Mix Sustentável

Aesthetic Uniqueness: The Recovery of Glass Waste as a Design Differential

Singularidade Estética: A Recuperação de Resíduos Vítreos como Diferencial Projetual

Singularidad Estética: la recuperación de residuos de vidrio como elemento diferenciador del diseño.)

Fellipe Dalcin Lacorte[1]
Felipe Luís Palombini[2]

[1] PPGAUP - Programa de Pós-graduação em Arquitetura, Urbanismo e Paisagismo, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brasil
[2] PPGAUP - Programa de Pós-graduação em Arquitetura, Urbanismo e Paisagismo, NOVA Lab - Laboratório de Inovação e Sustentabilidade em Design, DDI - Departamento de Desenho Industrial, UFSM - Universidade Federal de Santa Maria, Universidade Federal de Santa Maria, Santa Maria, Rio Grande do Sul, Brasil

Correspondência para: fellipe.lacorte@acad.ufsm.br, felipe.palombini@ufsm.br

Resumo: As tecnologias que marcaram as Grandes Revoluções Industriais aumentaram exponencialmente a produção de produtos e, consequentemente, a geração de resíduos sólidos descartados de maneira inadequada na maioria das vezes. Um dos materiais mais desperdiçados é o vidro que, apesar das propriedades que permitem sua reciclagem incontáveis vezes, encontra desafios de logística e

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necessita de procedimentos complexos para sua recuperação industrial. O presente trabalho tem como objetivo analisar o potencial de valorização do vidro descartado, reinserindo-o em cadeias produtivas para novos produtos. Os procedimentos experimentais seguiram uma metodologia aplicada e exploratória, dividida em duas etapas: revisão bibliográfica e experimentos práticos. A partir do processo de fundição de vidro em moldes cerâmicos e forno tipo mufla (glass kiln casting) e da escolha de quatro ciclos térmicos com parâmetros diferentes, obtiveram-se quatro módulos volumétricos que apresentaram características físicas e estéticas distintas, passíveis de implementação em projetos arquitetônicos. A pesquisa concluiu que é possível recuperar resíduos vítreos utilizando processos mais simples que resultam em peças com potencial de serem empregadas em projetos arquitetônicos e de design nos quais a singularidade estética é atributo de valorização.

Palavras-chave: Economia Circular; Reciclagem; EcoDesign; Fundição de vidro em forno; Vidro.

Abstract: The technologies that marked the Industrial Revolutions exponentially increased product manufacturing and, consequently, the generation of solid waste that is improperly disposed of in most cases. Glass is one of the most wasted materials, which, despite properties that allow its recycling countless times, faces logistical challenges and requires complex procedures for industrial recovery. This study aims to analyze the valorization potential of discarded glass by reinserting it into productive chains for new products. The experimental procedures followed an applied and exploratory methodology, divided into two stages: bibliographic review and practical experiments. Through the glass kiln casting process using ceramic molds and a muffle furnace, and the selection of four thermal cycles with different parameters, four volumetric modules were obtained, presenting distinct physical and aesthetic characteristics suitable for implementation in architectural projects. The research concluded that it is possible to recover glass waste using simpler processes, resulting in pieces with potential for use in architectural and design projects in which aesthetic singularity is a valorization attribute.

Keywords: Circular Economy; Recycling; EcoDesign; Glass Kiln Casting. Glass.

Resumen: Las tecnologías que marcaram las Revoluciones Industriales aumentaron exponencialmente la fabricación de productos y, en consecuencia, la generación de residuos sólidos que se eliminan de forma inadecuada en la mayoría de

permite o compartilhamento do trabalho com reconhecimento da autoria e publicação inicial nesta revista.

Contribuição dos autores segundo a Taxonomia CRediT

Autor 1: Fellipe Dalcin Lacorte, FDL Autor 2: Felipe Luís Palombini, FLP FDL: Conceptualization, Resources, Investigation, Visualization, Writing – original draft. FLP: Conceptualization, Resources,Investigation, Supervision, Writing – review and editing

