Material Library System for Circular Economy: Tangible-Intangible Interaction for Recycled Composite Materials

Alessia Romani, Fabio Prestini, Raffaella Suriano, and Marinella Levi

Abstract Currently the development of new circular materials has brought up the necessity to transfer their knowledge amongst the interested stakeholders for their real exploitation. This chapter aims to illustrate the design of a physical and virtual library system of the FiberEUse project. In particular, this library system wants to foster the development of new applications and value chains through the showcase of the new recycled composite materials and archetypal remanufactured products developed during the project. After the definition of the system concept, specific taxonomies were designed for the physical and virtual parts considering the technical properties and the expressive-sensorial qualities of the new recycled materials and products. A hierarchical organization was then designed to allow both tangible and intangible interactions with the samples, resulting in a coherent experience to explore these new recycled materials. Meanwhile, the physical exhibitors and the library website were developed to collect the physical and virtual samples. At the end, the whole system will be freely accessible through the library website and by booking a visit to the physical part. Thanks to its transdisciplinary nature, this system can stimulate the real exploitation of new value chains and applications.

Keywords Design for sustainability · Circular economy · Material library · Materials experience · Material driven design · Glass fiber reinforced polymers · Carbon fiber reinforced polymers

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1 Introduction, Motivation and Objectives

1.1 Knowledge Sharing of Circular Materials and Technologies

In recent years, socio-economic and environmental challenges have increasingly emerged and led to the affirmation of new ecologically correct development models, also named sustainable development models [1]. The first definition of sustainable development was given by the United Nations Commission on Environment and Development in 1987 as follows: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs", which should belong to the following sustainability dimensions: social, environmental and economic [2]. For this purpose, in 2015 the member states of the United Nations proposed and began to foster the 2030 Agenda for Sustainable Development. This resulted in the adoption 17 Sustainable Development Goals, which are based on the three sustainability dimensions [3]. Among sustainable development systems, circular economy has been identified in the literature as a paradigm with its own benefits and limitations [4–6]. The implementation of circular economy practices has led to the definition of at least the so-called 10 R-imperatives [7], among which Reuse and Recycling are ones of the most used in literature [8].

However, the use of circular materials is hindered by some barriers, which can be recognized in the identification of new solutions in waste management and materials recycling technologies [9]. More specifically, the development of circular products requires a better sharing of waste- and recycling technology-related knowledge as well as real collaboration between all the potential actors of the new circular product chains (i.e. designers, policymakers, managers, engineers, etc.). In the case of polymer composites, the perceived lack of recyclability or the limited choice between existing recycling technologies could also limit their further development, possibly leading to the progressive elimination from some market segments [10].

Composite materials are heterogeneous, being constituted by several components, which makes their disassembly a fundamental requirement for recycling. It consists of the product dismantling by separation of the material components. Moreover, the recycling processes can be non-destructive or destructive, depending on the final damage level of the components. Shredding is an example of a destructive disassembly process, and it is the most efficient and time-saving technique, even though it limits the possibility of material reuse, remanufacture and recycle due to its high damage level [11]. On the contrary, the material components can be undamaged if a non-destructive disassembly process is carried out. However, the non-destructive disassembly approach is difficult to be implemented, because it poses technical problems, such as strict tool requirements and high operational costs. Usually, a partial disassembly process is employed to sort only the main material components, which can be reused. In addition to the recycling technologies, several consolidated or non-conventional processes can be employed to create new value-chains starting from new recycled polymer composites (i.e. extrusion-based additive manufacturing) [12, 13].

Considering the complexity of circular economy system and the numerous involved players, it is therefore evident that the development of new circular materials, in particular reinforced polymers, and value-added market segments is strictly related to the possibility of showcasing the real technological solutions to all the potential stakeholders. This will encourage the real exploitation of products and materials composed of recycled Glass Fiber Reinforced Polymers (rGFRPs) and recycled Carbon Fiber Reinforced Polymers (rCFRPs).

1.2 Research Goal: Materials and Products Showcase from FiberEUse

This chapter aims to stimulate the scouting of new added-value markets through the showcase of the results achieved within the FiberEUse project. For this reason, a physical and virtual library system was realized including the new recycled materials and the archetypal remanufactured products made with rGFRPs and rCFRPs. The main goal of the library system is to foster the development of new applications and value-added markets by showcasing the main results of the FiberEUse project to all the potential stakeholders that could implement these solutions in new value-chains (i.e. designers, engineers, technicians, industries, and so on). In other words, the purpose of the library system is to encourage the real exploitation of new products and materials made of rGFRPs and rCFRPs by sharing their knowledge through a freely accessible physical and virtual library system.

A taxonomy was deeply studied to classify these parts according to the materials (recyclate fibers and matrix), the manufacturing technology, the process conditions, the surface finishing, the post-processing, and the field of application of the products. Generally speaking, the materials, technologies, and demo-cases developed in the previous experimental activities were considered for inclusion in the library system.

The two main parts of the library system (the physical and the virtual ones) were then created to be available to all relevant European stakeholders involved in the composite sector. Moreover, this library system will be set up and continuously updated. As a matter of fact, the library system is available for all the interested stakeholders according to the different fruition of the two parts, the physical and the virtual parts. The first one can be used, seen, and touched at Politecnico di Milano upon reservation, while the second one can be found at: https://fibereuselibrary.com/.

2 Positioning of the Solution

2.1 Aim of a Material and Product Library

Currently, the real exploitation of new circular materials has been assuming a key role in fostering sustainable models of production and consumption. For this reason, the relevant knowledge related to these materials should be shared to foster the development of new applications. However, their knowledge is not yet well-established amongst the potential stakeholders that could generate new value-chains such as designers, practitioners, and engineers. Furthermore, rGFRPs and rCFRPs are mainly characterized from a technical point of view with little consideration of other important aspects. Indeed, there is a considerable amount of literature on the importance of the material surface finishing for the perception of new products. As a matter of fact, a specific material does not only affect the functional features of a product, but also its expressive-sensorial qualities. While the first ones are strictly related to quantitative data and analysis, the latter ones are more intangible and often measured by means of qualitative methods of investigation [14, 15].

