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EDITORS:
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Forming bacterial cellulose: a research activity exploiting digital fabrication technologies

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Bacterial Cellulose (BC) is a material gaining increasing interest in design research. Being produced by the fermentation of Kombucha tea, it is classified, as others, as "growing material". Growing BC offers different research inputs in terms of producing cellulose without extraction practices, reversing the current raw material supply dynamics. By monitoring the materials growth, designers are able to customise shapes, colours, finishes and other aesthetic characteristics of the material while producing it. In this study different experimental activities concerning aesthetic characteristics of grown BC will be presented and discussed. To have a better control on the BC shaping it has been necessary to deploy digital fabrication – and particularly additive manufacturing – techniques to realise masks and drawer moulds, supports for the drying and other tools. Therefore, this contribution offers a case study on the mix between digital craft approaches and codesigning with living beings, to understand the possibilities of working with different production perspectives.

Keywords: bacterial cellulose; digital fabrication technologies; growing materials; digital craftsmanship

1 Introduction

Linear productive models have been dramatically discussed in recent years, leaving space for formulating innovative ones that embed in their vision environmental and social themes (Gaziulusoy, 2010). The increased awareness of the natural resources' finitude has been extremely stressed in scientific literature, focusing attention on monitoring natural Planetary Boundaries (Steffen et al., 2015) trespassing and pushing towards new productive assets: however, production models are very hard to change on already existing companies (Berna-Martinez & Macia-Perez, 2012),and in fact is common practice in big companies to prefer buying newborn productive activities instead of changing existing internal structures. Therefore, a dramatic change in how we conceive production and products is demanded by current urgencies, striving for zero-resource depletion and zero-waste design, production and economies (Ellen MacArthur Foundation, 2014).

On this topic, from one side, the technological evolution of manufacturing processes is working in this direction: the increasing performance level of Digital Fabrication Technologies (DFTs), and especially Additive Manufacturing (AM) technologies and techniques is a strong signal of using a controlled number of resources “right where it's needed”.

For what concerns design practice instead, in recent years it has been registered a growing interest in designers and the academic community for the bio-fabrication (Mironov et al., 2009), understood as the process of producing materials - e.g., Growing Materials (GMs) (Camere & Karana, 2018) - and complex objects through the co-design with living organisms. Through the dialogical exchange between the world of design and that of applied sciences (Antonelli & Alersey-Williams, 2008; Miodownik, 2007) among the various innovative practices explored in design research, there is increasing interest in the study and deployment of GMs instead of extracted ones.

If designers have traditionally been concerned with the process of material selection (Ashby & Johnson, 2013), today the focus is slightly moving on the creation of experimental materials (Wilkes et al., 2016; Rognoli et al., 2015), going to question linear productive logics (taking natural co-creation dynamics as reference), since in GMs practice the principal assumption is to co-design with other organisms (Hays et al.,2015). Even though GMs are inherently renewable and biodegradable (Camere & Karana, 2018), current experiments slightly consider the production system from the perspective of circularity, integration, and optimization with potential applications.

Design as a discipline, being into the use of DFT and the experimentation with GMs, may play a significant role in changing the productive paradigms by inverting how a single product is conceived. Being a discipline built on industrial processes and mechanisms, design can coherently promote a change. By formation, designers can promote changes and innovation in productive contexts (Coops et al., 2022), and their attitude is of fundamental importance: it has been esteemed (European Commission, 2015) that 80% of product’s total impact may be defined at the design stage. Therefore, design choices are not simply “style-related” decisions but can reverberate at different levels, determining the efficiency of designed products and systemic interdependencies surrounding productive companies (ing productive companies (Gaziulusoy & Öztekin, 2019).

Using digital fabrication as an enabler for the construction of ecosystems in the cultivation of GMs, the intent is to arrive at the envisioning of an experimental and flexible production system that allows a priori integration of formal choices, surface/aesthetic treatments, and additional elements, in a zero-waste logic and overall circularity (Standoli, Casciani & Bolzan, 2020). This is because there is great potential for sustainability and the implementation of the circular economy by favouring a conscious integration of digital fabrication technologies in synergy with GMs, rather than using them solely as tools for visualizing solutions designed through modelling software (Ferraris, 2023).