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los casos. El vidrio es uno de los materiales más desperdiciados, el cual, a pesar de poseer propiedades que permiten su reciclaje innumerables veces, se enfrenta a desafíos logísticos y requiere procedimientos complejos para su recuperación industrial. Este estudio tiene como objetivo analizar el potencial de valorización del vidrio desechado mediante su reinserción en las cadenas productivas para nuevos productos. Los procedimientos experimentales siguieron una metodología aplicada y exploratoria, dividida en dos etapas: revisión bibliográfica y experimentos prácticos. A través del proceso de fundición de vidrio en horno (glass kiln casting) utilizando moldes cerámicos y un horno de mufla, y la selección de cuatro ciclos térmicos con diferentes parámetros, se obtuvieron cuatro módulos volumétricos que presentan características físicas y estéticas distintas, aptas para su implementación en proyectos arquitectónicos. La investigación concluyó que es posible recuperar residuos de vidrio utilizando procesos más simples, obteniendo como resultado piezas con potencial para su uso en proyectos arquitectónicos y de diseño en los cuales la singularidad estética es un atributo de valorización.

Palabras clave: Economía Circular; Reciclaje; EcoDesign; Fundición de Vidrio en Horno; Vidrio.

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1 INTRODUCTION

Four Great Industrial Revolutions represent moments in history when new production processes arrived in the industrial sector, significantly increasing the quantity of products produced by humans. Along with technological development, the organization of labor also needed to be adapted to meet the needs of ever-increasing productivity (Schwab, 2016; Sacomano *et al.*, 2018). According to Elhacham *et al.* (2020), the mass of objects manufactured by humans has surpassed the living biomass on Planet Earth, disregarding the waste we generate during our existence. According to ABREMA (2024) overview, each Brazilian generated more than 1 kg of waste per day in 2023, totaling 81 million tons of waste per year within the territory of just one country. Furthermore, of this amount, only 6.6 million tons were effectively recycled. In Brazil, while more than 90% of the aluminum generated is recycled, this figure only reaches 25% for glass (ABREMA, 2024; CNN Brasil, 2024). While this metal is valued by industry, resulting in a high recycling rate, glass waste, on the other hand, requires complex procedures for transportation, cleaning, and separation of cullet types. The density of the material and the distances that must be traveled to reprocessing centers also make it less attractive to companies, reducing its purchase price (ABREMA, 2024). The difficulties related to its collection end up not being worthwhile for recyclers, mainly due to the low added value of the secondary material (Palombini; Cidade, 2022). Despite the recyclability of glass, the challenges go beyond economic, political, and social spheres, making it necessary to restructure a complex system to enable an effective reprocessing cycle.

We can call "problematic materials" or "invisible waste" those materials that, like glass, are present in our daily lives and, despite having difficulties in recovery at various stages of the production chain, do not attract the attention of the general public as being problematic to society (Palombini; Cidade, 2022). In addition to incentive policies and efficient collection and separation systems, it is also necessary to change society's disposal culture, especially regarding its valuation, to enable a circular economy with glass artifacts. Even so, technical solutions need to be explored and developed. Bristogianni e Oikonomopoulou (2023), for example, discuss glass recycling in volumetric models. The authors conclude that imperfections will generally be concentrated inside the piece where there will be less chance of receiving critical stresses for rupture. These imperfections may originate from contaminants or casting processes with less control compared to industrial ones. Such action has the potential to reduce the complexity of preparing glass shards for reprocessing, opening up the possibility of recycling to smaller glass studios than the glass industry (Bristogianni; Oikonomopoulou, 2023).

By decentralizing glass recycling from large centers, more project alternatives emerge to optimize the life cycle of these products. For Manzini e Vezzoli (2016), industrial design has the responsibility of uniting what is technically feasible with what is ecologically necessary. The authors also describe that, for the development of sustainable products, it is of paramount importance to analyze the necessary resources and the consequent emissions of each stage of the product-system life cycle – pre-production, production, distribution, use and disposal – in addition to seeking circularity within the system and/or extending the useful life of the artifacts. Cidade e Palombini (2023), for example, describe how jewelry design can stand out for its unique

aesthetic and thus benefit from sustainable attributes by using problematic materials, already in the disposal stage, in its manufacture, being reintroduced in the pre-production of a new product. Mostardeiro, Oderich e Cidade (2019) corroborate this issue by developing a recycled glass pendant from the melting of shards deposited in ceramic molds and heated inside a muffle furnace. The irregular colors resulting from the process, as well as textures or patterns, end up making the pieces unique, adding value to the product and the raw material. However, a factor to be considered in glass recycling is the amount of reprocessed material. In jewelry, due to its characteristics, the amount of glass waste used tends to be small even considering its potential to add value to secondary materials. This highlights the importance of exploring design approaches capable of incorporating more significant volumes of glass waste, directing the debate towards larger-scale applications, such as in the built environment and interior design, where recycling can act more broadly and voluminously in the circularity of the material.