Human perception strongly affects the expressive-sensorial qualities of a material, that mainly derives from the senses, especially from vision and touch. Moreover, perception could subjectively change, according to the specific context or user background [16, 17]. Despite the intrinsic qualitative nature, quantitative technical properties (i.e. physical and chemical properties) play an important role in the perception of a specific material [18]. Therefore, technical properties and expressive-sensorial qualities are equally fundamental for the design of new products, and several studies developed new tools for the material selection by merging these two aspects [19–21].

For these reasons, the attention on the expressive-sensorial qualities is increasingly growing amongst all the stakeholders involved in the product development process. Because of different expertise and level of engagement in the design phases, misunderstandings could be frequent. As a matter of fact, the description of some sensorial aspects with quantifiable physical properties can be extremely challenging and inaccurate. On the contrary, physical samples give the possibility to directly experience expressive-sensorial qualities avoiding the loss of sensorial information [22, 23]. However, some issues should be considered. For instance, managing a large quantity of samples without a well-defined taxonomic classification may lead to confusion.

In this complex scenario, material libraries assume a crucial role. As the term suggests, these libraries collect and showcase different material samples organized according to one or more criteria. In this way, materials can be explored and selected with a strong interdisciplinary approach, taking into consideration both technical properties and expressive-sensorial qualities [17, 24, 25]. On the one hand, material libraries are similar to databases, and help designers and engineers during their activities. On the other hand, they represent a *lingua franca* for the material-oriented professionals, and translate unquantifiable sensorial data without any ambiguity.

For some aspects, material libraries are able to lead materials from the development to their real application [24]. As a matter of fact, they can promote the use of a new material by spreading its knowledge amongst the stakeholder. Thanks to the physical samples, designers can directly understand how to best consider new materials for the design of new products. Especially for recycled materials, this point becomes actually more relevant, since the overall perception of a designed product may be strongly affected by the recycling and remanufacturing processes. For this reason, designers should be aware of the possibilities allowed by the recycled materials thanks to the direct approach that a material library offers.

Recently, a circular material library was designed with this specific purpose. One of its peculiarities is that it includes both material samples and prototypes. Moreover, only recycled materials are showcased in order to demonstrate that virgin ones can be replaced in the existing value-chains [26]. Similarly, the aim of FiberEUse is the demonstration of new value-chains based on the recycle of composite materials. As a consequence, a material and product library system would be a suitable way for the showcase of the complex framework within FiberEuse. As can be imagined, this kind of material library should consider the new recycled materials together with the developed products, giving an exhaustive idea of the real design application.

2.2 *Tangible and Intangible Fruition of a Material Library*

Although the tangible interaction with the material represents the key point of each material library, this experiential learning method is not always possible or even the most reasonable. Actually, this can be influenced by several economic, social and environmental aspects.

Generally speaking, a material library can be considered as a linking point amongst different stakeholders, i.e. the waste producers and the design practitioners, and it is meant to be consulted more than once during the whole design process and value-chain creation. As a result, several reasons could motivate the use of a material library: from the inspirational seeking in the early stages of design to the material selection during the product development phase. Since a material library is generally placed in a physical space, each interested stakeholder should at least book its use and plan to visit the physical space. However, some external factors may hinder this physical fruition and, consequently, the handling of the samples. As an example, the current situation due to the Covid-19 pandemic has strongly reduced the travelling possibilities of the individuals, hence the in-presence activities have been also affected, including the use of these experiential learning tools [27, 28]. As for other contexts (i.e. education), the knowledge-sharing activities shifted from physical to virtual spaces, and most of the them have been carried out in virtual settings by using different tools, websites and virtual meetings software. Focusing on the material libraries, the design of meaningful intangible experiences therefore represents the main issue to overcome, especially considering the lack of tangible interactions with new materials.

Even if the virtual material tinkering cannot fully replace the tangible fruition of the physical samples, it could be seen as a valid alternative for the early phases of the design process, or even a complementary part of an integrated system that can be used regardless of the specific historical situation. Currently, some consulting companies developed virtual databases that showcase different material samples through pictures and technical datasheets. Moreover, some of them have been connected to the corresponding physical material libraries [29, 30]. This results in a wider experience that allows to preliminary browse the materials and to handling the physical samples at later stages, including both intangible and tangible interactions. To sum up, this opens the way for a paradigm-shift toward the concept of "material library system".

3 Methods and Workflow

3.1 Approach and Workflow

Within this project, the following terms were used to distinguish the different kinds of materials (Fig. 1a):

- Waste: materials from End-of-Life (EoL) products provided by the "waste producers", which means Gamesa Renewable Energy S.A. (GAM), Aernnova Aerospace (AER), and Rivierasca S.p.A. (RIV);
- Recyclates: mechanically and/or thermally recycled composites provided by the "recyclate producers", which means Consiglio Nazionale di Ricerca—Sistemi e Tecnologie Industriali Intelligenti per il Manifatturiero Avanzato (STIIMA-CNR), Tecnalia (TEC), and RIV. They can be constituted by either shredded glass fiber reinforced polymers or recycled carbon fibers;
- Recycled materials: new composite materials reinforced by the recyclates.

The workflow of the experimental activities is resumed in Fig. 1b. First, the partners of the consortium that developed the materials, technologies, and products were contacted to collect all the relevant data for the library system. A hierarchical taxonomy system was then designed for the whole library system according to the provided materials (i.e. technical information about the materials and the remanufacturing process, 3D models, physical samples, pictures, and rendering). Later, specific taxonomic rules were defined according to the different interactions of the stakeholders, hereinafter considered as the main target user of the system, with the physical and virtual parts of the system (i.e. physical fruition of the samples, virtual tour of the products). At the same time, the physical and virtual samples were created according to common guidelines. Then, the physical and virtual exhibitors of the library were designed and developed (physical stands and website) to facilitate the showcase of the samples for the stakeholders. In the end, the link between the physical and virtual parts of the library system was checked and fixed to ensure the coherence of the contents.