Among other GMs, Bacterial Cellulose (BC), also known as microbial cellulose, is a biodegradable, natural cellulose that is synthesised by bacteria. BC can be easily grown into controlled cultivation conditions (Kosseva et al., 2020), and the result is a layered structure presenting unique properties as biocompatibility, water-holding capacity, high tensile strength in wet state and others (Ducheine, 2015). Moreover, it is possible to embed singular design features in the BC while growing (Papile et al., 2022; Bolzan & Regaglia, 2022) to intervene by design directly while the material formation is happening. Finally, BC is completely biodegradable under controlled conditions (Torgbo & Sukyai, 2020; Lee et al., 2020).

Considering all the mentioned trends, this contribution explores the connection between the experimental trend of growing BC and the concrete possibility of transforming it into a material that can be imagined as integrated into sustainable production chains.

With these premises, the innovative character of this research lies in the shift in focus, from the simple growth of the BC to its planning and design exploiting DFT. By building a material from scratch, it is possible to modify the traditional processing chain, anticipating needs and constraints currently left to post-production. This could enable new production and entrepreneurial paradigms. In this perspective, the proposed research aims to offer a case study on the mix between digital craft approaches and co-designing with living beings, to understand the possibilities of working with a different production perspective.

2 Digital fabrication as enabling technology for exploratory activity

The research methodology adopted during the development of the presented project is similar to that of experimental research (Bang & Eriksen, 2014), in order to identify the causal relationships between the variables at play, such as the growth of the material, the manufacturing process(es) and the insertion of components within the material itself during the different growth and drying phases. Commonly, BC samples are growth by monitoring precise solutions of fermented tea (composed by tea brews and a Symbiotic Culture of Bacteria and Yeast – or SCOBY) and eventual additional elements (e.g., food colouring). This control and monitoring, repeated in an iterative manner, was supported by the application of techniques and processes proper to the activity of design (design and realisation of tools, supports and prototypes) with a crucial role in the production of innovative theoretical content - research through design & research prototyping (Stappers & Giaccardi, 2017). In this methodological framework, all those rapid prototyping processes that can support the designer both at an ideational level and for the realisation of optimised supports for research activity acquire relevance.

Digital Fabrication Technologies (DFT) - especially those that can be found in Fab Labs and makerspaces - provide important assistance to design for sustainable purposes since they give designers the ability to effectively and efficiently simulate new production systems and approaches on a small scale. They also make it possible to intervene on the aesthetic and sensorial outcomes of designed products and components.

For these reasons DFT and, specifically, Additive Manufacturing (AM) and Laser Cutting (LC), have been identified as disruptive technologies that may have great potential for sustainability and the implementation of the circular economy. Indeed, it is not strange to associate DFT with strategies for the circular economy, in contrast to more traditional manufacturing technologies, which have lately supported the linear economy.

The linear production model (Jiang, 2022), from one side it has brought economic growth and prosperity, however, nowadays is no longer sustainable from the resource consumption point of view (Sariatli, 2017). To ensure the implementation of circularity perspective in the productive process, the Design is called to rethink and redefine priorities when conceiving, designing, prototyping, producing and using a product. Design in the Circular Economy is requiring a transformation in thinking, by shifting 'from the current product-centric focus towards a more system-based design approach' (RSA, 2014). Circular Design seeks to produce a product or service that is useful and composed of the best materials to give the highest performance while reducing its overall negative impact (Aho, 2016). In this scenario AM technology represents an opportunity with benefits at both the product and system levels and has a high potential to serve as a facilitator of the circular economy (Garmulewicz, et al, 2018), offering the opportunity to better manage the resource consumption.