In this context, this paper aims to analyze the aesthetic potential of recycled glass from the casting of post-use shards, considering the variations in color and texture resulting from the process as attributes that enhance the value of the material. The study starts from experiments conducted with the casting of glass waste in refractory plaster molds that revealed distinct and unintentional visual behaviors. To this end, a brief theoretical-technical survey was conducted on the concepts and properties of materials and equipment. Then, the experimental procedures were conducted, performing four experiments with variations in time and temperature intervals. Finally, the results were observed, synthesizing them to begin the discussion. By adopting a focus on the aesthetic and design dimension, the paper seeks to discuss how these different chromatic and surface aspects can contribute to applications in the built environment and in interior design, expanding the symbolic and functional value of recycled glass and reinforcing the role of design in the re-signification of waste in the context of sustainability.

2 GLASS: A DISTINCTIVE MATERIAL

According to Akerman (2000) and Lefteri (2015), glass is a material produced from silica and other minerals that, depending on their proportion and chemical composition, result in raw materials with distinct physical properties and characteristics. Generally, it is an amorphous solid, meaning its atomic structure does not present a standardized crystalline organization. Furthermore, glass exhibits the phenomenon of glass transition, in which the mobility of atoms is progressively reduced as the temperature decreases, without the typical structural ordering of crystalline materials occurring (Groover, 2014). These characteristics have made glass an important material for human technological development, making it possible to produce lenses for microscopy and even telescopes due to its translucency that refracts light. Being an inert material, that is, one that practically does not react with other substances, it has allowed chemical advances, being a raw material for glassware (Callister, 2006; Lefteri, 2015). Currently, it is used in the screens of mobile devices popularly known as smartphones, allowing for handling through touch and still allowing light to pass through (Akerman, 2000; Lefteri, 2015).

In architecture and design, glass is a structural and expressive component that can convey lightness, luxury, and delicacy depending on the project in which it is used. The material plays a fundamental role in civil construction, integrating the interior and exterior, allowing light to enter while blocking harmful agents from the outside. From flat glass, it has been possible to construct facades, windows, roofs, and entirely glazed structures (Wiederhorn; Clarke, 2022). However, this product requires great care in its production because, unlike volumetric models, it is more prone to receiving critical stresses and may break more easily (Bristogianni; Oikonomopoulou, 2023).

This inherent variability in post-consumer glass can make recycling it a challenging design process, especially when seeking aesthetic standardization or rigorous control of final properties. In certain contexts, this condition can discourage the recovery of the material. In this sense, Bristogianni e Oikonomopoulou (2023) discuss the use of volumetric models as a design strategy capable of absorbing the characteristics of "as-received" glass, enabling its recovery with less dependence on additional preparation steps, such as color separation or pre-treatments, and expanding the spectrum of applications of the recycled material.

Volumetric models also increase the possibilities of glass recovery in architectural projects, potentially adding semantic differentiation to constructions. Figure 1 illustrates two examples in which the material plays a central role, although employed through different technologies, resulting in completely different aesthetic and functional interpretations. These examples demonstrate how appropriate design approaches can give new meaning to recycled material, exploring its properties and variability as attributes, not limitations. On the left of Figure 1, you can see Heineken's WOBO bottles, developed for reuse after use, as modules for building architectural structures (center of Figure 1). On the right, glass was used to construct the facade of the Chanel store in Amsterdam in 2016, with bricks made of flat glass joined by transparent adhesive tape, integrating the building's historical facade with technological development (Heineken Collection Foundation, 2025; Sequin, 2016).

Figure 1 – WOBO bottle and Chanel store facade in 2016



Source: Heineken Collection Foundation (2025) and Sequin (2016)

While Chanel sought to incorporate the glass facade into the store, linking the material to the luxury befitting its products, the WOBO bottles aimed for a project interconnected with the circular economy, with

the goal of using modules in the disposal stage to build new consumer goods, reinserting them into the pre-production stage. Although Heineken discontinued the research due to the brand's market positioning, both projects illustrate the use of glass in civil construction and highlight design as an indispensable discipline in transdisciplinary projects for the recovery of problematic materials.