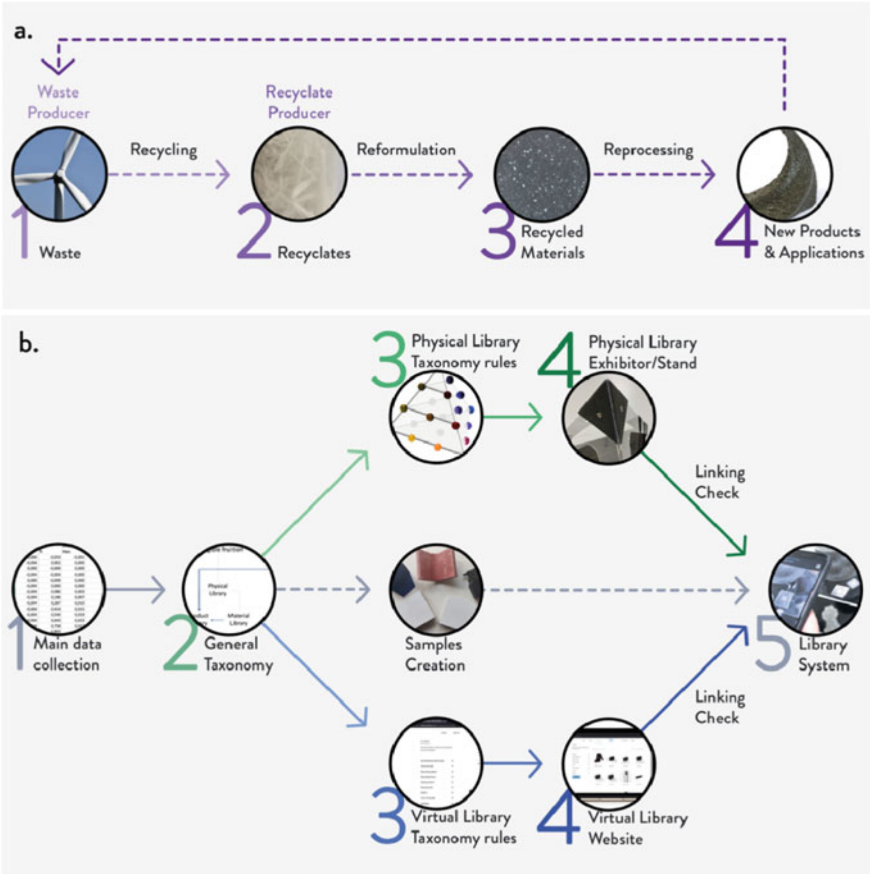

Fig. 1 Main workflows of this work: **a** terminology of the different kinds of materials; and **b** organization of the experimental activities related to the development of the library system

3.2 Physical Library

The Physical library collects the physical samples of the materials and products developed within the project. To better understand the background, a preliminary literature review on the existing material libraries was carried out, especially focusing on the different materials and information showcased. As mentioned before, these libraries are mainly focused on the showcase of different materials rather than products. Furthermore, their taxonomic organization is not always easily recognizable, and each library has its own taxonomy according to the specific samples. Nevertheless, a material library should encourage to see, touch, and compare the physical samples through several aspects, i.e. the process parameters, the visual qualities, the finishing. In most of the cases, the physical samples have similar shapes and dimensions, since the shape itself can strongly affect this experiential comparison. Contrarily, a product library could take advantage of different shapes (and products) because they represent multiple ways to exploit a specific kind of material and/or process. For these reasons, two different paths were followed for the realization of the Physical Material Library and the Physical Product Library. In detail, the Physical Material Library contains flat samples (dimensions: 75 × 75 × 6 mm), while the Physical Product Library is made of cut-off or scaled parts of existing products (dimensions: 80 × 80 × 80 mm max). This dimensional homogeneity allowed to easily manage the spaces of the Physical Library and facilitates their physical handling for comparisons.

The physical material samples were realized by pouring the reinforced polymer in 3D printed molds. The same thermosetting matrix was chosen for the samples to allow the comparison of the recycled fibers. Diverse types and percentages of the recyclates were added to the matrix, and different post-processing was carried out onto the hardened samples. The following ranges for the fiber parameters and post-processing methods were considered:

- Recyclate type: rGF from EoL wind turbine blades (waste producer: GAM; recyclate producer: STIIMA-CNR), rGF from EoL structures (waste and recyclate producer: RIV), rCF from expired prepreg (waste producer: AER; recyclate producers: TEC and STIIMA-CNR);
- Recyclate dimensions: from < 100 μm to 4 mm, long fibers/textiles;
- Recyclate percentage: from 20 to 50% by weight (wt%);
- Post-processing: no post-processing (matte finishing), sanding (matte finishing), gelcoat (glossy finishing), painting (matte and glossy finishing).

The physical product samples were made by the partners of the consortium according to the products from FiberEUse. The samples were cut off to give a dimensional homogeneity of the samples to be handled. A spatial taxonomy based on four different variables was designed to consider the differences related to the specific materials and processes. Different "process units" were created by considering:

- Recyclate type: rGFRPs and rCFRPs;
- Remanufacturing processes: 3D Printing (Liquid Deposition Modelling), Casting, Injection Molding, Lamination, Reuse of components;
- Recyclate dimensions: < 100 μm to 4 mm, long fibers/textiles;
- Recyclate percentages: from 20 to 65 wt%;
- Post-processing: no post-processing, sanding, gelcoat, painting, metallization by PVD (Physical Vapor Deposition);
- Specific process parameters related to some remanufacturing processes: layer height and printing mode (3D Printing), mold finishing (fine-coarse);
- Shape complexity: according to the specific remanufacturing process.

A further literature review was performed to design the taxonomies of the Physical Material Library and Physical Product Library. In particular, the preliminary concept of the latter one is inspired by the spatial color systems (i.e. Munsell color system, the NCS—Natural Colour System®), where the three dimensions represent different parameters, and the spatial position of a specific color is represented by the variation of these three combined parameters. The physical realization of the library was designed by using a CAD software. The custom parts were created by using a desktop 3D printer and laser cutting, and they were then assembled to create the stands of the Physical Library. At the end, a set of QR codes was placed near the physical samples to easily visualize the product and material data.

3.3 Virtual Library

The Virtual Library is a way to virtually collect the samples of the Physical Library, aiming to showcase the samples of the products and materials from FiberEUse. Firstly, a preliminary literature review on the existing virtual material libraries has been carried on and, at the same time, the main tools to design them were searched.