There are two main features (Jimenez et al., 2019) of AM to leverage, because they not only provide significant competitive advantages but also reduce manufacturing costs:

- The geometrical complexity of the part can be easily manufactured based on the geometrical template obtained from a 3D CAD (Computer Aided Design);
- The customization of the part can be simply manufactured, and products that are identical or wholly different can be obtained without affecting the process or expending additional costs.

According to Attaran (2017), AM also has advantages within industrial component manufacturing, which are summarized in the table below.

Table 1. Advantages of AM technologies in industrial component manufacturing according to Attaran (2017).

Advantages	**Short Description**
1. Reduction of the time it takes new designs to reach the market	When additive manufacturing is used as a manufacturing technique of the end-product and not only in the production of prototypes, many of the current launch and validation phases can be drastically shortened. Another advantage is that it provides great flexibility when it comes to responding to the continuous changes in market demand.
2. Short production runs	The size of the production run con be minimal to the extent of being on a per unit basis while hardly influencing manufacturing costs (if the depreciation of the equipment is not considered).
3. Reduction of assembly errors and their associated costs	Ready assembled components can be obtained with the only subsequent operation being the quality control inspection.
4. Reduction of tool investment costs	Tools do not form part of the 3D printing process. This represents a great deal of flexibility as regards adapting to the market and a reduction, or even elimination, of the associated costs (toolmaking, stoppages due to referred changes, maintenance, and inspection).
5. Hybrid processes	It's always possible to combine different manufacturing processes in this case combining 3D printing processes with conventional processes might be interesting to make the most of the advantages offered by both.
6. Material consumption	Optimum usage of materials material wastage is reduced to a minimum. Any waste material can be easily recycled.

Laser cutting technologies (LC) also offer similar advantages to those mentioned above. The subtractive processing technique of LC, while not offering the same three-dimensional expressive freedoms as AM, has the distinction of being very fast and can be used on many organic and non-organic media. Thanks to LC, sheets with complex shapes and with cuts, half-cuts and engravings can be obtained with great simplicity and speed-both in the generation of the two-dimensional files and in their processing (Khatak, 2022). The outputs appear as artefacts with an aspect resembling those of more traditional industrial productions.

By using DFTs (i.e., LC and AM) to do small-scale proof of concept, some of the advantages listed above are already present. Specifically, the advantages related to the production size (2), the possibility to implement corrections in a short time (3), but also the possibility to combine DFTs with other processes and components (5), as well as the reduction of material consumption (6) whose finished parts often do not need additional moulds.

When working with a material that is growing and "alive," and for this reason unstable and unfamiliar in industrial production, all these aspects play a crucial role in the possibility of devising new design solutions and production processes that can speed up the potential adoption of BC in the production of design artefacts.

3 Results: when bacterial cellulose meets digital fabrication

This contribution aims to present the approach and evidence gathered in understanding the specific world of BC as a GM to be produced, optimised and fully understood for potential applications in the industrial design field. This objective has been set as the basis for the De_Forma project, which is funded by the Design Department of Politecnico di Milano's Basic Research Fund for Young Investigators.

The focus on GMs and specifically on BC has been structured on the intent to explore and verify the possibilities offered by the interaction between bio-fabrication processes and DFT, through the filter of design as a holistic discipline. Once the growth process of the various cultures had been defined, reiteratively tested, and consolidated using a SCOBY hotel (Bechtel et al., 2021). DFT has been envisioned as an enabler for the construction of tools and growing chambers for the optimised cultivation of GMs. This is because, after defining replicable recipes for growing a film of material in timescales and aesthetic qualities useful for use in product making, there was a need to understand what other interventions can be applied to the material to reduce the production and post-production chain, as well as to foster the designer's interpretive expressiveness. The intent was to create an experimental and flexible set of options for a hypothetical production system that allows designers to manage the a priori integration of formal choices, surface/aesthetic treatments, and additional elements, in a zero-waste logic and overall circularity (Standoli, Casciani & Bolzan, 2020).

