workshop focused on communicating and discussing the digital fabrication technologies most interested the participants (3d printing, Laser cutting, and Circuit production). For each of them, we followed the same format:

- 1) we introduced the strategies relevant to the specific technology;

[7] `https://instrumentinventors.org/agenda/designing-durable-instruments-and-installations-eco-nime/`

- 2) we presented relevant tutorials within the Eco NIME Wiki;
- 3) we used physical prototypes brought both by us and by participants to showcase the presented strategies;
- 4) we opened up a discussion.

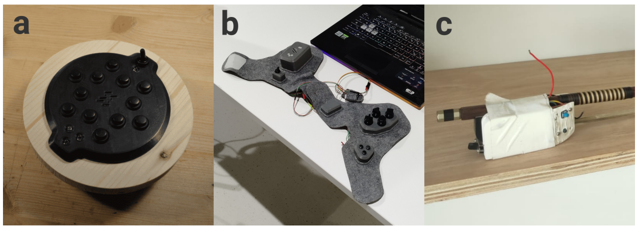

Figure 5: pictures of the prototypes used during the activities: a - the DCM [39]; b - the "Below58BPM" wearable interface [40]; c - The bow developed for "Knurl" project

Furthermore, we provided an additional focus on the strategies related to optimization, open standard and interoperability, and we briefly mentioned other digital fabrication technologies.

Finally, we opened up a more general discussion on the workshop's content, where we explored possible ways to facilitate the adoption of the strategies and possible improvements to the wiki. To conclude, participants completed a final questionnaire inquiring about their prior knowledge and use of strategies and their likelihood of using them post-workshop.

To obtain authentic feedback from participants, we endeavored to maintain an informal atmosphere during the activities by employing a casual tone and occasional humorous interventions [58, 54]

5. WORKSHOP RESULTS

We analyzed the discussions emerging during the workshop using an inductive thematic analysis [49]: The discussions were recorded during the activities and manually transcribed by the paper's first author. we then coded the discussion into 16 codes and recursively harmonized and clustered the codes to obtain themes and subthemes. The overall process has been verified by two authors of this paper and produced **five themes** (in bold) with several subthemes.

5.1 Theme 1: Adoption of open-source tools

The first theme we identified revolves around the **adoption of open-source tools**, and it comprises four subthemes. **Education** (subtheme 1.1) emerged as an issue in relation to open-source and includes consideration in formal and informal settings. P1 highlighted that universities do not teach open-source software to their students and said that they personally found it annoying to be forced to pay a license after graduation to keep doing what she learned. P2 argued that universities are often market-driven in their choices. Concerning informal self-education settings, participants had opposite experiences. For instance P3 mentioned their difficulty in accessing the knowledge to use 3d printing, on the contrary P2 brought forward that there are many tutorials for open-source projects.

Open source experience (subtheme 1.2), emerged as a second topic. For instance, P3 highlights that open-source tools are generally more complicated than mainstream alternatives. This led to a general consideration on what is needed to actually make these strategies accessible: should people be prepared to spend more time acquiring technical skillsets or should open source software be more user-friendly? P3.
Open source is also **stereotypically considered non-professional** (subtheme 1.3). For instance P1 argued that open source projects are non-professional, thus tend to break. Similarly, P2 argued that the market usually requires designers to operate with proprietary tools and that proprietary software tends to be considered standard and better.

The last issue that emerged concerns **management of time** (subtheme 1.4). Often the timeframe of a design process is limited, and there might not be the time to learn all the various skills necessary to implement the workflow presented (P5) or to produce accurate open documentation (P4). P5 also pointed out that in his view it is better to establish collaboration rather than learning everything by oneself.

5.2 Theme 2: Documentation

The second theme that emerged is related to the technical and functional aspects involved in project documentation. This theme comprises three subthemes.

During the workshop, our participants expressed interest in **technical aspects of project documentation** (subtheme 2.1). For instance, P6 explicitly asked: "Can you provide more information about documenting a project?", referring to what materials (drawings, files etc..) are needed and what tools can be used to make them. Then P7 thought about adopting machine code (i.e. assembly) as a purest form of documentation, but that would be the most complex and therefore less usable for actual reuse.