This research brought to three main conclusions. First of all, the core of all the existing library systems is a single database, rearrangeable with some filters. Secondly, the research underlined how much important is to design a User Experience that simplifies the actions that the user needs to find what is looking for. This does not mean that the user must be driven, but that the design of all the needed actions should be precise. Finally, while designing a website, it is particularly important to amaze the user or, at least, to engage him as much as possible to bring him back on the website.

As the number of samples to be showcased in the Virtual Library was substantial, the easiest and fastest way to build a website without coding, i.e. WordPress (https://wordpress.com/it/), was selected and used. As a matter of fact, this choice allows the integration with WooCommerce (https://woocommerce.com/). This plugin is designed for online shops, but it has a lot of useful tools for complex databases, hence for the Virtual Library. The key feature of WooCommerce is filtering. As previously said, the core element of a virtual database is the presence of filters and WooCommerce allows to easily manage a lot of them.

To manage user interactions to the virtual library, a 360° visualization was added for each product by using a set of nine renderings for each product and a JavaScript developed and shared by 3d web (https://3dweb.nl/). At the same time, the most important part of the work was set, which means the design of the whole experience. For this part, a tool to build quick prototypes and test them with people, called Figma, was used to have first insights of the work done. Finally, surveys were conducted using Google Forms (https://www.google.com/forms/about/) to assess the overall experience related to the use of the Virtual Library.

4 FiberEUse Library System

4.1 From a Library to an Integrated System of Libraries

According to the main goal, a library system was developed to encourage the spread of new applications and value-added markets starting from the results achieved within this project. As mentioned before, the idea of an integrated system of libraries derives from the well-known concept of "material library". From literature, this term refers to an organized collection of samples that allow to showcase, compare, and explore the main technical properties and experiential qualities of one or more materials. Hence, diverse kinds of knowledge can be compared (i.e. mechanical properties, visive and tactile qualities) with a direct experience of the stakeholder that can handle the different samples for an experiential assessment of the potential exploitation. This concept could be used also for the new materials from EoL products developed during the FibeEUse project. However, concrete examples of new applications are generally not part of a material library although their presence may bring additional details on how to best use a specific material. Indeed, their presence could stimulate new different ideas by the users, and, at the same time, they could show some technical features and constraints derived by the material itself and/or the remanufacturing process. The library can also be a point of contact between a future interested customer and the expert who has manufactured the material or the industry that has manufactured the demonstrator. Last but not least, the consultation of a material library can be affected by several economic, social, and environmental factors that do not allow the stakeholders to be physically present or to directly handle the physical samples, i.e. the recent global situation related to the Covid-19 pandemic [27, 28].

For these reasons, an integrated system of libraries was designed and created to merge materials and products on one side, and the physical and virtual fruitions on the other. In this way, distinct levels of fruition can be offered to the stakeholders, reaching a broader scale of potential users. Figure 2a shows the general organization and connection of the library system. According to the different fruition, two parts of the system were developed: (i) a Physical Library linked to the tangible fruition, which means the in-person handling of physical samples; and (ii) a Virtual Library linked to the virtual fruition, which means the remote consultation of virtual samples (i.e. 3D models, pictures, renderings, technical datasheets). In turn, the Physical library is divided into two main parts: (i) a Physical Material Library that contains the physical samples of the new materials from EoL products; and (ii) a Physical Product Library that contains the physical samples of the products developed within FiberEuse. In the same manner, the Virtual library contains the pictures of the new materials and the renderings of the products in the Virtual Material Library and Virtual Product Library, respectively. In addition, the information of the recyclates is shown in the Recyclate Library, as a part of the Virtual Library. Figure 2b represents the various kinds of knowledge that the system gives to the users.

On the one hand, the Physical Library adds the experiential dimension to the showcased materials and products related to the senses and the direct handling of the

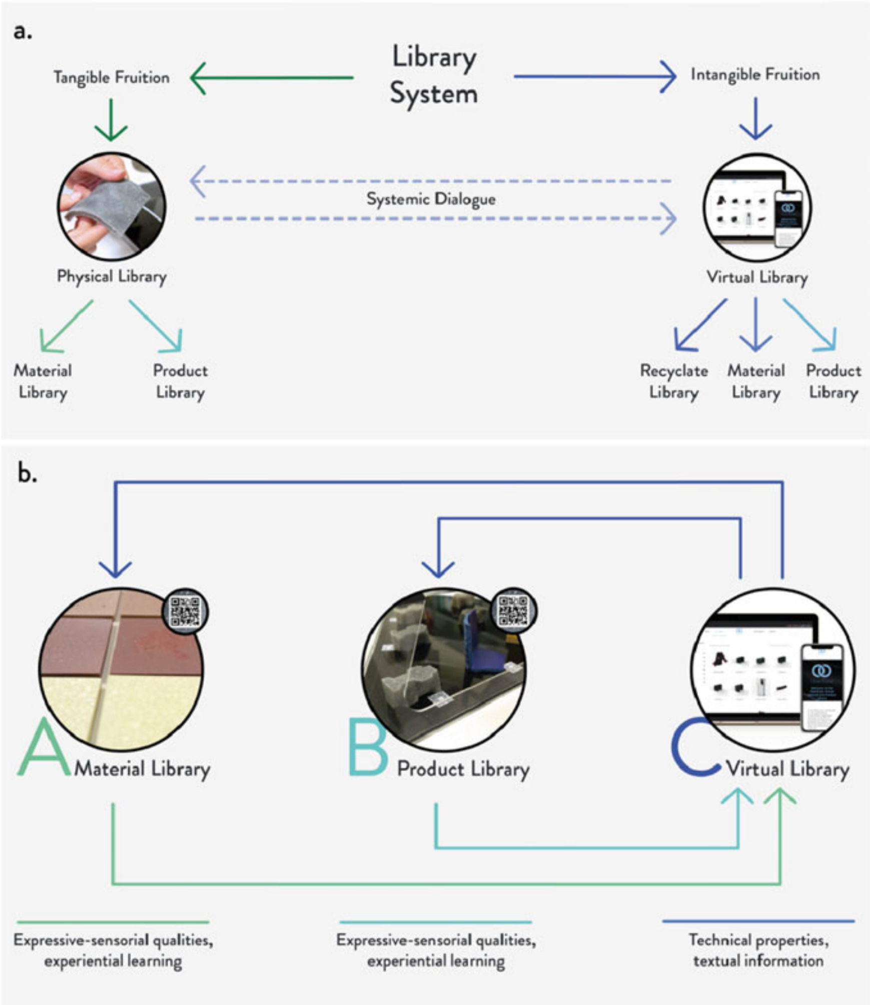

Fig. 2 Library system: **a** general organization and connection of the parts; and **b** the different kinds of knowledge provided by the various parts of the system

