Materials Libraries: designing the experiential knowledge transfer through prototyping

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Abstract

Experiential knowledge plays a crucial role in exploiting new materials within real contexts, i.e., designing products and applications. As a result, understanding and transferring this kind of knowledge has gained increasing attention, as well as developing new experiential tools addressing this challenge.
This contribution investigates the role of physical prototypes in designing new experiential tools for the knowledge transfer of emerging materials and technologies, i.e., Materials Libraries. The analysis is performed through a reflective practice approach based on two practical case studies dealing with new materials from waste for 3D printing. The former Materials Library focuses on the recycling of composite materials from products at their End-of-Life in industrial contexts, i.e., wind turbine blades. The latter one, RepMat Library, is an ongoing experimentation that aims to develop an open source Materials Library to collect new 3D printable materials and applications from waste-based polymers and biomass involving distributed networks and local communities, i.e., makerspaces and fablabs.
After briefly explaining the two case studies, this work defines an outline proposal of the main contributions of prototypes in designing new Materials Libraries, which means: (i) generating and detecting the experiential knowledge to transfer; (ii) categorizing and defining the taxonomy of the tool; (iii) testing the experiential knowledge transfer; and (iv) speculating on new possible ways of using Materials Libraries. In short, prototypes were mainly used as a physical learning medium to preliminary tinker with materials and technology, as well as a validating tool for the interaction between the users and the library. Furthermore, prototypes may contribute to envisioning new ways of developing and using Materials Libraries to spread experiential knowledge, i.e., democratizing the design process of the tool by encouraging *distributed*, accessible, and collaborative work within local communities and distributed networks.

Materials Experience; Material Tinkering; Research through Design; Material Driven Design; 3D printing.

Experiential knowledge is a tacit and non-discursive way of knowing that originates from practical experiences and experimentation (Groth et al., 2020; Niedderer, 2007). Contrarily to other kinds of knowledge, it cannot be entirely articulated by textual or verbal media, and it often requires different non-textual approaches for its effective transfer, i.e., translating abstract concepts into tangible artifacts (Niedderer, 2007; Nimkulrat, 2021). Experiential knowledge has a crucial role in design practice. Designers often rely on hands-on approaches to build new practical knowledge for their professional activities, i.e., through samples and prototypes (Camburn et al., 2017). Furthermore, this kind of tacit knowledge is a powerful way to connect theory and practice, especially dealing with practical implementations of new products and applications. This approach has been recently linked to new emerging materials and technologies within the design field, fostering new practical inquiries. Material designers interact with materials and spread new content through different experiential ways of knowing (Clèries & Rognoli, 2021; Santulli & Rognoli, 2020).

In general, samples are the most spread and effective way to interact with materials and encourage experiential knowledge transfer among designers through their tangibility and immediacy (Barati et al., 2019; Karana et al., 2015; Parisi et al., 2017). However, samples only represent the final stage of a deeper investigation and analysis, especially when dealing with emerging materials and technologies to be implemented in real contexts. In this case, intermediate prototypes may add further insight and perspectives to the resulting outcome, i.e., learning how to handle and process a specific material or highlighting some non-quantifiable aspects to be further investigated, such as expressive-sensorial qualities (Camere et al., 2018; Veelaert et al., 2020). Furthermore, using prototypes at different stages is a valuable practice when directly experiencing new materials, helping acquire new experiential knowledge from hands-on activities and direct experimentation. However, transferring this knowledge to a broader audience of practitioners may be difficult, especially when practical experimentations are not engaging them. To this end, experiential tools may help foster this knowledge transfer, and prototypes potentially support their design and development. As a matter of fact, experiential tools should be seen as new artifacts to be designed, tested, and refined through prototypes, including the interaction between the tool and its potential users. Among those, Materials Libraries represent a good way to foster experiential knowledge transfer linked to materials and manufacturing processes. These collections of physical material samples aim to support designers and practitioners during materials selection by providing a tangible experience with materials, understanding their expressive-sensorial qualities, and transferring part of the experiential knowledge entangled in their materiality (Akın & Pedgley, 2016; Rognoli & Levi, 2004; Wilkes & Miodownik, 2018). However, the contribution of multiple prototyping activities in the design of this knowledge transfer has not been adequately explored, and a definition of the different contributions given by prototypes during the whole process is still missing.