During the discussion, a participant (P3) also proposed the idea of **including non technical information** (subtheme 2.2) in the documentation, and l preserve details also about the aesthetic and artistic ideas, eventual dramaturgy, and the overall meaning of the DMI. P3 conducted by arguing that materials per se are fragile. Thus, the object's intrinsic value can be dematerialized by not residing in the physical items but in the repository. I am running a few minutes late; my previous meeting is running over.

P3, also introduced the concept of the **timeframe of project documentation** (subtheme 2.3). She remarked that the idea of "future" is quite abstract - "is it 20 years?, 30 years?"(P3) - , this led to a reflection on how long in the future the documentation produced can be expected to survive.

5.3 Theme 3: Physical preservation of artworks

Another theme that emerged from our analysis is related to preserving the existence of an "artwork" intended as a physical object. P8 introduced the issue of DMI's **resistance to external conditions** (subtheme 3.1), specifically mentioning that, in warm or humid conditions, hardware can heat to the point of ceasing to function. Then, P2 questioned the use of materials like 3D printed ceramic that can be easily damaged by external actors (transport workers, audience etc...). Additionally, P3 mentioned that in the field of preservation, there is a problem related to the fact of **the natural decay of certain materials** (subtheme 3.2) such as plastics as a barrier for long-lasting devices. Finally, a discussion on digital **formats and obsolescence of the devices** (subtheme 3.3) emerged; in this context, parallels with objects developed in different domains became relevant.

5.4 Theme 4: Community aspects

Another theme highlights that social aspects have an impact on design choices and sustainability of the projects. For instance, P2 highlighted that researchers and academics work with open-source software in computer science departments, but administrative offices usually rely on commercial software acquired at an administrative level. In these two cases, the **context determined the choice of the software** (subtheme 4.1). Another observation was made by P3 who said that there are many open source projects developed by cultural organizations and universities, but it is often difficult to access or retrace them because small communities maintain them. Overall, **communities are needed to sustain projects over time** (subtheme 4.2). After the workshop, a conversation highlighted how different projects can **join the effort and mutually sustain each other** (subtheme 4.3). Indeed, two members of the iii extended network are working on similar projects. P1, who is currently working on an augmented bow for a string instrument. Another participant (P3) of the workshop saw the prototype and saw a similarity with Andi Otto's "Fello.

5.5 Theme 5: Improvements of the dissemination material

From the workshop, a number of suggestions of topics that can be included in the material presented and in the wiki emerged. Firstly, P9 introduced the idea of **sourcing alternative materials** (subtheme 5.1). For example, they mentioned an existing project focusing on 3D printing material from bottles. The second improvement in the strategies is a dedicated section focusing on the **relationship with manufacturers** (subtheme 5.2). Indeed, while using techniques such as CNC milling is often advisable, in the case of a big production, it can be more sustainable to rely on manufacturers (P6). In this case, however, P3 argued that it is important to try to look for nearby manufacturers to reduce shipping impact. The last possible improvement that emerged from our analysis, is having dedicated sections in the wiki on the **relation between size and repairability** (subtheme 5.3); indeed, while CNC milling allows for custom reparable circuits, it also imposes bigger component sizes (P9).

5.6 Questionnaire

The questionnaire results (presented in detail in attachment 2) suggest that, after attending the workshop, participants changed their attitudes regarding the strategies presented. We summarize here the main points that emerged from the questionnaire. Concerning **Open Standards and Interoperability**, only 10% of the participants claimed to have relied on the strategies presented before attending the workshop (assigning a value above 3 on the Likert scale). After the workshop, 56% of the participants replied that they will likely use the strategy. Concerning **Optimization and Durability**, only 10% of the participants claimed to have relied on the strategies presented before attending the workshop (assigning a value above 3 on the Likert scale). After the workshop, 81.8% of the participants replied that they will likely use the strategy. Although our sample size is too small to perform any comparative statistical analysis, these results are promising in regards to the potential of initiatives aiming at disseminating/teaching the strategies to groups of artists/designers.