In this context, colors and textures play a fundamental role in the qualification of the built environment, since they directly influence spatial perception, the incidence and diffusion of light, and the sensory experience of users. Traditional design methodologies incorporate specific stages aimed at the chromatic and textural definition of materials, which are supported by exploratory research and experimentation processes, fundamental for making design decisions (Löbach, 2001). Exploratory research, in this sense, allows us to understand the behavior of materials when subjected to different processing parameters, enabling aesthetic variations to be incorporated as project attributes.

Glass kiln casting presents itself as a suitable technique for this type of investigation, consisting of melting glass by positioning shards inside refractory molds and placing them inside furnaces that withstand high temperatures (Persico, 2007). This experimental approach can be incorporated into the methodological procedures of design, and its application is feasible with the use of the equipment available at NOVA Lab at the Industrial Design Department of the Universidade Federal de Santa Maria, Brazil (UFSM), integrating material research and design experimentation.

3 EXPERIMENTAL PROCEDURE

3.1 Materials and methods

This research is characterized as applied, seeking practical solutions based on existing knowledge, and exploratory, given that the results revealed possibilities not initially anticipated. The investigation was structured in two complementary stages: first, a bibliographic review on glass, recycling, and design for sustainability; followed by practical experiments involving glass casting of recycled glass cullet in four distinct thermal cycles using a muffle furnace, which resulted in samples with differentiated visual characteristics and potential for application in architecture and design projects.

The experiments were conducted following the Glass Kiln Casting methodology of Persico (2007), introducing fusion parameters from the research of Bristogianni e Oikonomopoulou (2023), and manufacturing the molds using FDM (Fused Deposition Modeling) technology at NOVA Lab at Universidade Federal de Santa Maria. The molds were produced in refractory plaster for metal casting from the TapCamp brand. According to the manufacturer, the plaster withstands up to 1000°C and is a proprietary blend of special, highly refractory materials with specific binders (Tapcamp, 2025). The furnace used for thermal procedures related to mold production and glass casting is a Jung brand, model 2713, from 2011, and is located at NOVA Lab. Accordingly, the thermal cycle parameters were established based on the work of Persico (2007) and Bristogianni e

Oikonomopoulou (2023), adapted to the technical limitations of the refractory plaster molds and muffle furnace employed.

The steps for manufacturing the molds started with the design of volumetric models and digital matrices, followed by their production in PLA using the equipment of NOVA Lab. Then, the plaster was mixed with water following the manufacturer's instructions and poured into the matrices. After a week at room temperature, the refractory plaster molds were extracted and placed on a surface at 90°C for the second drying stage. The final drying of the molds was carried out prior to casting when the glass shards were already positioned internally. For this, the oven was heated at 1°C per minute until it reached 220°C, maintaining this temperature for 1 hour and 30 minutes. Immediately after that, the casting cycles would begin.

The raw material used was glass shards from colorless long neck bottles recovered from disposal by the author. This choice was made because this container is not returnable to the beverage industry – unlike some 600 ml containers, for example, which are returned to companies and refilled with liquids to return to the market after sanitization – and is discarded in regular trash, generating negative impacts on the environment and on people who circulate in the same space.

The bottles were cleaned with soap and water, and their labels were removed manually. Due to the manual nature of the procedures, the surface of some containers was not free of contaminants. Figure 2 shows the bottle surface with glue residue from the labels and traces of ink used in packaging details. After complete drying, the bottles were manually crushed without particle size control.

Figure 2 – Example of a long neck bottle with contaminants



Source: Authors.

The casting process consisted of the following steps: depositing glass shards inside refractory plaster molds, placing the molds inside the furnace, adjusting the thermal cycle (heating rate, maximum temperature, dwell time, and cooling time), removing the molds from the furnace, and extracting the pieces for evaluation. A total of four volumetric modules were obtained with four different thermal cycles. Figure 3 illustrates the glass shards deposited in the molds inside the muffle furnace.

Figure 3 – Glass shards deposited in the molds



Source: Authors.

3.2 Results

For the first experiment, the thermal cycle was programmed to reach the liquidus point of the glass. According to Bristogianni e Oikonomopoulou (2023), this point is slightly below the melting point, but the viscosity of the glass mass is low enough to allocate contaminants to the center of the piece, in addition to helping the disappearance of air bubbles and moisture. Then, after drying the refractory plaster, the casting process began by heating the inside of the furnace 1.5°C per minute until reaching 1100°C and maintaining it for 5 hours until the furnace was turned off. The result can be observed in Figure 4.