samples (Fig. 3a). On the other hand, the Virtual Library gives all the information and quantifiable properties of the samples. This can be possible using a set of QR codes linked to the website of the Virtual Library (Fig. 3b). To sum up, the two libraries, the physical and the virtual ones, can be used separately, but the most complete experience and the highest knowledge transfer can be achieved only through the joint fruition of both parts.

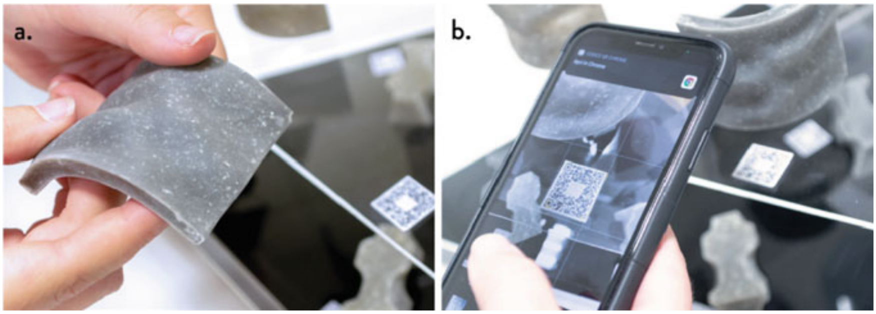

Fig. 3 Showcasing of the library system: **a** direct handling of the Physical Library; and **b** use of the QR codes for the fruition of the Virtual Library

4.2 Physical Library

Physical Material Library. As previously mentioned, the physical material library aims to showcase the recyclates and the recycled materials that the stakeholders can exploit for new applications. For this reason, three variables mainly related to the materials were selected for the taxonomy: recyclate dimension, recyclate percentage, and post-processing.

The resulting samples were organized in different matrixes to let the user make a direct comparison of the samples. To sum up, the Physical Material Library is made of 99 different flat samples divided in three main clusters, as shown in Fig. 4. Further details about the variables and parameters are resumed in Table 1.

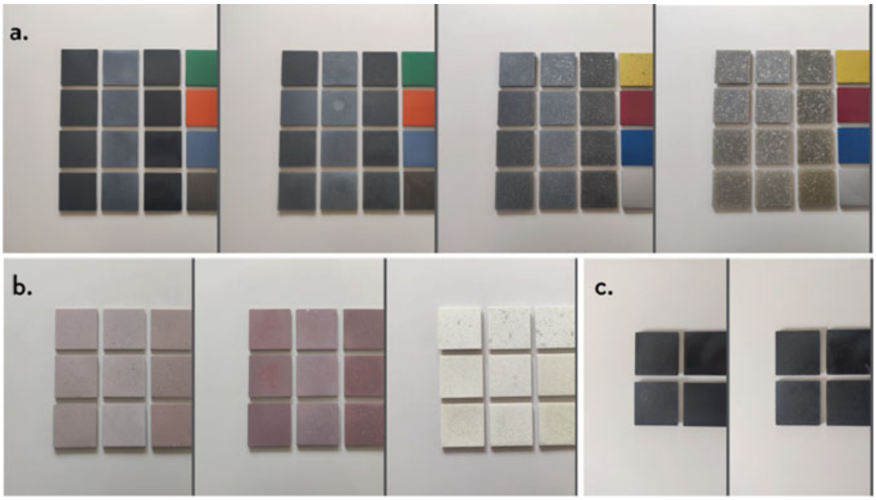

Fig. 4 Physical Material Library: **a** rGFRPs from EoL wind turbine blades; **b** rGFRPs from EoL structures; and **c** rCFRPs from expired prepreg

Table 1 Physical Material Library: the three clusters, the variables and the specific parameters

Fiber	Waste (Cluster)	Variables and parameters
rGFRP	EoL wind turbine blades (64 samples)	1. Recyclate percentage: 20, 30, 40, 50 wt%; 2. Recyclate dimension: 80 μm, 200 μm, 1 mm, 4 mm; 3. Post-processing: no post-processing (matte finishing), sanded (matte finishing), gelcoat (glossy finishing), painting (matte and glossy finishing)
rGFRP	EoL structures (27 samples)	1. Recyclate percentage: 20, 30, 40 wt%; 2. Recyclate dimension: 100 μm, 100 μm with contaminations, 4 mm; 3. Post-processing: no post-processing (matte finishing), sanded (matte finishing), gelcoat (glossy finishing)
rCFRP	Expired prepreg (8 samples)	1. Recyclate percentage: 20, 40 wt%; 2. Recyclate dimension: 100 μm, long fiber textile; 3. Post-processing: no post-processing (matte finishing), gelcoat (glossy finishing)

Physical Product Library. In this case, the physical product library is focused on the showcasing of the technical and experiential possibilities that can be achieved by using the materials shown in the physical product library, especially related to the remanufacturing processes investigated within the FiberEUse project. As a matter of fact, a specific process strongly affects not only the feasibility of a single product but also the expressive-sensorial qualities of the final shape.

For the taxonomic organization, other catalogs and databases were studied to understand the rationale behind complex cataloging systems of samples. Considering the different nature of the processes involved during the project, a unique taxonomy may be not enough to give an exhaustive idea of each process. Hence, a more flexible solution was required, and the starting concept of the taxonomy was built on a system made of different process clusters with the same taxonomic structure based on the most relevant variables of the specific process and/or material.