6. DISCUSSION

The last few years saw a growing interest over the environmental impact of NIME research and practice [34], which further entangled its reflection on longevity [35, 45]. Our model and the nine strategies contribute to both sustainable and longevity discourses. Indeed, we suggested both design strategies that can reduce the environmental impact of fabrication of a DMI and design strategies that facilitate long term maintenance, thus potentially ease a longevous lifecycle. We discuss a few key points in light of the elements emerged in the workshop.

6.1 Documentation

Our work connects to the ongoing reflection on how to document NIME. In this sense, we align with Calegario and colleagues [9] on the importance of adequately documenting DMIs to make them accessible projects. Withih the NIME literature reflecting on documentation Bin's [3] work is particularly relevant as it proposes practical parameters to develop effective NIME documentation (Collaborative, Ongoing, Flexible, Open, and Complete). While we embrace this model, in our workshop it emerges the difficulty to produce documentation due to people's inexperience (subtheme 2.1). Furthermore, it emerged that often people don't have time to properly document their works (subtheme 1.4). For these reasons there arguably is a necessity in finding approaches to support documentations (e.g., specific fundings or calls).

6.2 Learning, FLOSS and sustainability

In our workshop, it emerged that formal and informal education settings related to digital fabrication processes and DMI fabrication do not specifically focus on sustainability. Recent papers have discussed the importance of pedagogy for NIME analyzing teaching approaches and repertoire building [33, 7]. While all these aspects are relevant, we suggest that sustainable design should be included in thinking about teaching DMIs design. This is particularly true when it comes to software selection. Indeed, despite the existence of a regulation to promote open-source in Europe (where the workshop took place) we collected insights on the scarce use of open-source software inside teaching institutions, and in particular in class (sub Themes 1.1, 1.3, 1.4, and 2.1). Additionally, teaching actors have yet to overcome the misconception that open-source software does not align with professional ambitions (subtheme 1.3). Overall, while the potential of open-source software is known and discussed outside [18, 5, 57, 23] and within NIME [37], this potential has yet to be entirely actively supported by educators.

6.3 Design, Use and Longevity

The strategies related to avoiding disposal point to the role of the person(s) who will use the DMI once the initial design process is concluded. In this regard, our research links to the "Design in use model" [13], that fosters a vision blurring the distinction between design and use. By rethinking "use" as a form of appropriation, and rejecting a stereotypical vision of the "user"[50], we hope to foster an approach to DMi where repairing, fixing, and hacking are part of the lifecycle of an instrument. This approach would mitigate issues concerning natural decay (subtheme 3.2), material resistance (subtheme 3.1), and obsolesce (subtheme 3.3), as the "use" of the instrument would imply taking care and repairing it. While a few examples that presented research on DMI updates exist [4, 30], this is far from being the norm. With our model approach this issue from a more systematic way, actively accounting for design choices grounded in decades of design research.

Another reflection connected to the proposed strategies lies in disambiguating research and artistic goals - e.g., creating/building new NIMEs as technology probes or research products (see Jack, et al. 2020 [24]) vs. building instruments for real-world use. They have different aims and expected longevity which reflect on their production. Lastly, the issue of documentation and preservation stewardship calls for further introspection. Since the design process does not end by delivering a DMI, the debate on who is in charge of keeping the source files and the documentation and where, is still ongoing [51].

6.4 Specific Institutional actions

While we have discussed the problems associated with DMIs that become debris after being barely used [45], the fault does not always rest with the individual researcher or designer. Rather, it often derives from external pressure. This can be particularly true in academia where publications are essential even keeping one's position, pushing people to build new DMIs rather than cultivate long-term engagements [41]. In addition to the environmental impact caused by such obsolescence, the creative potentials of many DMIs are not fully explored [15], equating a waste of not only resources but also a missed opportunity for creatively exploring said technologies.

In our workshop, we observed how the context determined specific design choices (subtheme 4.1) and that communities are needed to sustain projects over time (subtheme 4.2). For this reason, it is particularly important that a space is open to research that values long term engagement with DMIs. This can also produce fruitful collaboration where different projects can join effort and mutually sustain each other (subtheme 4,3).