This work investigates the role of physical prototypes in designing new experiential tools to spread the knowledge of emerging materials and technologies, such as Materials Libraries. Two practical case studies dealing with waste-based materials and 3D printing are here outlined to critically reflect on the use of prototypes within the design process of the two Materials Libraries. The first one originates within the Horizon 2020 EU Project FiberEUse and considers recycled glass and carbon fiber composite materials as new resources for materials and applications. The second one is an ongoing work focused on new materials and products from waste-based polymers and biomass within distributed networks and communities. After briefly explaining the methodology, the two case studies are presented by resuming the design and development of the two Materials Libraries, the FiberEUse project Library and the RepMat Library. The contribution given by prototypes in designing new Materials Libraries is then provided, resulting in four different possible uses, as well as different roles in shaping and spreading new experiential knowledge.

Methodology

Reflective practice through prototypes

Reflective practice, or Reflection-in-action, helps in linking theoretical concepts of inquiry to real contexts by using practical experimentations and projects to reflect on new theory (Schön, 1992), using design practice as a way to perform research (Friedman, 2008; Goldkuhl & Sjöström, 2018). In other words, artifacts, exhibitions, or products are intended as practical inquiry tools to conceptualize and build new theoretical knowledge from practice (Reich, 2017). Considering the design field, prototyping is one of the most common ways to explore new concepts from the practical context and translate them into theoretical knowledge (Horváth, 2016; Mäkelä, 2007). Prototypes are approximations of artifacts, features, and concepts aiming to refine, communicate, explore, and learn new contents, i.e., products, services, or even knowledge (Camburn et al., 2017; Mäkelä, 2007). From a certain point of view, prototypes are also seen as a tangible result of design experimentations, extending their use in research contexts (Brandt & Binder, 2007).

For the sake of this work, prototypes may assume a double interpretation as methods of inquiry: as an experiential knowledge transfer or a medium to conceptualize theoretical knowledge. The former aspect is discussed within the following sections, and its investigation falls under the objectives of this work. The latter one represents the approach used to understand the role of prototypes in the experiential knowledge transfer or Materials Libraries. In particular, the two case studies described hereinafter represent some situational design inquiries directly performed by the authors. These inquiries allowed us to theorize the role of prototypes through post-evaluation analysis, using the two cases as practical sources for abstraction (Goldkuhl & Sjöström, 2018). This evaluation was performed after the development of the two Materials Libraries, resuming the main steps for the development of the tool itself and the use of prototypes in each phase. The prototypes used during the experimentation were collected and classified according to the main development steps of the two Materials Libraries, better explained in the next section. These prototypes were then analyzed according to: their objectives; their way of use, i.e., to refine the contents or the structure of the library; and their refinement, for instance, preliminary, intermediate, or advanced conceptualization of some parts of the tool. The main contribution of prototypes within this process was then outlined by mapping these differences.

Experimenting with materials from waste for 3D printing

As mentioned, artifacts play a key role in design research and practice, acting as inquiry tools to build new theoretical and experiential knowledge. They may be seen as possible outcomes of design experimentations, which, in turn, are meant as ways to frame new knowledge through making (Brandt & Binder, 2007; Mäkelä, 2007; Niedderer, 2007). This practical approach in design research has been previously exploited to investigate emerging materials, as well as new technologies and digital fabrication (Bauer, 2019; Karana et al., 2015), entangling them with complex socio-technical aspects such as sustainability (Clèries & Rognoli, 2021). As a result, these experimentations aim not only to develop new materials or emerging technologies but also to build tacit and experiential knowledge during the whole process, as well as to foster their transfer to design practitioners (Dew & Rosner, 2019; Santulli & Rognoli, 2020). From the literature, designers are not always aware of these new possibilities for their work. Hence, new ways to foster the knowledge related to emerging materials and technologies are currently required in the next few years (Romani et al., 2021).

The two case studies analyzed in this work are practical experimentations on developing two different Materials Libraries. Their goal is to spread emerging materials and technologies, i.e., materials from waste for 3D printing, for their implementation in real contexts. The main phases of the two case studies are resumed in Figure 1. These steps also correspond to the process followed for building the two Materials Libraries, representing a possible design process for this kind of experiential tool. In detail, the practical experimentations linked to the libraries were structured as follows: (a) Tinkering with the emerging materials and technology through sampling; (b) Defining a taxonomy to classify the knowledge to showcase; (c) Designing and producing the samples according to the classification; (d) designing and developing the structure of the Materials Library; (e) testing the knowledge transfer of the tool, and (f) releasing the new Materials Library.