Through experimental and self-produced processes for the growth and understanding of the material itself, numerous application studies are developing design and manufacturing approaches that can incorporate living organisms to create biomaterials, hybridizing its nature and its growth processes (Myers, 2012). BC main properties have been already listed above, but for the presented experimentation the programmability of BC growth in predetermined shapes has been considered as crucial characteristic.

Within the framework of the mentioned experimentation, and in parallel with the necessary steps aimed at gaining knowledge of the material in all its phases - from controlled growth to its use in possible design applications, without neglecting its growing, drying, and characterising steps - a major role has been played by DFTs. In fact, having physically located the De-FORMA project experimentation in a university Fab Lab - Polifactory, interdepartmental laboratory of Politecnico di Milano enabled easy and responsive access to all major DFTs, which have been critically important in expanding the exploratory and application possibilities of BC.

An already built-up knowledge and familiarity with DFTs by the authors made it possible to integrate these technologies, and particularly the additive ones, into the different stages of interaction with the BC material. By combining inductive and adductive approaches, it was possible to categorise the inferred stages of an hypothetical new production asset involving BC and DFTs according to three categories, that consider different moments and purposes of intervention, which can be summarised as follows:

- DFTs for BC growth;
- DFTs for BC drying;
- DFTs for BC formation.

Indeed, these are the stages in which the designer can intervene in the material to make a priori changes that will then facilitate its application in in the conception and realization of design artifacts. In the following sections, a more in-depth discussion of the methodological integration between DFT and the diverse BC growing stages is presented.

The samples obtained have been qualitatively evaluated in terms of appearance, efficiency of the DFTs use for interacting with BC and aesthetic attributes.

3.1 DFTs for BC growth

BC growth takes place inside containers where a controlled liquid environment permits the material formation on the liquid's surface. The liquid environment is commonly composed by a tea, a starting mother culture called SCOBY, and additives to maintain the colony alive (e.g. sugar and vinegar) (Bolzan et al., 2022; Wood et al., 2023). The resulting material has the appearance of a layered sheet that has roughly constant thickness and its shape is given by the inner section of the container used for its growth. In case one wants to replicate the recipes used for material growth, it is possible to refer to some of the setups given in the table below.

Table 2. BC growing monitoring for the three starters tea.

Name	Ingredients and quantity	T°C	Jar material and diameter	Day	pH	Brix (%)
SCOBY Karkadè	Karkadè – 330 ml Sugar – 33 g Vinegar – 0 ml SCOBY – 48 g Starter liquid – 75 ml	35°	Glass 95 mm	1-21	2.33	9.1
SCOBY Green Tea	Green tea – 330 ml Sugar – 33 g Vinegar – 10 ml SCOBY – 45 g Starter liquid – 75 ml	35°	Glass 95 mm	1-21	3.00	9.4
SCOBY Black Tea	Black tea – 330 ml Sugar – 33 g	35°	Glass 95 mm	1-21	2.27	8.2

Vinegar – 10 ml
SCOBY – 45 g
Starter liquid – 75 ml

At this stage of BC creation, DFTs have been deployed for three different purposes: to realise elements able to modify the geometry of the final material and obtain precise shapes, different from the original container; to produce masks to block growth in certain areas of the surface and obtain a final material with different thicknesses; and to create vessels specifically designed to achieve different and controllable colourations on the same layer of BC.

An example of the first type of application of DFTs for BC growth can be seen in Figure 1, in which (from left to right) we can see a hollow shape affecting the BC growth into a cylindrical container. The hollow shape has been realised in PLA with a 3D Fused Deposition Modeling (FDM) printer and then inserted into the container of one of the cultures while growing. This procedure enabled the researchers in generating a final BC sample with an altered shape in respect to that of the initial container, that can be seen on the right side of the picture. This first methodological procedure shows that layers of BC can be produced with specific geometries, which do not necessarily have to undergo further cutting and shaping processes in post-production. Thanks to this strategy, it is possible to reduce the generation of waste of already dried BC after subsequent cuts. The scalability of this technique is particularly useful when products or components in BC need to be produced that do not have a shape like standard containers available in the market or when multiple sizes exist for the same production output (e.g., for products with different fits). During production, there will be no need to modify the growth tank system. Instead, preformed elements can be introduced into larger tanks using a nesting operation, maintaining production efficiency while also making it flexible.