7. CONCLUSION

This paper presents two main contributions: the first is a two-dimensional model devised to support sustainable digital fabrication in NIME; the second is the analysis of how a group of practitioners reacted to the model's strategies during a dedicated workshop.
The horizontal axis of our model includes nine strategies that point to a series of sustainability-related objectives that DMIs makers can set when designing their instruments. These strategies import knowledge from relevant literature in design and manufacturing as well as from policies aimed at fulfilling long-term plans for sustainable development (presented in section 3.2). By harvesting contributions from such consolidated works, we are confident that the horizontal axis of our model can realistically represent a long-lasting set of guidelines.

The vertical axis of the model includes specific contemporary digital fabrication technologies that DMI makers can use in their work (section 3.5). The areas at the crossings between the strategies are to be filled with specific tutorials and tools. Attachment 1 shows a complete table filled with some notions that represent the state of the art. We did not include this filled model in the paper, as these tutorials (contrary to the strategies) are more likely to evolve over time. The community can fill the empty areas as newer solutions emerge, linking the work presented to the ongoing project of the Eco NIME Wiki. We call for future updates of this work.

In our research, we also analyzed how a group of practitioners reflected upon the strategies that we propose. These analyses resulted in a demonstration of interest in adopting the strategies, which emerged from a questionnaire (see section 5.6) as well as a series of reflections on specific topics that arose from conversations we had with the group of participants, which were organized into 5 themes (see section 5), and then discussed in section 6.

7.1 Limitations and future works

The two-dimensional model integrates a series of strategies aimed at guiding NIME practitioners to improve the sustainability of projects involving the use of digital fabrication technologies. However, our research findings do highlight certain limitations that should be addressed in future studies.

The model is formulated assuming that NIME practitioners already know which digital fabrication technology is the most sustainable for their specific project(s). However, as emerged during the workshop, this is not always the case. This part of the design process is not yet included in the model, and further research on this topic would allow providing a more complete set of guidelines.

Furthermore, although based on a solid background of relevant literature and presented to experienced practitioners to collect their feedback, the strategies proposed have yet to be tested as part of an actual project's development. We believe that a series of studies aimed at contextualizing the strategies within specific case studies might be beneficial to expand upon the table presented in this paper.

In general, the research presented covers only a portion of the wide and complex issue of sustainability. For this reason, we acknowledge the need for further research aimed at expanding and completing the outcomes we provide.

8. ACKNOWLEDGMENTS

The authors of this paper would like to thank the Instrument Inventors Initiative Foundation and, indirectly, all its founders for all the support provided in organizing and actuating the activities presented in this paper. In particular, we would like to thank Yun Lee and Matteo Marangoni for the precious guidance, the feedback, and the work done, and also to the participants of the workshops who participated in our study with passion and engagement. Lastly, an enormous amount of gratitude goes to the no longer existing foundation named STEIM, which is where the seeds for the research presented were originally planted (long live STEIM!)

9. ETHICAL STANDARDS

This paper adheres to the ethical standards established by the New Interfaces for Musical Expression (NIME) community [8]. In accordance with these standards, informed consent was obtained from all participants involved in the study. Each participant signed an informed consent form that detailed the study's objectives, the voluntary nature of their participation, and the measures taken to ensure their

[8]https://www.nime.org/ethics/

privacy and confidentiality. To further protect our participants' confidentiality, we have used neutral pronouns and have omitted any names or identifying information in the presentation of our findings.

This work aligns with the environmental ethos outlined in the NIME ethical code.

We hereby declare that there is no conflict of interest in the conduct and presentation of this research. The integrity of the research outcomes remains unbiased and unaffected by any personal or financial relationships.

The research presented in this paper is partly funded by a PON scholarship (grant number DOT1487343-5) from the Italian Ministry of Research. To enhance the quality of our manuscript, we employed artificial intelligence algorithms for minor tasks, such as grammar and spelling checks. These technological aids were utilized strictly for the purpose of improving the readability of the paper and did not influence the research findings or conclusions.

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