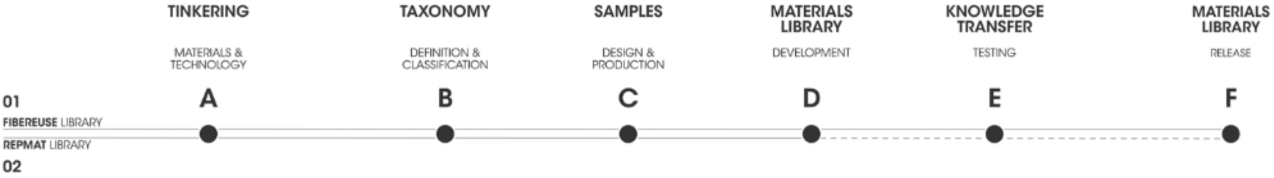

Figure 1: Phases of the practical experimentations from the two case studies: (a) Case study 1 (FiberEUse project Library); (b) Case study 2 (RepMat Library).

Materials Libraries case studies

The two selected case studies aim to spread the experiential knowledge of new materials from waste for 3D printing, fostering their use for new products and applications. The former one, FiberEUse project Library, deals with recycled composite materials from industrial products at their End-of-life, such as wind turbine blades. The latter one, RepMat Library, is a work-in-progress project of an open-source replicable Materials Library for new 3D printable materials from waste-based polymers and biomasses. The case studies were selected for their practical approach to experiencing materials and 3D printing, avoiding those experimentations that focused on designing new applications through prototypes. Indeed, their focus is on developing new experiential tools, in this case, Materials Libraries, because the main goal is to frame the role of prototypes in building and spreading new experiential knowledge.

In short, the two case studies are both focused on Materials Libraries containing new materials from waste for 3D printing. For this reason, the selected process parameters are similar, resulting in similar sample categories. The same taxonomic model was mainly used, and the second case study represents the refinement of the taxonomy used in the first one. Similarly, the second case study can be considered a step ahead in terms of possible uses of the materials library, introducing the concept of replication and structured hands-on activities. To this end, the concept of guided practical experimentations emerged after the development of the FiberEUse project Library as a possible implementation of the experiential tool.

Consequently, the second case study considered this aspect during the development of the second library.

FiberEUse project Library: Materials and Product Library System

The first case study comes from the Horizon 2020 EU Project FiberEUse. It mainly focused on recycling and reusing glass and carbon fibers from waste, especially from products at their end-of-life, i.e., wind turbine blades, construction structures, and technical components from aerospace. The project aimed to integrate new solutions based on recycling and reuse, developing new materials and products by linking research and practical contexts, i.e., industrial partners and designers.

This project resulted in several exploitations dealing with emerging materials and technologies within different application fields, i.e., furniture, sport, and automotive. To better spread their knowledge and foster new practical collaborations, a Materials Library has been designed to include all the solutions from the project. In detail, the original concept of materials libraries has been reconsidered, defining a new experiential tool that includes a physical and virtual experience with materials and products (Romani et al., 2022). This tool, a “materials and product library system,” aims to collect materials samples and new products, applications, and other non-textual content. The system comprises two parts: the Physical Library, focused on tangible use, and the Virtual Library, linked to the virtual fruition. Flat samples, product cut-offs, photos, renderings, and technical data can be used and experienced throughout the whole design process, making more accessible the knowledge related to these emerging materials and technologies. After a demo showcased at Milan Design Week 2021, the system has been released for consulting. The physical part is freely accessible on request, whereas the website (anonymized website) includes the virtual part.

This case study mainly considers the Physical Library, which is divided into two parts: the Physical Materials Library (Fig. 2a) with flat material samples and the Physical Product Library (Fig. 2b). This last part represents the focus of the experiential knowledge transfer thanks to physical cut-offs or parts of the main products developed during FiberEUse. The taxonomy of the Physical Product Library was designed to create different three-dimensional structures, one for each combination of material and manufacturing technology, where each sample is defined with a coordinate system and a position. This four-variable spatial taxonomy allows linking a set of variables, i.e., finishing, shape complexity, and process parameters, to a specific spatial position, facilitating comparisons and assessment amongst different parts (Romani et al., 2022).