The basic structure of this concept is a triangle area with three different variables at the vertexes. Each of them can vary along the three sides of the triangle. This variation creates a coordinate system. In the beginning, a number of variations can be defined (i.e. 3, 5, …), and this number of variations defines the same number of points along the three sides of the triangle, including the vertexes. Then, the segments parallels to the three sides are created by coupling those points, generating a triangular grid. Each intersection represents a sequence of three values, one for each variable, and represents the position of a specific product. A sample can be therefore defined through the combination of the three variables (i.e. recyclate dimensions, recyclate percentages, and post-processing), and each specific variable changes along its corresponding side of the triangle. In addition, the number of the samples, representing a single variable, varies from more pieces along the side to a single object at the vertex, which represents the most complex variation to be achieved with the specific process.

Nevertheless, three variables were not enough to showcase all the possibilities that a specific remanufacturing process can achieve. For this reason, a fourth variable was added, creating a tetrahedral structure. The same concept of the planar taxonomy can be applied to this 3D visualization, creating a four-variable coordinate system, where each sample is described by four values of the variables. In this case, the fourth variable is the same for the entire system, here defined "shape complexity". This variable is an arbitrary value related to the shape and the technical features of a specific product according to the selected process: the more the part is complex to obtain with the process or requires further steps, the more the part will be near to the fourth vertex. This hierarchical spatial taxonomy is resumed here below. Figure 5a represents the triangle unit of the taxonomic organization with the three variables at the vertexes, while the examples of the planar coordinate system and the tetrahedral structure derived from the four-variables system are shown in Fig. 5b and c, respectively.

The Physical Product Library is made of 73 different cut-off or scaled parts of products that are organized according to the hierarchical taxonomy based on four different variables (and previously explained). Two main clusters can be detected according to the fiber type obtained from the EoL waste, which means:

- Glass Fibers (3 tetrahedral structures shown in Fig. 6a): "Liquid Deposition Modelling—3D printing" structure, "Casting" structure, "Lamination and Injection Molding" structure;
- Carbon Fibers (2 tetrahedral structures shown in Fig. 6b): "Casting and Injection Molding" structure, "Reuse" structure.

Further details related to the variables and the parameters are resumed in Table 2.

4.3 Virtual Library

Virtual Product Library. The Virtual Product Library mainly contains the samples of the Physical Product Library, but it differs from the corresponding physical part for the different interaction. First of all, the samples are not organized following the same specific taxonomy of the Physical Product Library. Since the fruition of the two parts (the physical and the virtual) changes a lot, the samples of the Virtual Product Library are arranged in a cluster.

A series of filters, the "Virtual library organizers", was then designed based on the taxonomy of the Physical Library, considering the different contexts of use related to the virtual fruition. By changing them, the cluster of samples changes and so the library will display only that section of products identified through the filtering actions selected by the user. They can be grouped into the following three main categories: (i) Manufacturing processes; (ii) Recyclates; and (iii) Recycled materials. Further details about the filters of these categories are described in Table 3.

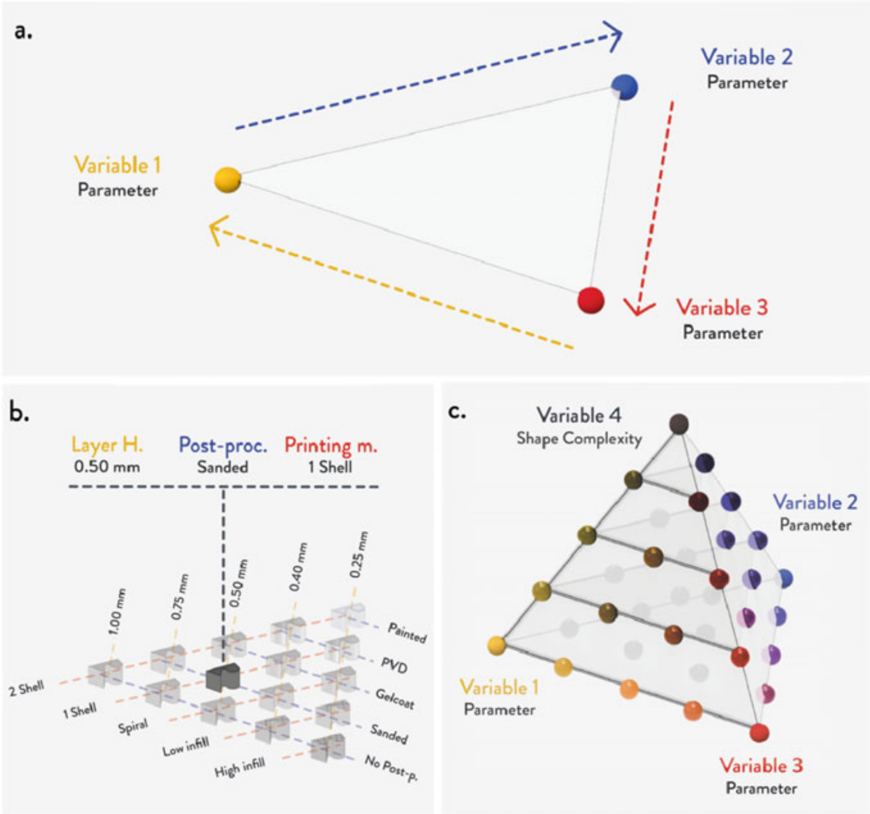

Fig. 5 Physical Product Library spatial taxonomy: **a** basic structure of the spatial taxonomy with 3 variables; **b** example of the planar coordinate system (3D printing); and **c** basic structure of the spatial taxonomy with 4 variables

To simplify the user's experience in finding what he is looking for, three distinct colors were selected to identify the different kinds of recyclate with an immediate visual inspection in addition to the filters. In this way, the user can easily recognize which recyclates were employed to develop the products and the corresponding waste and recyclate producers thanks to the identification of the colors. Accordingly, a common visual identity was designed for each product page. For this reason, mostly realistic renderings on a white background were used. These renderings are also useful for a 360° visualization of the products. This allows to better visualize the products and, at the same time, to engage the user during the fruition. Furthermore, each product has a data chart with all the information about the production, the material, and the recyclate. Figure 7 a shows a preview of the webpage with the filters and clusters of the Virtual Product Library, while an example of the 360° visualization of the products is visible in Fig. 7 b.

