



RE-FACADE GLASS PANELS

made by Construction & Demolition Recycled Glass

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STUDIO

SUSTAINABLE DESIGN GRADUATION STUDIO

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Having completed my journey as a master's student at the Faculty of Architecture and Built Environment of TU Delft, during a period of an unprecedented global health crisis with consequences on a social and personal level, these two years have had a considerable influence on my way of thinking and life. This influence was not just in academically level but also on a personal one, witnessing my maturation not only as an architect and engineer part of society but moreover as a citizen of the world. Specifically, the past eight months, in which I am involved in my graduation thesis, have been a unique and exciting learning experience with ups and downs in the whole study and research process.

This timeframe and needed tasks would not be possible without the assistance and encouragement of many people. I would like to thank from the bottom of my heart those people who, either with their presence or despite their earthly absence, stood as my helpers, guides, and animators.

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In general, working on a thesis like this is an experience like no other before. The exciting world of glass technology and recycling is not something that I was accustomed to, since my background is based on architectural design and expression. However, due to the fact that the more I read about glass as a material, the more fascinated I become about it, acting as an encouragement to get one more step at a time. I taught myself to look into the things that are possible to be done in a way, instead of letting myself be led by the difficulties and challenging situations I fell into.

I wish and hope that my adventure in the world of knowledge does not end with this postgraduate course but new "windows" will open and new scientific challenges will be set before me, transparent, bright, and multifaceted as glass!

ABSTRACT

Although glass is a known material for centuries, extensive usage and today's technology –with modern construction methods– made glass one of the most valuable materials of the present and future. Witnessing an immense progression and a broad innovative boost in the construction field, creating the perfect link between indoor and outdoor environments.

Given the growth of the world's population and its constant need to improve the way of living, the demand for new flat glass production, and the replacement of the older ones are rising. However, what is happening at the end-of-life of such architectural glass waste coming from the construction and demolition sector? A significant amount of post-consumer flat glass waste is generated, which is either down-cycled into low-value applications or discarded at the end of the life cycle, aggravating the existing problem of glass recycling whilst resulting in a significant impact on the ecological footprint.

Glass is a readily recyclable material, that can be remelted and reformed indefinitely into articles with the same quality and properties as the original one, nominating it as a perfect candidate in the transition efforts for a low-carbon environment. Even though the glass packaging industry is a successful recycling market, the same is not true for the floating glass industry, which occupies a more complex position. The vast majority of the remaining waste is rarely recycled into the same product, due to the lack of an organized recycling scheme, the incompatibility of different glass recipes, and the contamination rates of glazed products that could lead to risks in the total production line.

Among the down-recycled or landfilled glass, there is a great proportion of high-value float glass, pointing out the large potential in upgrading the glass recycling process from a linear chain to a circular one. The main scientific contribution of this research is the development and experimental verification with the aim of casting technique, not only new design concepts and engineering their fabrication following the design criteria, but also an ideal recycling collection system for cullets coming from the C&D sector while utilizing tools to check the product's performance and assessing its life cycle impact to the environment.

The casting method, as a more flexible process, that easily shifts between different recipes, and is less energy-intensive than float line, proves feasible for the fabrication of 100% recycled panels out of post-consumer flat glass waste. These findings are introduced by means of closed-loop alternatives that extend their service life, establishing at the same time the foundation for a circular life-cycle of architectural glass, while can assist as guidelines for further exploration. These components are monolithic elements with higher thickness, compared to the conventional thin-walled glass to tolerate a higher contamination rate, intended for building envelope applications. Their format is adopted and explored through a strategic approach of a translucent composite product, which is made out of specific glass waste layering arrangement between different purity grades of cullet in such a manner to form an advantage tensile strength on the recycled panel, which is transferred on the surfaces and reinforces the object.

Grasping the boundaries of glass recycling, which has been continuously stretching, in the last years, only some primary attempts have been made by TU Delft. These are referred on the fabrication of 3-dimensional strong glass components or glass panels emphasizing the aesthetic result always with the method of casting, unveiling the ambitious potential of glass upcycling for the building sector.

Identifying the scientific gap, the focus of this research is the proper mapping of the current situation of glass recycling, and the identification of the most promising glass C&D waste through experimental research by contacting melting and tools that have not been utilized before. The experimental analysis of the new concept concentrates on the development of the composite panel and the thermal shock testing in uneven temperatures, as the strength of recycled glass has already been investigated previously. Additionally, this concept will be assessed for further analysis and understanding of the whole effectiveness of the proposed supply chain of this recycling method, which is carried out for the first time.

The development of the new composite panel and its experimental evaluation displayed strong findings for further exploration. This thesis set-up could be a promising strategy for float glass recyclability but also in this product's performance, for transcending the main barriers of flat glass refusal owing to either impurities or different glass synthesis, while it is aligned with the 2050 Dutch policy of zero waste in the construction field and the European guidelines linked to the sustainable movement. Recovering discarded glass in cast glass products opens new paths to reintroduce such waste back to the supply chain, as a closed-loop approach.

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00 | INTRODUCTION

01 | RESEARCH FRAMEWORK

00.1 PROBLEM DEFINITION

Hardly any other material, that is present not only in our everyday environment but also in the built one, could sufficiently meet the current extensive usage of glass. An existence, so ordinary that we infrequently notice, glass is a material that has always fascinated architects and engineers. It witnessed an immense progression in the architectural sector creating the perfect link between indoor and outdoor environments.