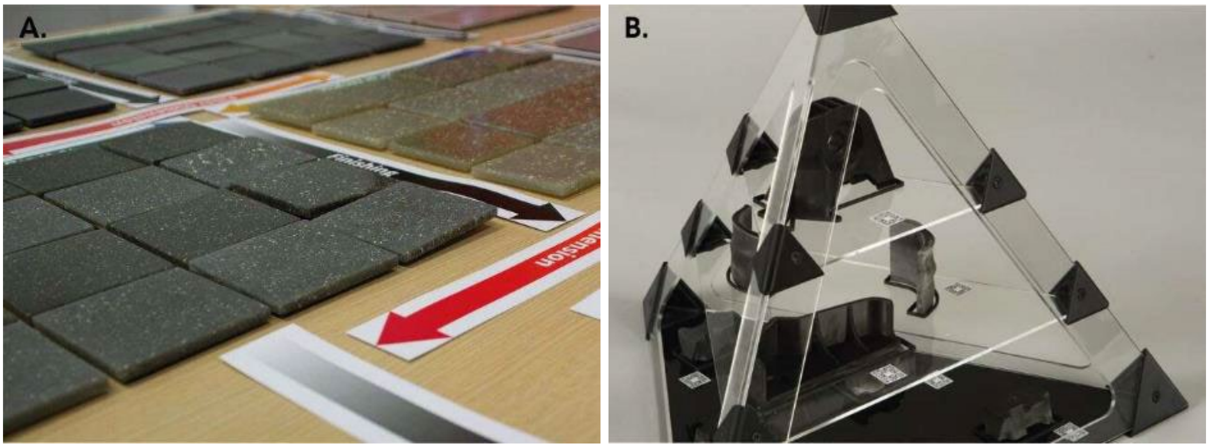

Figure 2: Insight of the Physical Library (Materials and Product Library System) from FiberEUse project: (a) flat samples from the Physical Materials Library; (b) one of the tetrahedral structures of the Physical Product Library.

RepMat Library: Open Source Materials Library System

The second case study is part of RepMat (Replicating Materials Library), an ongoing work focused on new materials, applications, and strategies to implement new circular practices starting from waste-based polymers and biomass. This project originates from the collaboration with local partners, i.e., design studios and maker spaces, aiming to understand the interaction with emerging materials and technologies within the distributed networks of local communities from the Maker culture (Camburn & Wood, 2018; Haldrup et al., 2018; Rayna & Striukova, 2021).

The project's name, RepMat, is explicitly inspired by the RepRap project (Replicating Rapid prototyper: https://reprap.org/wiki/RepRap), the first project aiming to develop a self-replicable Open-Source low-cost 3D printer in 2005. As for the previous case study, this project explores different applications, i.e., furniture, sport, and healthcare. The experimentations have focused on polymer waste from industrial processes and post-consumer goods, i.e., 3D printed scraps, and biomass from the agro-industrial sector, such as hemp hurd. Considering the framework of this project, a more accessible Materials Library is being developed to allow the free use and replication of the system amongst distributed networks of local communities, such as makerspaces. The previous concept of “materials and product library system” has been modified to define an open source system to be freely replicated, modified, and even improved by the users, allowing *distributed* collaborations. Also in this case, the tool will collect different physical and virtual contents, sharing local experimentations and good practices in a distributed virtual environment. This system will be freely released, as well as the materials to allow its replication.

The organizational structure is comparable to the FiberEUse project Library described in the previous sub-section, although its use is meant to give more freedom to the user. In this case, the generative path of the library structure is part of the knowledge transfer that the users can experience through RepMat since it encourages them to directly tinker and experiment with emerging materials and technologies. The Physical Materials Library (Fig. 3a) and the Physical Product Library (Fig. 3b) are therefore meant as practical experimentations rather than just collections of samples. The RepMat Library uses the same taxonomy as the FiberEUse project Library and encourages the user to interact with it by choosing the possible variables to be compared.