Figure 1. DFTs adopted to generate a specific BC shape while its growing, preventing secondary cut operations on BC samples.

DFTs can be also deployed to produce layers of BC with non-constant thicknesses, acting in the BC growth phase. As mentioned earlier, the growth process of BC generally takes place on the surface of an additive liquid of the bacterial culture. Since BC grows on the surface of the liquid, the layering of the final material generally has a fairly constant thickness - net of any defects caused by excess fermentation (bubbles) or failure to float part of the new culture being formed.

Three-dimensional textures can be created by applying masks of floating material (e.g., raft, cork, or cardboard) after an initial BC layer has formed homogeneously on the surface. The mask stops the functional exchange of oxygen and CO2 in certain parts of the BC layer, encouraging its further growth only at the unscreened parts. Figure 2 shows (on the left) the cork mask cut with a LC machine. The same mask has then been applied over the culture, and (on the left side of the picture) a detail of the thickness difference formed on the BC sample is shown.

When drying, this range will be drastically reduced, but will still be perceptible both to the eye and to the touch. The black edge visible around the most prominent dots is the result of burning the laser-cut cork. If this type of effect is not desired, other tools, such as the vinyl cutter, can be used to make the masks. This technique, like the one previously mentioned (visible in Figure 1), allows for a customized and flexible production of BC parts, in this case for elements characterized from an aesthetic point of view. Both strategies of modification during the growth phase can be combined, creating BC pieces with predefined shapes and textures for efficient application in the final product.

Figure 2. DFTs adopted to realise masks that enable designers in generating BC samples with different thicknesses.

A final experiment in the use of DFTs to intervene in the BC growth phase was the creation of specific containers to create predefined colour shades in the samples. A series of containers with an internal division and liquid access channels on the sides were designed and 3D printed in FDM. Figure 3 shows one of the containers created. At the basis of the design idea there is the need to be able keeping two different mediums separate for an initial phase of BC growth, with the possibility of adjusting the liquid level at a later stage thanks to the lateral channels of the container. In this way it is then possible to connect the two parts, which will create a single piece of BC presenting different colouring areas.

Unfortunately, this type of experiment has not yet been adequately investigated because the first trials of containers, made of PLA and then waterproofed internally, did not withstand the stress of the medium and bacterial cultures for long (as can be seen in the right-hand side of Figure 3). It has not yet been possible to obtain a finished sample through this technique, which requires a material replacement for the realisation of the final containers.

Regardless, this technique has the limitation of being more difficult to integrate into an industrial or semi-industrial production process because it would require the replacement of standard containers with others that have a higher manufacturing cost and that need constant liquid-level control intervention. For this reason, this strategy was considered less promising than those previously shown in this section.

Figure 3. DFTs deployed for the realisation of growing chambers to realise BC samples with different colour shades.

3.2 DFTs for BC drying

Once dried, BC samples can be successfully engraved with a laser cutter by creating patterns through the removal of a thin material layer in post-production. However, it is possible to obtain similar aesthetic effects, both in two and three dimensions, during the drying phase already. This is particularly convenient when designers want to reduce processing times or when they need to reproduce the same texture in several copies.

In Figure 4 it is shown one of the samples obtained by drying a BC layer by contact and compression with a PMMA sheet. The contact surface has been designed to present perforations (obtained through LC technique). During the drying phase, the texture impressed on the PMMA sheet was transferred onto the drying BC sample.