In the European Union, buildings figure to be an elementary source of more than a third of all waste produced (European Commission, 2011). Sizable quantities of various materials and products in the C&D sector and extended construction areas constitute a significant waste stream while representing the ideal and inviting circumstances, where recycled materials could be exploited in a circular economy. Looking at the world of construction, glass panes are all the time used material. However, the continuously increasing trend in the architectural and engineering field towards wider applications of glass surfaces and demand for transparency in the building facades has spread the need for float glass production. The intense industrial manufacture of glass derives a high volume of embodied energy. Moreover, it implies the generation of a considerable amount of post-consumer sheet glass waste mainly discarded at their end-of-life, resulting in a significant impact on the ecological footprint.

Glass is a readily recyclable material, that can be remelted and reformed indefinitely into articles with the same quality and properties as the original one, nominating it as a perfect candidate in the transition efforts for a low-carbon environment. With apparent benefits in the recycling loop, aiming in the reduction of raw material use and non-renewable energy, the CO₂ emissions shrinkage and finally conclude in products' whole life-cycle. At the moment, a neat closed-loop system is carried out just for the post-consumer containers. Even if the glass packaging industry has long been utilized as a successful recycling market, the case isn't the same for the float glass industry which occupies a more complicated place. The vast majority of the remaining glass waste is rarely recycled into new glass products. Due to the lack of an organized recycling scheme, the incompatibility of different glass recipes, and the contamination rates of glass products, this waste are either downcycled to low-value applications or sent into the landfill, aggravating the existing landfill inextricable problem of glass recycling.

Among the down-recycled or landfilled glass, there is a great proportion of high-value float glass, which is used for architectural purposes, coming from the Construction & Demolition sector. This quantity of building glass category is rarely recycled into new glass products in its end-of-life, pointing out the large potential in upgrading the glass recycling process. More recycled glass cullets in the production line could preserve 1.23 million tons of raw materials and minimize by 230 thousand tons the gas emissions per year in Europe (Deloitte, 2016). Within the recycled flat glass, only small efforts have been made on the use of minor proportions of high-quality cullet back into the thin-walled glass production (ARUP).

Generally speaking, there are four principal barriers in the upcycling of C&D glass, related to the collection and manufacture of flat glass, and the glass status.

- Starting with, cullets coming from **disparate glass compositions cannot be easily homogenized in a mixture**, owing to different rates of melting points, thermal expansion coefficients, annealing times, and recipe compatibility.
- Secondly, **the inability of glass products to accommodate contamination** from unwanted foreign materials remains the main technical barrier in glass recycling. Contamination especially from C&D waste glass is technically challenging and strenuous to be removed (e.g. lamination, adhesives, coatings). Such contamination, when recycled in the glass batch, is capable of causing stress concentration, congesting failure by stress loss, or creating product foaming on the filling line. Besides, it can jeopardize the optical properties of the thin-walled glass, a rigorous prerequisite in float production line since it owns a characteristic color tint; thus, even completely clear (non-contaminated) cullet yet of a different color hue is not acceptable by float line production.
- What is more, **the float line industry is a rigid, fully automated, and continuous process, which is not flexible to switch its flow stream**, since it operates only under a determinate recipe and rigorous requirements for optical and compositional contamination; a change in the raw material batch would result in a considerable loss of production for competently modifying the material composition in the continuous ribbon.

- Finally, flat glass waste currently has a low market value and low recyclability potential, seeing that a **properly organized recycling collection and treatment system is absent**. Due to the lack of local treatment & recycling facilities to handle the source waste, following as a consequence in demanding logistics that diminish the associated environmental and financial profits of glass recycling.

The use of recycled cullet with diverse compositions or contamination could lead to crucial risks in the total line of float glass. These could jeopardize not only the quality of the final glass production, but also it risks the whole industrial process and facilities and it may lead to unwanted atmospheric emissions.

To overcome most of the aforementioned probabilities, the cast glass method will be explored for the manufacture of the glazed component. An interesting method that enables the fabrication of monolithic glass components with higher thickness than conventional flat glass. Owing to this monolithic nature, panels out of cast glass are allowed to carry more contamination and flaws than a sheet of thin-walled glass, barren of jeopardizing the strength or optical quality. Further, glass casting is a non-automated small-scale technique, which affords opportunities for experimentation in the firing schedule and glass formulas (Oikonomopoulou, 2019).

This technology could be a promising strategy for transcending the main barriers of C&D cullet refusal, owing to either impurities or different glass synthesis. In this direction, extensive research and primary attempts at TU Delft in an effort to enable the circular use of glass waste and its potential, have already proven that cast glass is a favorable solution. Recovering discarded glass in cast glass products opens new paths to reintroduce such waste back to the supply chain, as a closed-loop approach.

00.2 RESEARCH QUESTION

In accordance with the above stated problem statement, the main research question can be formed as follows:

« In what ways can we develop a glazed facade panel made by recycled glass, coming from Construction & Demolition cullets, through an upcycling approach and taking into account its life-cycle assessment? »

The main research question can be further analyzed into the following sub-questions:

1. What is happening at the end-of-life of architectural flat glass?
2. Although the glass packaging industry has long been utilized as a successful closed-loop recycling market, which are the causes why the float glass industry occupies a more complicated position?
3. What are the main practical implications and limitations of recycling C&D glass elements?
4. What are the dominant advantages of implementing product-life-extension strategies in C&D glass?
5. In what ways can we redesign an efficient and viable supply chain that can scale up the recommended upcycling of C&D glass waste?
6. How can the linear model of C&D glass recycling be modified to better suit the circular economy?
7. How the different purity grades of recycled cullet of flat glass could influence float glass production?
8. How casting methods can be employed for the glass panels manufactured for built environment applications and what are the advantages and limitations of this method?
9. How C&D glass waste could be transformed into reusable flat glass products for facade envelopes?
10. What are the main design variables for the fabrication and challenges involved in the development of a glazed facade panel made by C&D cullet?
11. In what ways can different thin-walled glass products coming through various treatment processes affect a new manufacturing procedure and thus the feasibility and marketability of the resulting product?
12. To what extent could the strategic approach of the composite panel of defined and undefined composition cullet layers be achieved?
13. How do the various defects caused by contaminants influence the remelted glazed product performance?
14. Which is the risk of damage from thermal shock due to the rapid change of the temperature on the external surface of the new panel?
15. What are the current end-of-life scenarios and which could be the circular life options with the aim of the life-cycle assessment?
16. Is the outcome of LCA efficient enough compared to the float glass industry products and how do the assumptions affect it?