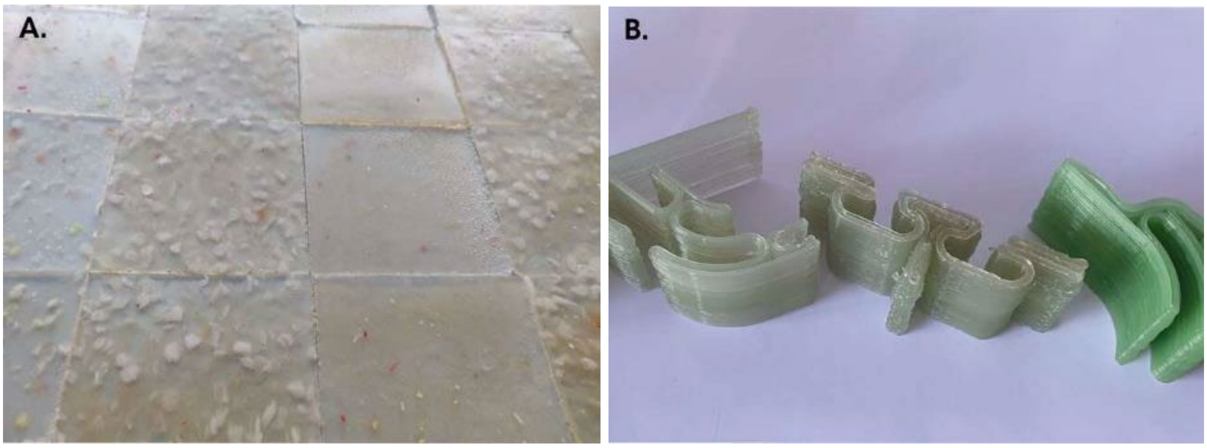

Figure 3: Insights from the open source Materials Library system of RepMat: (a) flat samples from the Physical Materials Library; (b) some physical 3D printed product cut-offs of the Physical Product Library.

Prototypes and experiential knowledge

According to the analysis of the different prototypes used during the development of the two libraries, prototypes may assume different meanings and functions in designing knowledge transfer, especially when dealing with experiential knowledge and new tools. Depending on the phase of the design process of the library (Fig. 1), prototypes can give different contributions in shaping their structure, interactions, and uses. As shown in Fig.4, four different roles of prototypes are outlined in the following sub-sections, thanks to the analysis of the prototypes used in the two case studies. In detail, prototyping helps in: (i) generating and detecting the experiential knowledge; (ii) categorizing and defining the taxonomy; (iii) testing the experiential knowledge transfer; and (iv) speculating on new ways of using Materials Libraries.

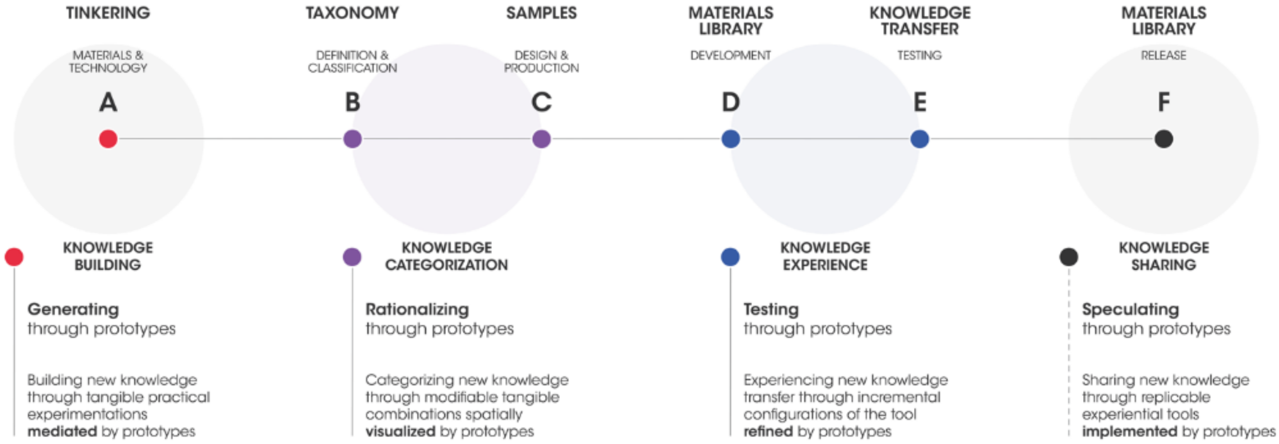

Figure 4: Contribution of prototyping in developing new Materials Libraries and their experiential knowledge transfer linked to the specific development phases.