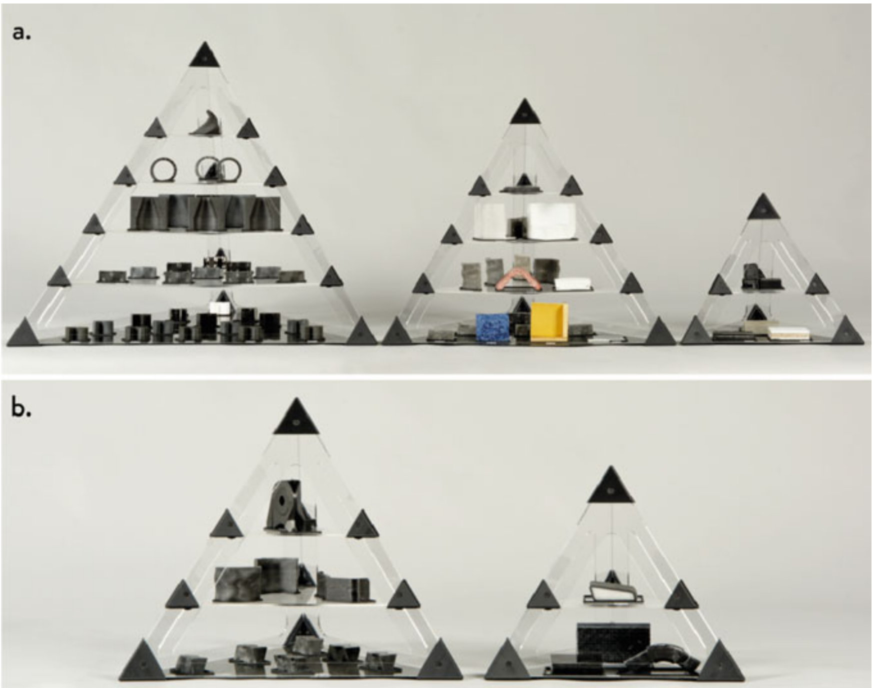

Fig. 6 Physical Product Library: **a** GF structures (from left to right: "liquid deposition modelling—3D printing, casting, lamination and injection molding); and **b** CF structures (from left to right: casting and injection molding, reuse of components)

Virtual Material Library and Recyclate Library. The Virtual Material Library was designed to showcase the variations related to the recycled material itself, in particular to the concentration of the recyclates types: rCFs and shGFRPs (shredded glass fiber reinforced polymers, rGFRPs). By changing the recyclate size and percentage and trying different finishes, the recycled material changes not only for its specific technical properties but also considering its expressive-sensorial qualities. Although this experiential investigation can be done through the Physical Material Library, it is interesting to show this aspect in a section of the website for a complete overview of the recyclate materials. As mentioned before, the same matrix material (epoxy resin) was chosen to better compare the recyclates.

In this section, there are only two filters for the classification of the sample pictures: rCF and shGFRP fibers. The main data related to the recycled materials are displayed through the name of the specific sample. As an example, the image below (Fig. 8) shows the name of one of the samples: "shGFRP 50% 4 mm—from mold". In this case, "shGFRP" indicates the recyclate type, "50%" the weight percent of recyclate, "4 mm" the recyclate size (fibers length), and "from mold" the finishing (in this case, no post-processing).

Table 2 Physical Product Library: the five tetrahedral structures, the variables and the specific parameters

Fiber	Cluster	Variables and parameters
rGFRP	Liquid deposition modelling 3D printing (35 samples)	1. Layer height: 0.2, 0.4, 0.5, 0.75, 1 mm; 2. Printing mode: two shells, one shell, spiral, low infill, high infill; 3. Post-processing: no post-proc. (matte finishing), sanded (matte finishing), gelcoat (glossy finishing), PVD (metallic glossy finishing), painting (glossy finishing); 4. Shape complexity: Five different 3D models from the base to the top of the tetrahedral structure
rGFRP	Casting (20 samples)	1. Recyclate percentage: < 35, 40, 45, > 50 wt%; 2. Recyclate dimensions: 80 µm, 1 mm, 2 mm, 4 mm; 3. Post-processing: no post-proc. (fine matte finishing), no post-proc. (rough matte finishing), sanded/polished (glossy finishing), PVD (metallic glossy finishing); 4. Shape complexity: 11 different 3D models from the base to the top of the tetrahedral structure
rGFRP	Lamination and injection molding (4 samples)	1. Recyclate percentage: 25, 30 wt%; 2. Recyclate dimension: 1, 5 mm; 3. Finishing: fine, rough; 4. Shape complexity: 4 different 3D models from the base to the top of the tetrahedral structure
rCFRP	Casting and injection molding (10 samples)	1. Recyclate percentage: 20, 30, 40 wt%; 2. Recyclate dimension: < 100 µm, > 100 µm, 1 mm; 3. Post-processing: no post-proc. (fine matte finishing), no post-proc. (rough matte finishing), sanded/polished (matte finishing); 4. Shape complexity: 4 different 3D models from the base to the top of the tetrahedral structure

(continued)

Table 2 (continued)

Fiber	Cluster	Variables and parameters
CFRP	Reuse (4 samples)	1. Fiber percentage: 50, 65 wt%; 2. Process: Infusion, pultrusion; 3. Post-processing: no post-proc. (matte finishing), gelcoat (glossy finishing); 4. Shape complexity: 4 different 3D models from the base to the top of the tetrahedral structure

Table 3 Virtual Product Library: the filters categories, namely the "Virtual library organizers"

Filter category	Filters
Manufacturing processes	1. Re-Manufacturing Processes: additive manufacturing, closed mold pressing, compression molding, continuous lamination, indirect manufacturing, infusion, injection molding, open mold casting, pultrusion, spray lay-up; 2. Producers: the consortium partners
Recyclates	1. Recyclate type: shGFRP or rGFRP, rCF, CFRP; 2. Recyclate producers STIIMA-CNR, TEC, RIV; 3. Recycling process: mechanical shredding, pyrolysis, reuse; 4. Waste producers: AER, GAM, RIV
Recycled materials	1. Recyclate size: 80 µm, 100 µm, 200 µm, 1 mm, 2 mm, 4 mm, 5 mm, 6 mm, long fiber textile; 2. Composite matrix: acrylic, epoxy, polyamide, polyester, polypropylene, polyurethane, orthophtalic unsaturated polyester; 3. Recyclate percentage: 20, 25, 30, 35, 40, 45, 50, 55, 65 wt%; 4. Finishing: not required, gelcoat, painted, sanded, PVD