00.3 OBJECTIVES

For the time being, it is obvious that a linear flat glass waste chain incurs, so the need to switch towards a circular life-cycle of such waste is rising. The growing interest, in this transition to closed-loop recycling, can be also seen and encouraged by float glass industries and different actors in the whole construction sector.

The scope of this research is to develop and experimentally verify with the aim of casting, not only new design concepts and engineering their fabrication in accordance with the design criteria, but also an ideal recycling collection system for cullets coming from the C&D sector, while assessing the life cycle analysis of the new recycled product.

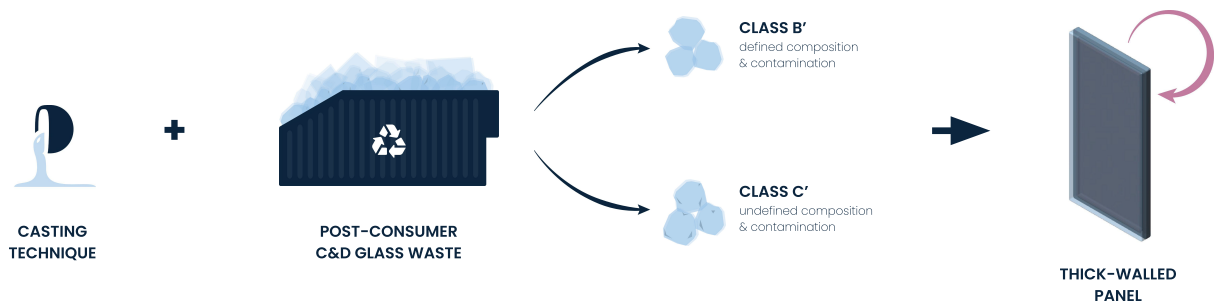


FIGURE 00.1 | Schematic representation of the panel's generation plan.

These new building components can be introduced by means of closed-loop alternatives that extend the service life of these products, establishing at the same time the foundation for a circular life-cycle of architectural glass. However, to comprehend totally how this upcycling method could be performed, first and foremost it is crucial to identify all the recycling obstacles that rest on the conventional life-cycle of C&D glass and must be overcome. With the aim of such glass waste as raw material, monolithic components will be created for built environment applications, produced through the casting method, with higher thickness compared to the conventional thin-walled glass, in order to be able to tolerate a higher contamination rate. This more flexible process that also follows a small-scale production compared to the common float-line, can play a major role in minimizing logistical and environmental costs of waste collection and transportation, whilst confining the necessity for further treatment and purification. Moreover, throughout the experimental research, the strategic approach of a translucent composite product is adopted where the defined composition's cullet that the contamination rate is known, will be placed on the outer surfaces of the panel to "reinforce" in this manner the variable cullet that the contamination rate is not possible to be counted, and will be placed in the inner body of the element.

Grasping the boundaries of glass recycling, which has been continuously stretching, only some primary attempts have been made in the last years by experts, companies, scientists, designers, architects, and engineers, unveiling the ambitious potential of glass upcycling for the building sector. These studies concentrate either on the fabrication of 3-dimensional strong glass components or in glass panels emphasizing the aesthetic result always with the method of casting. Identifying the gap in the research, the C&D glass waste can be transformed into a composite glass product for facade envelopes with exactly the same forming technique as the aforementioned attempts.

Nevertheless, the focus of this research is the proper mapping of the current situation of glass recycling, and the identification of the most promising glass C&D waste through experimental research by contacting melting and tools that have not been utilized before. The experimental analysis of the new concept concentrates on the development of the composite panel and the thermal shock testing in uneven temperatures, as the strength of recycled glass has already been investigated previously. Additionally, the whole embodied energy of this new concept will be assessed for further analysis and understanding of the whole effectiveness of the proposed supply chain of this novel recycling method, which is carried out for the first time.

Recycling C&D cullet is an ambitious path to meet the market's needs, while it contributes to the circular economy performance based on natural resources reuse. Design and specifications, for new facade components with the use of glass recycling, will take us a step closer to the national program «Circular Netherlands in 2050» that aids to reach pioneering material savings and become zero waste in the construction sector. Responsible manufacture and consumption will achieve results with significant social, economic, but most importantly

environmental advantages for the value chain. Considering glass recycling in the C&D field enables the reduction of ecological footprint by saving energy and raw materials, the mitigation of CO₂ emissions related to both air and water pollution, while it saves a lot of money and creates locally new employment positions in collection schemes and cullet treatment.

00.4 RELEVANCE

Generally, the sustainable design graduation studio focuses on innovative design technologies and methods in the scope of the built environment. This thesis topic is mainly related to sustainable materials and glass recycling held by the ongoing research at TU Delft, while is in line with the 2050 Dutch policy of zero waste in the construction field and the European guidelines linked to the sustainable movement.

Nowadays, the contemporary world is moving towards more robust and sustainably efficient environments on account of the present climate emergency, the abatement of nonrenewable energy, and the shortage of natural resources. The whole ideology, infrastructure, and legal system are crucial to alter all the more!