Generating and detecting the experiential knowledge

The first step in developing a Materials Library aims to understand and select which knowledge should be transferred through the new tool. For emerging materials and technologies, it also means beginning the generative path to give them concreteness. At this starting point, tinkering with the materials and technology allows building this experiential knowledge through practical experimentations, directly experiencing them in the physical world (Fig. 4, Phase A).

Prototypes are, therefore, explorative media that usually do not even appear in the final version of the Materials Library, as for the two case studies (Fig. 5). They aim to progressively define the kind of knowledge to be transferred, encouraging re-iterations during the experimentation. This means trying different material formulations and tuning the processing parameters, both in a structured or non-structured way. Prototypes can represent failures and good results, as both options help understand what needs further investigation. They also contribute to making tangible the tacit knowledge behind these experimentations, including unexpected results from the setup. During this process, the researcher also intertwines their learning process as the first-person actor of the experimentation. This aspect includes dealing with first practical problems and troubleshooting and is strictly linked to the skills of the user behind the experimentation, showing similarities with the concept of digital craftsmanship. Experiencing this crafting path with materials and technology helps detect the tacit contents to be considered during the design process of a Materials Library.

Prototypes contribute to building new knowledge (knowledge building) at this stage. They make tangible these first experimentations, including the troubles, successes, and intermediate results of the iterative tinkering activity. They support knowledge building through tangible experimentations, acting as physical and concrete mediators of this iterative process.

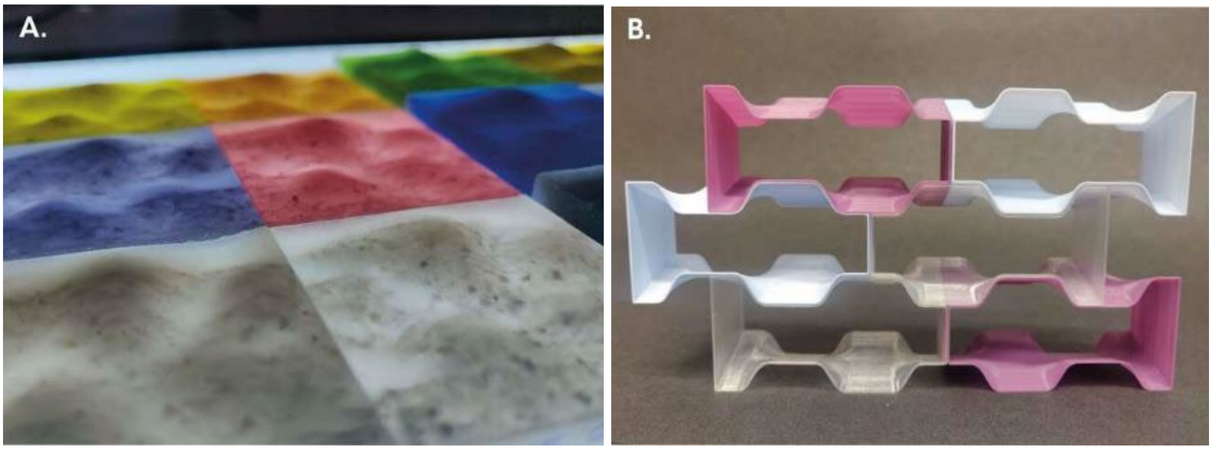

Figure 5: Preliminary prototypes during the tinkering phase with materials and technologies: (a) FiberEUse project Library and (b) RepMat Library case studies.

Categorizing and defining the taxonomy

The second step implies rationalizing and organizing the knowledge to be transferred through the new Materials Library. In this case, the selected knowledge should be categorized according to some meaningful criteria, leading to the definition of a taxonomy before designing the physical structure (Fig. 4, Phases B and C).