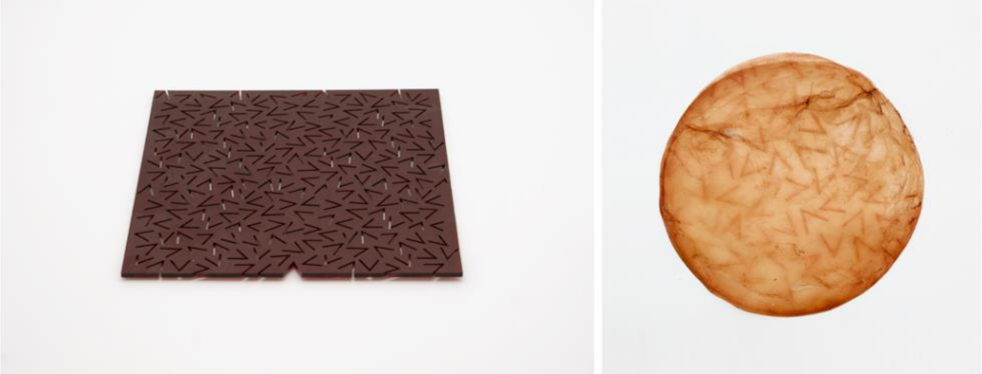

Figure 4. DFTs adopted to realise a negative texture sample, then impressed in the drying BC sample.

A similar, but even more emphasised effect, can be achieved through the production of 3D-printed textured plates. In the application example, visible in Figure 5, it can be seen (on the left) the FDM 3D printed element, (in the centre) a hydrated layer of BC placed on top of it, and (on the right) the post-drying result on the BC sample. In this case, drying did not occur by compression, but only by gravity, thus avoiding possible cracking of the material surface. At the end of drying, the BC sample presents a slight three-dimensionality, even maintaining the workability of any sheet material.

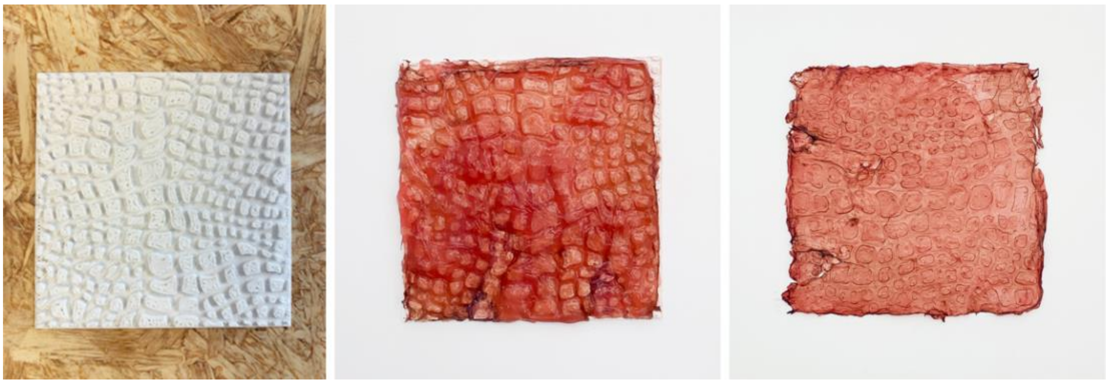

Figure 5. FDM realised mask where BC samples have been lay, gaining a three-dimensional texture when dried.

These two strategies appear most useful in the case where pieces are to be obtained from the same growth tank but with different surface finishes. In fact, it will not be necessary to intervene in the controlled growth phase, but specific effects can be imprinted directly in the drying phase. This gives designers more time to administer project decisions related to the soft qualities domain of the product. At the same time, the space required for the storage of different finishings is really reduced, and in terms of industrial scalability, the management of storage space and the possibility of combining different textures on the same layer of BC by pairing several modules are fostered. However, it is not recommended to simultaneously use sheets processed with LC and modules made in AM because the compression might not be homogeneous.

3.3 DFTs for BC formation

DFTs demonstrate additional application advantages when associated with one of the steps not typically referable to the creation of BC material, but rather to its manipulation according to formal criteria typical of industrial production. For this reason, we can speak of BC formation in association with DFTs.