Glass is one of the oldest synthetic materials, which carved its own path into human activity, not only in everyday life but also in the scientific and technological aspects (Dyer, 2014). A widely used material, likewise in the building industry, its production continues ascending, causing a significant environmental impact. Even if the glass is a material totally recyclable in theory, and the recycling of it has been conducted since its discovery (Dyer, 2014), only a small part gets recycled mainly by the packaging industry (Bristogianni et al., 2018). Essentially, glass waste remains a significant unresolved problem and a considerable part refers to float glass, mainly used for architectural purposes, coming from the construction and demolition sector. This results from the fact that there is not a proper recycling system for such waste and also most of the discarded cullet fail to pass the quality standards due to contamination, as set by the current rigid float glass generation process, aftereffects from coatings, lamination, adhesives or incompatibility to the recipe, closing their life-cycle in the landfill.

Consequently, with the growing demand for glass, and the waste that comes from the Construction & Demolition sector, it is deemed necessary to explore the possibilities and potentials of investigating and mapping a closed-loop recycling system that will provide us with the needful sustainable material to be applied for new concepts for the built environment. It is really important to mention that this upcycling system in exploration is a new approach based on data coming from the industries and glass experts, and not many experiments have been done in this field. As it is in the aftermath, this experimental approach may be really challenging but it would give great potential while probing new data through a case study. The mapping of this upcycling method, in combination with the final product and detailing, will provide a deeper understanding of float glass recycling. Any development within this field could act as a guideline and inspiration for future reference and investigation for architects, engineers, scientists, and the glass industry.

00.5 RESEARCH METHODOLOGY

The research consists of five main parts, which are categorized according to the whole process evolution of the novel upcycling system, the new concept design, and experimental investigation. Each phase has a specific focus, as shown in the figure below, and is divided into the introduction, literature review, the design & analysis, design application, and the results discussion of the overall process and findings of the current research.

PART I (00: Introduction)

The introduction concentrates its scope on the overall research's comprehension. An illustration of the initial overview of the thesis, from the definition of the problems linked to the C&D recycling topic, the scientific gap, and the focus of the current research to the concept objectives and the relevance to the society. Moreover, the main research question is formed and supplemented by the indispensable sub-questions included in the whole research.

PART II (01: Literature Study, 02: Towards a Circular Life Cycle)

The current part provides all the theoretical framework of the research coming from the essential literature review and data collection, which accrued by exploring various reports, papers, books, and sites on the web, relevant to the chosen topic.

It actually prepares every aspect lying on the background of glass technology to assist in the new concept evaluation and design, earning meaningful insights for the survey's subject. Moreover, it helps in thorough comprehending of the problem in question. This part is also divided into smaller chapters. The first chapter of the literature review includes the study of glass as a material, providing an overview of its origin, composition, properties, the families coming according to its specific characteristics, and the production-formation techniques of glass. The following chapter focuses on glass recycling and its aspects from the current linear system collection and the limitations to a more technical path about the contamination of glass, which affects the quality standards on recycling cullet. Based on the aforementioned segments, the next part in the line focuses on the Construction & Demolition of glass waste expounding the reasoning behind selecting the current glass waste stream and assists to understand the current situation of such waste, its promising exploitation of them, and how this can proceed back in the production loop.

Additionally, this part includes a section, which provides a step-by-step review of the ongoing linear status of flat glass recycling and represents all the barriers present in the circular approach, which should be addressed by suggesting improvements toward a sustainable concept of glazed waste management. Finally, it includes the illustration of a new circular economy model of C&D glass recycling as an imperative need while our world is moving towards more sustainable environments, highlighting the need for an upcycling method for sheet glass.

PART III (03: Experimental Research, 04: Sustainability Assessment)

Two main branches constitute the third part of the current report. On the one hand, is the whole experimental procedure and analysis of the findings, and on the other hand the LCA calculations of the panel fabrication.

The former branch develops the design procedure heading for the experimental validation of the proposed recycling and fabrication system, and the glazed facade panel deployed within the frame of the current study. More specifically, it indicates all the necessary preparation for the upcoming design through the decision making such as the material selection, the evaluated design criteria, the experimental set-up, and the explanation of the product's performance testification. Then, the elaborative analysis of the experimental research steps and the findings are developed through exploring methods concerning the casting process. At the end of this phase, a design evaluation is held to identify the final concept scenario for the manufacture of the recycling glass composite product, which is further explored within the presence of faults analysis in the product's surfaces and the bulk, the residual stress assessment with the aim of photo-elasticity and finally, the thermal shock tests are carried out.

Last but not least, a life-cycle assessment (LCA) is investigated. The aim is to calculate the embodied energy of the recycled panel composite, highlighting its sustainable benefits as a circular approach, which exploits the existing float glass waste.

PART IV (05: Design Application)

This chapter points out the possible applications of the glazed panel made by C&D glass cullet. It includes the implementation in case studies related to the built environment, from the outer skin of buildings to the inner partition walls and flooring, for the purpose of exhibiting the possibilities of the recycled panel design.

PART V (06: Conclusion)

The final conclusion indicates the overall evaluation of the research and experimentations. The presented conclusions, the reflection on production and design of the installation of the recycled glass panel made by C&D cullet through the casting method reveal all the contingents for further exploring and development for other applications and recommendations for future studies.