Prototypes are used to define possible classifications by combining them in multiple ways, following different criteria for the organization of experiential knowledge. This second approach in prototyping leads to producing some intermediate prototypes or even the final samples showcased in the Materials Library (Fig. 6). They aim to help find some classification criteria by interacting with them. The samples are directly experienced to assess their non-quantifiable aspects, i.e., expressive-sensorial qualities. They can also be used to design and try different taxonomies creating spatial structures to be replicated in the structure of the Materials Library, i.e., matrixes of samples. These interactions help in finding the criteria of the taxonomy and trying to rationalize their fruition. In this case, the different alternatives should be tracked to compare them and select the one that better matches the objectives of the new Materials Library. The researcher can use the experience from the previous tinkering phase to foresee some possible taxonomies, which would be validated or not by producing the prototypes. Experiencing this rationalizing path allows us to organize the tacit contents to be transferred with a Materials Library.

Prototypes contribute to this step in organizing new knowledge (*knowledge categorization*). Prototypes make tangible the classification criteria in the physical world. They help in categorizing new knowledge through modifiable tangible combinations by spatially visualizing the taxonomy.

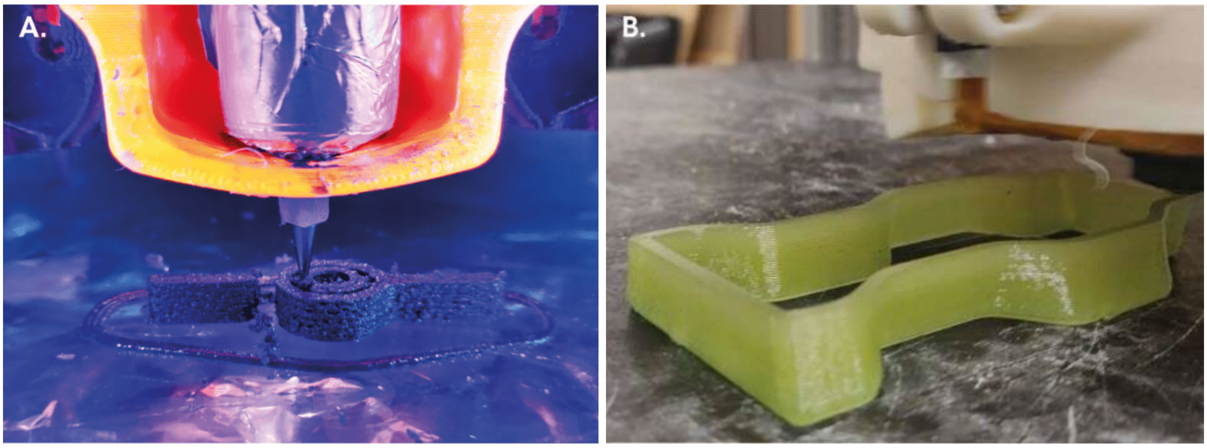

Figure 6: Fabrication of some intermediate prototypes to categorize the materials and process parameters: (a) FiberEUse project Library and (b) RepMat Library case studies.

Testing the experiential knowledge transfer

The third step focuses on designing the library's structure and its use to transfer new knowledge, influencing the experience of potential users with the samples. Developing and testing the physical configuration of the tool also means defining the interactions between the users and the contents (Fig. 4, Phases D and E).

Prototypes help in defining the final layout of the experiential tool. On the one hand, they can be details for testing a specific aspect of the Materials Library, i.e., the fruition of a specific textual or non-textual content. On the other hand, they may be rough versions of the whole product, aiming to refine it by testing it in the real world (Fig. 7). Their goal is to refine the Materials Library by considering it as a product to be developed and tested as in the design practice and industrial contexts. Hence, their use is strictly linked to the assessment and test of the provisional configurations of the library, improving the layout until reaching the final design. Tests may lead to a better understanding of how experiential knowledge is transferred, and iterations help refine this crucial aspect, especially by involving users in this path. The previous tinkering and categorizing experience of the researcher contributes to assessing the usability of the tool, making changes to improve the learning experience, and re-iterating tests. Experiencing this testing path improves the fruition of tacit content and knowledge transfer.

Within this step, prototypes contribute to refining the way to experience new knowledge (*knowledge experience*). They help test plausible interactions designed during the development of the Materials Library by trying and validating them. In addition, prototypes help in experiencing knowledge transfer through incremental configurations of the tool, refining its final design.