More in detail, an evolution of three-dimensional moulds, presented in the previous section, can serve as enablers for the creation of three-dimensional shapes through DFTs. Examples of some moulds made through AM with PLA printed in FDM and the resulting shapes in BC can be found in Figures 6-7. In Figure 6, it can be seen how it is possible to make a double curvature to a BC layer.

Figure 6. 3D printed mould to obtain a BC hemispheric sample and its resulting shape.

Figure 7. BC layer wrapped over a 3D printed mold.

In Figure 7, you can see how the principle of the drawer mould was applied to create a hollow truncated cone with a layer of BC, without having problems with removal from the mould downstream of the shrinkage of the dried material. Nevertheless, it should be considered how any material overlaps – visible on the left side of Figure 7 – are evident on the final output.

There is also the possibility of using the same strategy of the molds created with DFTs to make shapes from BC chopped, which is obtained from cultures that suffer defects on the surface or from scraps produced by other operations with BC. In Figure 8, it is possible to see the application of the same principle of the drawer mold in Figure 7 for the realization of the same shape using BC tartare. In this case the appearance of the final artifact is completely different and at the same time avoids the creation of overlapping parts of BC.

Figure 8. BC “tartare” sample over a 3d printed mold.

On the other hand, the left side of Figure 9 shows how DFTs can be used to make useful molds for spreading BC tartare, even when mixed with further inert waste materials, to obtain output with different thicknesses. In the same figure, it can also be seen how DFTs are useful for the creation of molds that can also integrate electronic components to be inserted into the BC chop, keeping them in a precise position. Specifically, the creation of some light elements to be integrated into fashion accessories was possible through the creation of a mold made by FDM in PLA, in whose bottom there is a part made with LC. The PMMA part produced with LC allows the LEDs to be placed in a precise position, as well as facilitating the extraction of the finished item.

Figure 9. Examples of moulds and their use for making BC tartare elements with integration of other components and materials.

All the techniques introduced in this section, aimed at facilitating the creation of shapes dissimilar to that of a simple sheet, are intended to assist designers in understanding and visualizing the additional possibilities offered by this type of material. In fact, BC can be treated as any other material for production in a structured and comprehensive manner, but only once the changes in state it can undergo through various processes have been mapped and demonstrated. The ability to transform a material that originates in layers (thus two-dimensional) into three-dimensional semi-finished products greatly expands its potential design applications.

4 Discussion

In the presented work, a sharp focus has been maintained on the productive aspects of BC samples when imagined to be a valid alternative for the linear production, which envisions materials mainly as mined. By inverting the conceptions of prime matter, GMs in general offer the vision of growing materials right in place, aiming to avoid scraps and post-processing operations as much as possible.

Through the presented experimental procedure and activities, it has been demonstrated that it is possible for designers not only to produce their own material, but also to determine some features while the material is growing, drying or forming. An interesting reflection is offered by the fact that all these experiments were conducted within an academic environment by researchers with a design background. Therefore, the proposed results represent a preliminary and relevant exploration of the initial needs for modification and intervention on a material from a design perspective. They can serve as a starting point for conceiving new design solutions involving BC material and can be further expanded and refined to demonstrate their practical applicability in the production field. Simultaneously, the divergent generative capacity of designers can lead to the identification of other techniques for BC growth, drying, and forming to address new specific design requirements, in a co-creation approach with the material.

What it has been obtained at the end of the experimentation was a huge amount of BC samples presenting different features obtained into the diverse phases of BC realisation. But if from one side certain aspects have been consolidated (e.g., forming techniques, shaping, texturing and colouring), on the other side some defects on obtained samples must be highlighted.