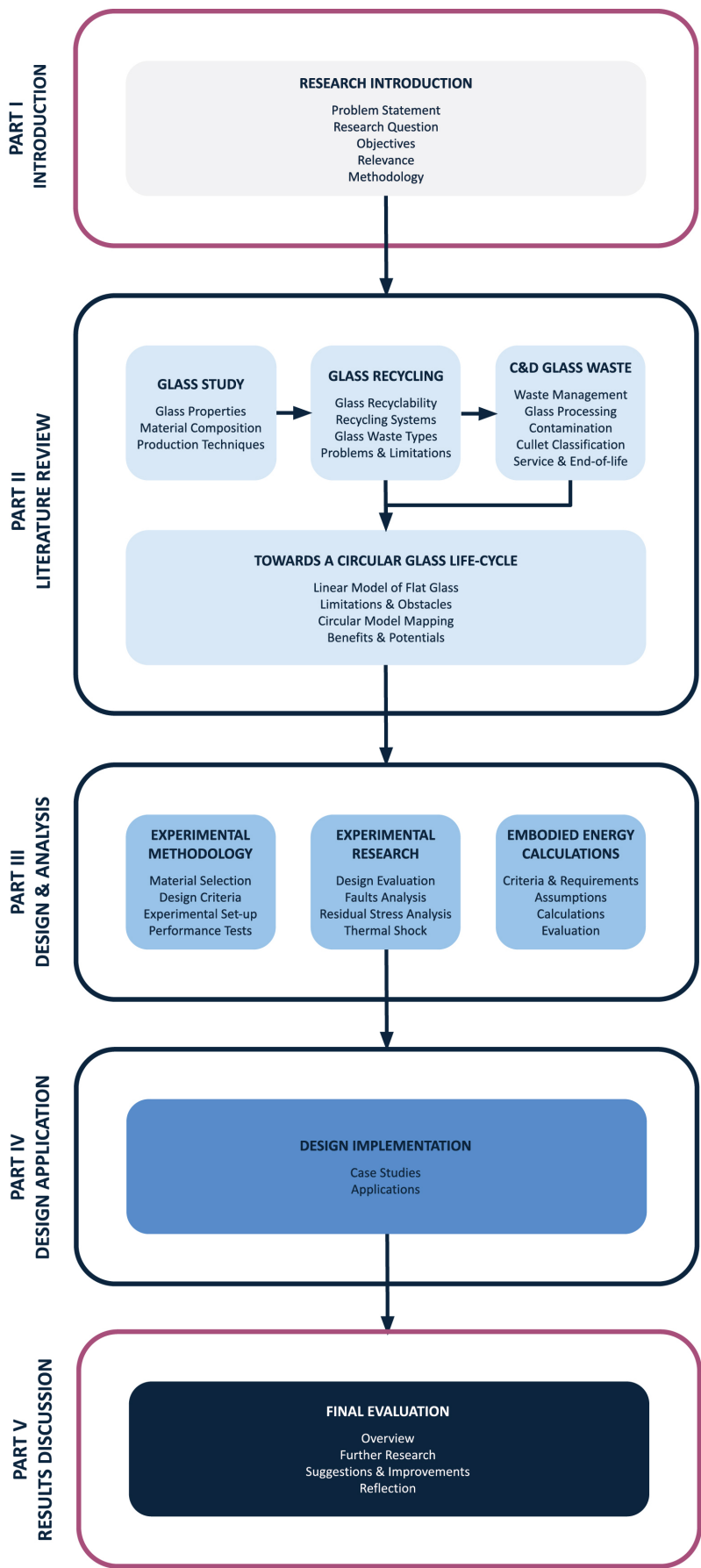


FIGURE 00.2 | Thesis outline diagram.

01 | LITERATURE STUDY

01 | GLASS STUDY

01.1 GLASS DEFINITION

In broader usage, “glass” as a term is said to be derived from the Germanic term “*glaza*” (Schittich et al, 2007) and the Latin word “*glaesum*”, both meaning “amber”, “glare” or “shimmer”. Its definition can also be traced back to the Old English word *glæs* (glass; a glass vessel), probably derived from an old Teutonic root *gla-*, a variant of *glo-*, having the general sense of shining. It is also related to the Proto-Indo-European root *ghel-*, denoting “to shine”, connected to the bright colors, especially “yellow” and “green”, or materials, such as gold, words having to do with shining and glittering (Harper).

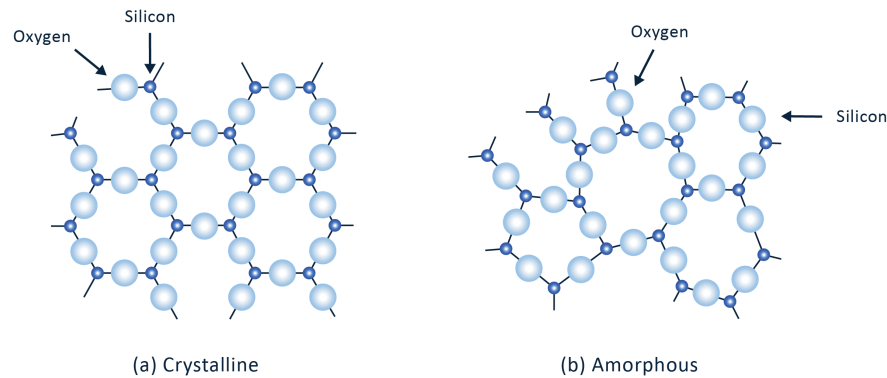


FIGURE 01.1 |

The two alternative structures for silica, the basis of most glasses: (a) Crystalline silica, and (b) Glassy or amorphous silica. (Ashby, 2019)

Glass is defined as “a non-crystalline, amorphous solid material completely lacking in long-range, periodic atomic structure, and exhibiting a region of glass transformation behavior” (Shelby, 2005), it is also understood as a hard, brittle, typically transparent substance but may be translucent or opaque, “with a relatively high softening point, substantially insoluble in water and organic solvents, and non-inflammable in usual sense” (Shand, 1958). From a technical point of view, glass is an inorganic product produced by fusion and rapid cooling of the molten in such a manner as to prevent the ordering of atoms into a visible crystalline formation. The latter statement indicates the point that glass molecules are in a completely random order, without any crystal lattice, so that their condition is connected to a solidified liquid. Meaning that, even if a material it does not have a melting point when heat is applied, its state progressively changes from a solid condition to a certain fluidity (plastic-viscous) and finally to a liquid one (Schittich et al, 2007).