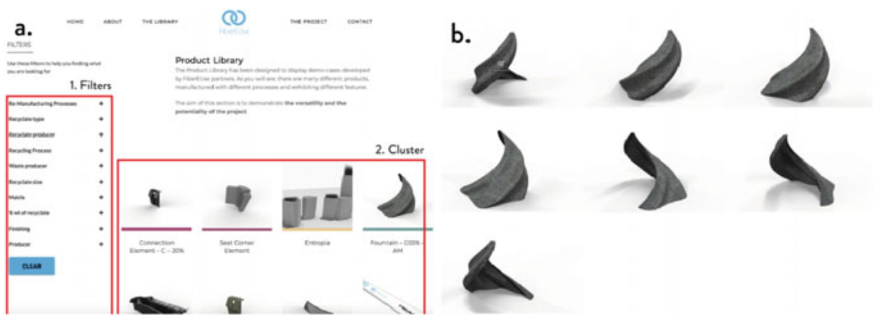

Fig. 7 Virtual Product Library: **a** preview of the webpage with the filters and clusters; and **b** example of the 360° visualization of the products

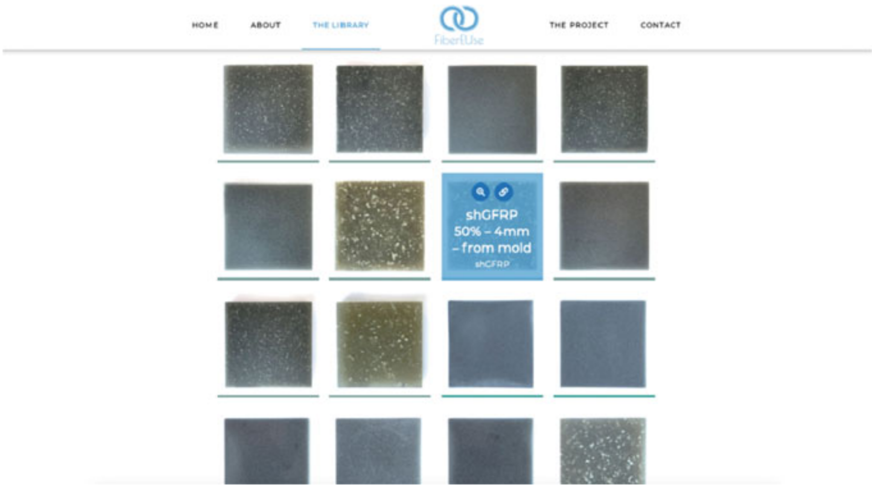

Fig. 8 Virtual Material Library: main page with the info from the Physical Material Library

Generally speaking, each recycled material of the library system is composed of a matrix and a type of recyclate. Each recyclate has its own features, and therefore it was important to better clarify them in a separate page. This page, named Recyclate Library, is linked to the Virtual Material Library and shows the technical information needed to understand the composition of each sample.

Virtual Library Website. The other pages of the website are meant to summarize the FiberEUse project and give an overview to arouse the user's curiosity. In general, the developed website was well received either by partners of FiberEUse and general users. Both the User Interface and the User Experience were designed to ease the user's navigation through the products through a neat and clean interface. This should allow its fruition from a large range of users. As a matter of fact, the Virtual Library has turned out to be interesting for a wide range of users: from naïves to materials-oriented professionals such as technicians, designers, engineers. In this case, the extensive work performed to summarize the contents (data and renderings), the tests and surveys done for each step of the process, and the collaboration between all the partners played a crucial role in determining the success of the Virtual Library and, consequently, of the whole library system.

5 Conclusions and Future Research Perspectives

This chapter aimed to illustrate the integrated library system developed within FiberEuse project. This material and product library system was designed to showcase the main output of the project. In short, it consists of a physical and a virtual part that are interconnected to communicate, and it contains the recycled materials and the archetypal remanufactured products made with rGFRPs and rCFRPs.

First, a brief theoretical perspective on the concepts of material libraries and library system was provided. After the collection of the data from the consortium partners, a preliminary concept of the library system was defined considering the physical and virtual fruition of materials and products. In detail, a hierarchical organization of the virtual and physical contents was designed to combine the physical and virtual fruition for a complete experience with the samples. Specific taxonomies were then defined considering the specific divisions of the library system (i.e. Physical Material Library, Physical Product Library, Virtual Material Library, Virtual Product Library, Recyclate Library). The virtual and physical samples were firstly produced and collected by Politecnico di Milano and the consortium partners and then placed in custom exhibitors, which means the physical stands and the library website. Finally, the coherence of the link between the physical and virtual parts was checked to ensure the right interconnection of the whole system.

Through this library system, new applications and value-added markets can be investigated to exploit the main results of the FiberEUse project. This tool can be seen as a way to facilitate the real exploitation of new products and materials made of rGFRPs and rCFRPs through the sharing of knowledge that it allows. As a matter of fact, the system will be freely accessible for the stakeholders through the library website and booking the consultation of the physical samples. Also, this system will be updated by the consortium partners with new products and/or materials, fostering the generation of new value-chains linked to the composite market.

In detail, the classified sample collection of the library system comprehends: (i) 99 material samples of three different kinds of recyclates in the Physical Material Library; (ii) 73 different samples of 28 products in the Physical Product Library; (iii) 8 recyclate samples from different EoL composites in the Recyclate Library; (iv) 99 material samples of three different kinds of recyclates in the Virtual Material Library; and (v) 89 different samples of 33 products in the Virtual Product Library. To conclude, this system can be considered a valid tool to foster the development of new real applications and follow-ups thanks to its transdisciplinary nature, merging technical and expressive-sensorial aspects with tangible and intangible materiality.

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