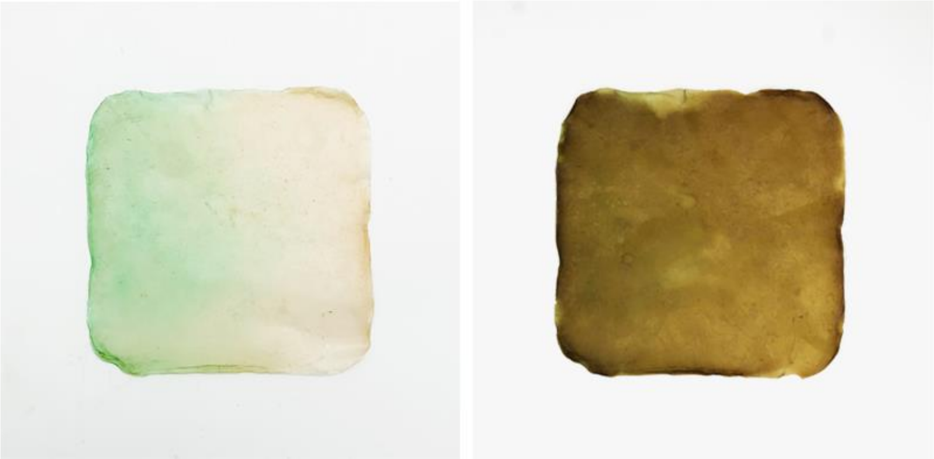

Figure 10. The same BC sample photographed (on the left) one week after drying, (on the right) about one year later.

In particular, the total absence of post-processing operations determined a quite rapid degradation of certain sample features. The most evident one is that of colour changing over a year (Figure 10), probably for the UV exposure of the samples. The brilliant colourations obtained in the very beginning of the sample realisation have been altered by the passing of time. This event opens the discussion of two possible future directions of the work: since features as colour cannot be affected by the intervention of different DFT, the BC samples can be coated with some other substances or the colour degradation, in a speculative approach, can be intended by the designer as an essential element (Rognoli & Karana, 2014).

Future developments of this work could be conducted exploring both ways, from one side by deploying coatings already adopted in non-bacterial cellulose protection and from the other side in questioning the possibility of turning material degradation in a strategic feature. In addition, different use of DFTs can be deployed to improve the three drivers presented (DFTs for BC growth, drying and formation), for example to experiment BC growth in shapes difficult to obtain with standard containers.

5 Conclusions

The presented work aims to provide an overview on the innovative possibilities of designing with DFT in combination with GMs. Even if the state of the art of these two methodologies is still underexplored, the presented work shows the promising wideness and freedom of design activities offered by DFT and BC growth in synergy.

This work should be considered as a starting point to initiate informed design with BC material, aiming to effectively integrate it into the production of functional artifacts as soon as possible. The presented experiments have not yet found integration into industrial or semi-industrial production, but they have proven highly useful for the development of concepts and prototypes carried out by students engaged in Master's thesis projects or those currently developing them. Specifically, sharing the knowledge gained through these experiments has facilitated the creation of a garment and a lamp.

In the case of the garment, growth techniques were used to obtain a qualitatively suitable material over the entire surface of a large-format piece. Drying and forming techniques were combined to reproduce typical fashion processes using a non-textile material, as well as to create buttons for the garment. On the other hand, for the lamp product, the optimization of the growth phases was crucial in creating a BC layer to form the fine-tuned diffuser with the desired geometry, thickness, and coloration. Drying and forming techniques were also combined to apply parts at suitable distances to enhance light diffusion. In this second product, considerations regarding the degradability of the material were integrated into the final design, which was intended to have a programmed lifecycle and duration.

Based on these experiments, it can be asserted that interventions during the growth phase can reduce subsequent material processing, but they are not exhaustive. On the other hand, drying and forming techniques, each having unique characteristics, can synergistically work together to complete the range of applicative possibilities of BC.

In conclusion, the different stages proposed in the experimentation aimed to simulate different phases of BC growth and corresponding design interventions that can be embedded in the process. The aim is to envision a new production framework where the designer is an active presence even in the optimisation of the production line: in this way, awareness of resources and materials used as well as the tooling necessary for producing a design artefact is, according to authors, of fundamental importance for a shift in production paradigms, towards more sustainable production.

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