01.2 MATERIAL ORIGIN

Generally, glass has a very abundant history. Its roots start back in ancient times, with the originative records being detected and placed 3,500 years ago in the Egyptian chronicles. However, humankind possessed the knowledge of glassmaking for at least 6,000 years, long before they had found out how iron is smelted.

Stone Age

In Stone Age, volcanoes served the role of glass furnaces for naturally occurring glass, called obsidian, generated by volcanic action. This type of natural glass can be found everywhere in the world since it is formed when certain typology of stones fuse, as a consequence of events like volcanic eruptions, lightning strikes, or meteorites impact, that creates the proper high-temperature conditions, and then rapidly cool and solidify (Ward-Harvey, 2009).

Paleolithic man is believed to have exploited the very sharp edges of the glass to make suitable cutting tools and weapons, such as arrows, spearheads, knives, and razors. These tools were made either from volcanic obsidian, usually black and translucent, or tektites, coming from ejected meteoric fragments during an impact, in gravel-sized bodies (McCall, 2001).

Archeological evidence indicates that Phoenician traders apprehended the existence of glass in the territory of Lebanon and coastal Syria, Mesopotamia, or ancient Egypt around 5000 BC. This might be the

place where man-made glass arose (Henderson, 2013). A glaze mixture made up of sand and minerals, which with the high fire temperature, melted and fused to generate an opaque liquid to create glass.

Bronze Age

The earliest pieces of evidence of technical glazed objects were on the whole glass beads and jewels, dated to 3500 BC. Premature glass derivatives were hardly ever transparent carrying impurities and small defects, even if it was of little importance for the manufacture of glass products (Ward-Harvey, 2009). Around the same period, in central Mesopotamia, glazes on the surface of utensils, like pots and vases, were produced with the aim of raw glass materials, which became widespread in the Mediterranean area due to the trade of Phoenician dealers and shipping (Rasmussen, 2015).

Around 1600 BC, there was a rattling development of glassmaking in Egypt and Mesopotamia; glass fragments demonstrated their existence in that region. These archeological proofs referred to colored glass sticks, beads, and vases (Henderson, 2013). Possibly the latter pointed out the derivation of hollow glass intentional manufacture. Nevertheless, extended detail on shapes and uses got more diverse with the input of glass blower's pipe technology, roughly by 50 BC (Cummings, 2002).

From the middle of the 2nd century BC, craftsmen had developed production methods of glass pots, vessels, and bowls with the assistance of casting molds. The earliest examples of such objects were found in Egypt carrying the name of the Pharaoh Thoutmosis III (Nicholson, 2006).

Iron Age

In the following years, there was limited information for further progress in glassmaking know-how until 900 BC. Over the next 500 years, the core of glass production was placed in Alessandria of Egypt, from where it possibly spread to Italy. Approximately that period, the first manual with the instructions on how to generate and form glass was written in tablets from the great library of the Assyrian king Ashurbanipal (Moorey, 1999).

A notable intervention in glassmaking was introduced with the discovery of glassblowing, probably attributed to the invention of the blowing iron by Syrian craftsmen about 200 BC (Carter et al. 2013). This novelty triggered the fabrication of thin-walled hollow vessels in an extensive variety of sizes and forms, a process with few discrepancies compared to the contemporary one (Schittich et al, 2007).

Roman Age

Ancient Romans played a crucial role in flourishing and evolving glassmaking technology and work across Europe. In 100 BC, the glass blowing inside molds was found thanks to them. An innovation that pushed the growth of available shapes for hollow glass products (Schittich et al, 2007). Moreover, Romans established the use of glass as part of building envelopes, with the discovery of clear glass that was cast or drawn (Macfarlane, 2003). Even, though these bluish-green panes lacked good optical quality, they appeared in the most important buildings in Rome and the surrounding area.

Roman glassmaking techniques spread to northern European countries, as a result of the migration wave. Merovingian Franks were the first who adopted the glass production tradition and extensively used it on building envelopes, especially in churches and monasteries (Schittich et al, 2007). During this period two principal glass formation techniques were found. During the 1st century AD, the ingenious Syrian craftsmen firstly discovered the way to produce flat glass using a blowing iron in the cylinder procedure, whilst they also developed the crown method to generate round shapes of flat glass by 400 AD (Schittich et al, 2007).

Middle Ages

Until the present time, there have been minimum alterations in the techniques and batch of ingredients used to make glass. Excavations held in Italian territory disinterred archeological pieces, dated between the years 700 and 800 AD, indicating a period of change from ancient to early Middle Ages in glassmaking methodology. In the 1st century, a semantic transition happened in the European area concerning the glassmaking process. This change had to do with the gradual replacement of soda glass as raw material for the potash, introducing the first differentiation in glass typologies along with Europe (Encyclopedia Britannica).