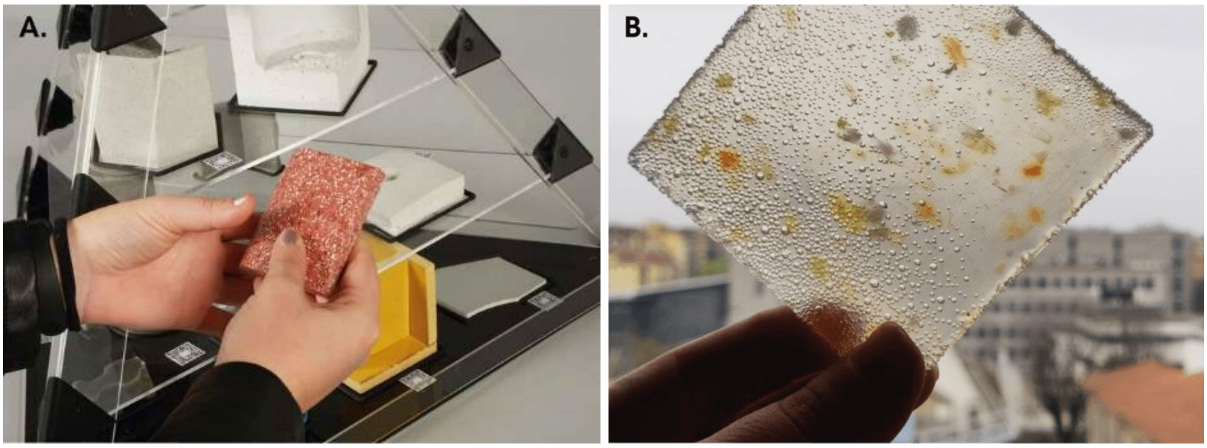

Figure 7: First prototypes of the Materials Libraries and their fruition to evaluate the knowledge transfer and user interaction: (a) FiberEUse project Library and (b) RepMat Library case studies.

Speculating on new ways of using Materials Libraries

A further step may be considered in developing new Materials Libraries, especially after the second case study. When dealing with emerging materials and technologies, the release of the library means starting a continuous process of modification and redefinition of the tool itself, according to the adaptive nature of the topic. This perspective leads to possible speculative reflections on different aspects, such as implementing new materials, technologies, and applications or envisioning new possible ways of developing and using the tool (Fig. 4, Phase F).

The final design of the tool can be seen not only as a prototype to be further refined and updated but even a *provotype*, a provocative prototype, to encourage participative work and hands-on activities (Boer & Donovan, 2012). As a *provotype,* the RepMat Library may foster critical reflections and collaborative ideation, engaging the users in a wider experiential path. The free replication of the library in distributed networks of local communities encourages the users to participate in knowledge sharing and democratizing experimental activities. Users can experience the creation of a Materials Library by replicating its structure and prototypes, trying a deeper kind of experiential knowledge transfer through practical engagement. Meanwhile, users are also participating in a collaborative process of knowledge building, making their experimentations with emerging materials and technologies tangible, generating new experiential knowledge to be shared and added. Experiencing this speculative path fosters the development of new tacit contents to be shared and new engaging paths in transferring experiential knowledge.

Finally, prototypes contribute to sharing new knowledge and speculative reflections (*knowledge sharing*), provoking new experimentations and replications. They help share new knowledge through replicable experiential tools, implementing and modifying them through distributed collaboration.

Conclusions

This work focused on the role of physical prototypes in designing new Materials Libraries to foster the experiential knowledge transfer linked to emerging materials and technologies. The different contributions of prototypes throughout the design process were investigated using a reflective practice approach on two selected practical case studies, the FiberEUse project Library and the RepMat Library.

Four different roles of prototypes were defined through this analysis. Prototyping contributes to (i) generating and detecting the experiential knowledge to be transferred through iterative tinkering activities (*knowledge building*); (ii) categorizing and defining the taxonomy of the Materials Library through spatial visualizations (*knowledge categorization*); (iii) testing the experiential knowledge transfer through concrete interactions in the real world (*knowledge experience*); and (iv) speculating on new possible ways of developing and using Materials Libraries through collaborative *glocal* actions (*knowledge sharing*).

Additional practical case studies should be considered to investigate further prototypes' roles in transferring new experiential knowledge. The analysis should also be performed by widening the perspective and considering different experiential tools, contexts, and users, i.e., non-designers. Nevertheless, prototypes represent a meaningful physical learning medium to tinker with materials or refine the configuration of the Materials Library and to conceive new ways of using these tools, fostering *glocal* collaborations to spread and build new experiential knowledge.

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