The second experiment resulted in the devitralization of the glass, meaning that the atomic structure of the material organized itself into crystalline structures, causing it to behave similarly to ceramics. This occurred due to the programmed thermal cycle: a temperature increase rate, after mold drying, of 1.5°C per minute until reaching 900°C, maintaining the maximum temperature for 11 hours until the furnace was turned off. Figure 5 shows the details of the devitralized volumetric modulus, exposing the surface heterogeneity, the whitening of the piece, and the loss of translucency.

Prolonged exposure to temperatures below the liquidus point is one of the factors that Bristogianni e Oikonomopoulou (2023) describe as possible causes of the phenomenon. Another factor the authors highlight is the cooling of the material, which should rapidly decrease from 1000°C to 570°C for the glass annealing

Figure 4 – Module obtained at 1100°C for 5 hours



Source: Authors.

stage. With this in mind, in the next experiment, the maximum temperature was increased to 970°C and the holding time was reduced to only 1 hour until the furnace was switched off, respecting the limits of the refractory plaster molds. The temperature increase rate was 2°C/min. After cooling, the piece was subjected to another thermal cycle. This time, the increase rate was 2.5°C/min until it reached 950°C and was maintained for only 15 minutes until the equipment was switched off. The furnace used does not have a cooling program; the temperature decrease was slow for all experiments. Figure 6 shows the result of the third experiment.

In the final test, Ruteniun brand refractory plaster, satin finish type, was used. This material is indicated for casting gold and silver and, according to distributors, is suitable for alloys with a melting point of up to 1200°C. The thermal cycle began with drying the mold containing the glass shards, programming the furnace to reach 220°C at a rate of 1°C/min, maintaining this temperature for an hour and a half. This step resulted in the darkening and dehumidification of the mold. Then, the temperature was increased at 2.5°C/min to 550°C, remaining there for thirty minutes to stabilize the refractory plaster, and subsequently increased at 2°C/min until reaching 1100°C, with a plateau of three hours and uncontrolled cooling. After opening the furnace, whitening of the mold, the presence of cracks, and the absence of adhesion between the plaster and the glass were observed, which allowed the removal of the vitreous module without difficulty, resulting in a piece with unique visual characteristics, as shown in Figure 7.

4 DISCUSSION

The results of the four experiments exposed the complexity in glass recycling and the delicacy of the material, which abruptly varies its physical properties with any changes in the melting parameters. Standardization of the material in industrial production requires automated equipment with more developed technologies for separating shards by glass type; efficient sanitization to remove external contaminants; special furnaces with complex thermal cycle programming that reach very high temperatures; and controlled environments because even the gases generated inside the furnace can influence the final glass product (Bristogianni; Oikonomopoulou, 2023). Although not ideal for the manufacture of glass products where translucency and

Figure 5 – Details of the devitrified module



Source: Authors.

lack of color are desired design characteristics, in bottles and flat glass, for example, chromatic and textural variations can be applied in design and architectural projects, standing out for their aesthetic uniqueness, which contributes to their value as a product.

The experiments using colorless glass shards highlighted the color and texture changes that can occur with alterations in temperature and exposure time during the material's casting process. The results showed greater translucency in the final volumetric modules outside the shards exposed to temperatures of approximately 1100°C in the first and last experiments. The temperature close to the material's liquidus point prevented the pieces from becoming vitrified, confirming the experiments of Bristogianni e Oikonomopoulou (2023). The second and third experiments resulted in vitrified, opaque pieces with different whitish tones. The second volumetric module showed colors closer to white compared to the third, despite exhibiting the same phenomenon. The long exposure to temperatures much lower than the liquidus point (11 hours at 900°C) was the main factor observed as responsible for the critical alteration in appearance.

Furthermore, it was observed that the presence of contaminants, and their origin, also influence the aesthetic characteristics of the cast modules. In the experiments reported in this work, it was not possible to identify the composition of the contaminants present in the bottle packaging or others derived from the manual handling of the glass shards. In the fourth and final experiment, a much more yellowish-green coloration was noticed, leading to the hypothesis that it originated from the composition of the Rutenium brand satin-type plaster, which had presented yellowish and brown colorations during the mold drying process.