During this period, extensive use of glass in windows of churches and cathedrals is observed, connected to the development of glass sheet production, remaining still great up to the Middle Ages (Schittich et al, 2007). The flat glass pieces thus generated would then be assembled with lead strips and pieced together

to compose the windows. Center of the glassmaking world took place on the island of Murano in Venice, Italy. The Venetian merchant fleet ruled the Mediterranean trade market and assisted to supply craftsmen with needful knowledge and techniques, becoming later the reason for glass production skills to be transmitted to other European parts, especially in Germany and France (Encyclopedia Britannica). Besides, Murano glassmakers invented the extraordinary purity and absence of color glass "*crystallo*", because of its resemblance to natural crystal, which was extensively used for vessels, windows, mirrors, ships' lanterns, and spectacle lenses (Ward-Harvey, 2009).

Modern Era

The glass outbreak came around the 17th century when glass became available for everyone (Schittich et al, 2007). In 1675, the lead crystal glass was patented by English glassmaker George Ravenscroft, a product with a high refractive index, which was suitable for deep cutting and engraving (Encyclopedia Britannica). Some years later, the Frenchman Bernard Perrot invented an important novelty for the production of flat glass as a result of "plate pouring" (Schittich et al, 2007). In this cast glass procedure, molten glass is poured onto a preheated flat table, pressed into a pane, and rolled out flat.

Along with the Industrial Revolution, the mechanical mass production of glass and in-depth scientific research of glass composition and qualities flourished (Freiman, 2007). In 1839, the Chance Brothers adapted a method of cutting, grinding, and polishing the blown cylinder to perfect the surface finish and prevent the products from breakage (Schittich et al, 2007). In 1856, Friedrich Siemens invented an upgraded version of a melting furnace with limited fuel consumption and continuous production of greater amounts of molten glass with better quality and at reduced prices (Encyclopedia Britannica). In the same period, German scientists Otto Schott and Ernst Abbey explored significant technological benefits of glass related to its thermal and optical properties, while the American engineer Michael Owens built a mechanical blowing machine for bottle production (Schittich et al, 2007). Finally, the American John H. Lubbers created an automatic procedure, which merges blowing and drawing (Cable, 2004).

Contemporary History

Throughout the 20th century, productive information exchanged between glassmakers from Belgium, Britain and the States guided the glass manufacture to vital novelties and improvements connected to the glass fabrication performance. These also played a crucial role in glass mass production and availability, placing it as a material component of the built environment and leading to novel applications.

In sheet glass production, the first innovation popped up in 1905 by Belgian Foucault with a vertically drawn production of continuous flat glass. In addition, another Belgian, named Emil Bicheroux introduced a procedure of molten glass poured into a pot and then through two rollers, for bigger thickness and easiest finishing methods (Schittich et al, 2007). Another launch came in 1910 by the French scientist Edouard Benedictus. He introduced the safety glass with the invention of the lamination procedure for further glass strengthening with the name "Triplex" (Encyclopedia Britannica).

In the period of early 1930s, the automatic production process of gob feeder and IS (individual section) machine boomed the rapid supply of bottles, which both processes combination remains the same in the mechanical glass container production until today (Glass on Web, 2012). Just after, the mass production of Depression glass came to light, a clear or colored translucent machine-made glassware, where cast pieces emerged from the mold with etched art on the top surface of glass products.

By 1959, the Pilkington Bros, in Britain perfected the float glass process (Ward-Harvey, 2009). High-quality and distortion-free flat glass ribbons are generated by drawing directly from the bath of molten tin, glass spreads, and flattens, and then passes to the annealing lehr (Nascimento, 2014). This procedure still forms the most widespread and efficient methods, providing at the same time the fundamental principle of most float glass production lines, today.

Although the history of flat glass came to an "end" roughly 60 years ago, technological evolution, manufacturing developments, and new techniques of glassmaking are still being carried out, by reinventing glass products and continuously improving where they can be applied. Worthy of mention is the flat glass boundaries, which have been kept on being stretched, with panel sizes reaching up to 20 meters in length. Glass has exemplified to be one of the dominant enablers of modern human civilization. Applications on the thin-walled glass of chemically strengthened, computerized control systems, touchscreens, structural glass, solar control technology, and many other innovations may not yet be ready, to be characterized as a part of the abundant history of glass.

01.3 OVERVIEW OF GLASS PROPERTIES

Glass, like any other material, carries some unique characteristics. These quantitative properties are used as a metric between different materials to be compared one to another for their benefits or drawbacks. Different glass families may possess some range discrepancies between one or even more properties, depending on independent variables such as their chemical constitution and the production process. Generally, glass is widely known for its transparency and brittleness, features that place it as a very engaging material and simultaneously very challenging. Consequently, selecting the proper typology of glass for a particular application equates to comprehending all of the properties' combinations that glass variants belong.

TABLE 01.1 | General physical properties of soda-lime glass. (Schittich et al, 2007)

Property	Symbol	Value with units
Density at 18°C	ρ	2500 kg/m ³
Hardness		6 units on the Mohs scale
Modulus of elasticity	E	7×10^{10} Pa
Poisson's ratio	μ	0.2
Specific heat capacity	c	0.72×10^3 J/(kg x K)
Average coefficient of thermal expansion	α	9×10^{-6} K ⁻¹
Thermal conductivity	λ	1 W/(m x K)
Average refractive index in the visible range of wavelengths 380-780nm	n	1.5

Mechanical Properties

As any other solid material, glass possesses its own mechanical properties, determining the level of stress that is able to resist, characteristics that sometimes are superior to unreinforced concrete (Oikonomopoulou, 2019). First and foremost, it presents elastic and strength properties to be restored to its initial shape when a force is applied to it. But even if it is a perfectly elastic material, it does not exhibit permanent deformation, until its breakage, which occurs always in tension. Consequently, as a material, it does not have a yield point. The latter witnesses that glass owes higher compressive strength than tensile one, due to the existence of imperfections or flaws, the majority of which are observed on glass surfaces (Shelby, 2005). Additionally, glass is described by its hardness, withstanding penetration, and friction.