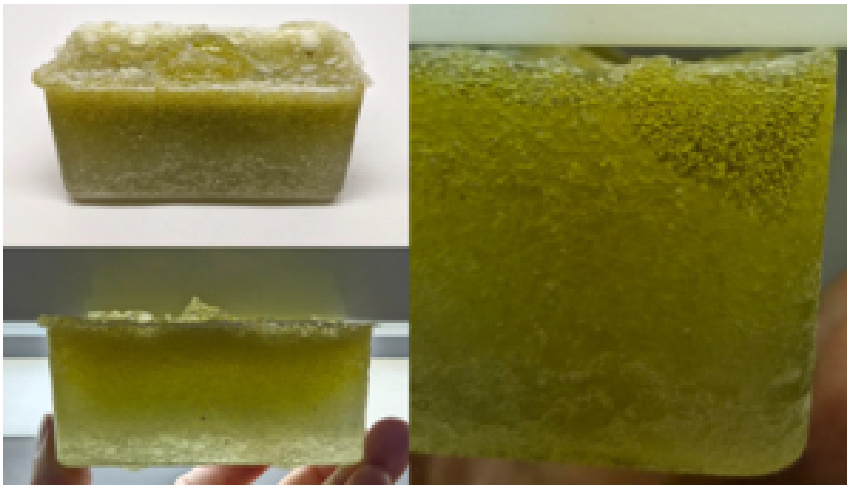
Although none of the experiments resulted in translucent and colorless modules similar to the glass shards recovered for the experimental procedures, it becomes relevant to analyze the pieces obtained from the

Figure 6 – Module resulting from the third experiment



Source: Authors.

Figure 7 – Module resulting from the fourth experiment



Source: Authors.

perspective that their unique appearance can constitute a design differential. In architectural projects, for example, the aesthetic characteristics of materials play a fundamental role in mediating the relationships between the built environment and the individuals who occupy it. Translucency can allow the entry and diffusion of natural light, altering spatial perception and the intended atmosphere according to the material's color and light refraction phenomena, enabling the creation of different ambiences depending on the project's objectives.

On the other hand, devitrified, opaque, and whitish pieces also show potential for application, either in partitions that do not require the passage of light, or as ornamental elements in specific points of the space, similarly to the traditional use of some natural rocks, such as white onyx. Figure 8 shows the four modules obtained in the experiments, highlighting the aesthetic differences observed between them.

The chromatic and textural variations obtained from relatively simple interventions highlight the experimental and exploratory nature of this research. The results indicate that small alterations in processing

Figure 8 – Modules obtained from side-by-side experiments



Source: Authors.

parameters are capable of generating a significant diversity of aesthetic effects, expanding the design possibilities for the reuse of recycled glass. The use of simple equipment and tools – refractory plaster molds and a muffle furnace without programming for multiple thermal cycles – shows potential for creating recycling centers with lower technological complexity, decentralizing glass recovery from large industrial centers and simplifying logistical challenges.

From a circular economy perspective, these results reinforce the possibility of reintegrating glass into closed production cycles, adding value to the raw material instead of discarding it. By transforming waste into new artifacts with aesthetic and functional qualities, the research contributes to the valorization of the material and to the reduction of the linear logic of consumption and disposal, aligning with the principles of circularity.

5 CONCLUSION

The technological advancements that fueled the Industrial Revolutions can promote societal well-being when used responsibly by industry. Otherwise, the results will be the development of a consumer culture and, consequently, the generation of waste that will not return to the production chain, negatively impacting the environment. Some materials have properties conducive to reprocessing, but the sorting procedures are complex and unattractive to the market. When the complexity of the system is greater than the technical complexity, we can call the material an invisible problem material, especially when it is a problem so intrinsic to our daily lives that we barely notice it. Even so, through design for sustainability, it is possible to find ways to value this raw material to encourage all agents responsible for recycling.

This work presented the possibility of recovering glass shards with simplified procedures, focusing on their use in projects where aesthetic uniqueness is a value-adding attribute. It was concluded that changes in the residence time and/or maximum temperature in the casting process alter the physical characteristics of the vitreous volumetric modules. These changes can be parameterized according to the needs of the architectural project, depending on the spatial perception and the intended environment that the client desires. In processes

with simple equipment – without programming multiple thermal cycles and without cooling control – it is suggested to reach the liquidus point for modules with greater translucency and enough time to expel bubbles. Otherwise, the chances of material devitralization will increase.

For future studies, it is suggested to (i) precisely parameterize temperatures and exposure time, specifying the possible colors, textures, and translucency to be achieved; (ii) conduct tests with additives for color changes; and (iii) conduct mechanical resistance tests to integrate into the parameterization of suggestion (i).

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