Thermal Properties

Glass is examined throughout a sequence of factors concerning the thermal properties and it clearly has a significant effect on the right choice of glass product. An important property is a thermal expansion, signifying the extension of the object to become larger in size when the temperature changes. This factor is vital in the glass's resistance to thermal shock and it defines the stresses, which are set up in a glazed object under heating or cooling that the glass withstands. Next is thermal conductivity, related to the amount of required heat flow that crosses the sectional area of a glazed object. However, this property varies in the manner of the ingredient components of different glasses, causing significant changes in how some glass types conduct compared to others. In contrast to crystalline solid bodies, this material does not have a defined melting point due to its amorphous structure. It is easily transformed from the solid state to viscous liquids at moderately high temperatures and it can be formed into a variety of shapes.

Optical Properties

Glass owes its transparent state to the absence of crystalline structure, caused by the completely random order of its molecules. It is a material optically isotropic; resulting in homogeneous properties in every direction it is measured, regardless of its size (Ashby et al, 2019). Of all the transparent materials in our possession, glass is the most widely used one and compared to some other solids, it transmits light in the visible region of the spectrum (Shelby, 2005). Moreover, it tends the greatest range of refractive index, and colors, while the latter is based on optical effects of wavelength. Glass is based on amorphous silica, a perfect solvent of dissolved oxides over a broad spectrum of concentrations, which easily lets the optical properties of glass to be adaptable to alternative design needs (Ashby et al, 2019). This results on account

of several measurements when designating the total amount of light passing through it, such as its capability to refract, reflect and transmit light.

When light falls on a glazed surface, a series of phenomena is held. A part of it, it is reflected, concerning the reflectivity when an amount of light is returned from the surface. The rest enters the glass body and refracts according to the material's density, meaning that the amount of light, which passes into the glass, bends through an angle. When light is in this transition face, from air to the denser optical medium of glass, its velocity of it changes and the ratio between these speeds is referred to as the refractive index. A part of the light energy is converted to heat, lost within the glass, and this quantity is neither reflected nor transmitted, but regards the absorption property of glass. Finally, the transmittance of glass measures the amount of visible light passing within the material.

Electrical Properties

Glass is a material that is utilized to a great extent by the electrical industry, especially in branches dealing with lamps and electronic devices (Shand, 1958). When choosing a product for such use, there are several factors to be considered when dealing with the electrical features of glass. In spite of the fact that they owe charged metallic ions, which have the ability to sustain electric stream, electrical activity is blocked by the high viscousness of the material, locating it as an excellent electrical insulator, related to the volume of resistivity of glass. However, different glasses can show different resistivity rates, linked to changes in glass composition and temperature. The dielectric constant of glass measures its ability of it to stably store electrical energy, useful in electrical or electronic device applications.

Chemical Properties

Among many different materials at our disposal, glass occupies a notable high place in the ranking of chemical durability. Generally speaking, these kinds of chemical properties are occurring when glass products incur a chemical change or just a reaction. Even if the glass is a remarkably corrosion-resistant material, this begins to be a matter of negotiation under some certain circumstances. Glass surface is affected when it is exposed to acid, sodium, or alkali metal ions, liquid or vapor, and sometimes in conjunction with high temperature. During these procedures, the actual material structure of glass changes, affecting the electrical, mechanical, chemical, thermal, and optical properties of the glass.

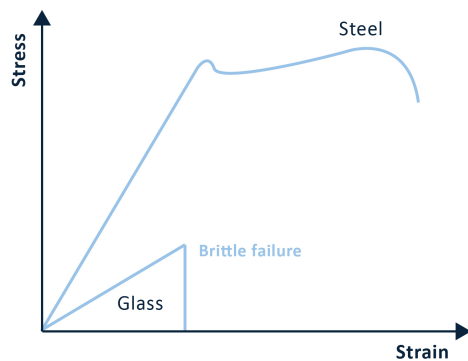


FIGURE 01.2 |

Stress/strain curve for glass and steel. (O'Regan, 2014)

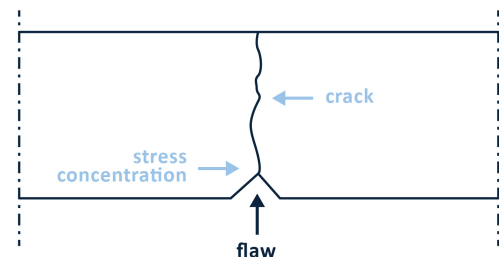


FIGURE 01.3 |

Schematic representation of flaw development to a crack on glass, by (Haldimann et al., 2008).

01.4 INGREDIENTS COMPOSITION

Since the natural glass was demonstrated to be practical and profitable to paleolithic man, it was a logical consequence to proceed in the development of man-made glass production ages ago. Over the centuries, experimentations with heated silica-sand and stabilizing oxides in fluxes have generated numerous varied glass recipes and generation techniques, placing glass in the position of the versatile material it is at the present moment.

Even if there is a wide variety of methods, the prevailing majority is made up of mixing ingredients that afterward melt at high temperatures to form molten glass. This process refers to the composition of raw material with the respective quantities for the batch recipe and the mixing of it to assure uniformity of the

mixture. Then, the batch is subjected to high temperature, where chemical and physical events occur to result in the fusion, whilst if it is needed further processing is happening to the melting glass, such as subtraction of unmelted remnants, bubbles, and specks of dirt. Before it pulls out of the melting unit, the glazed product is cooled to be manageable.

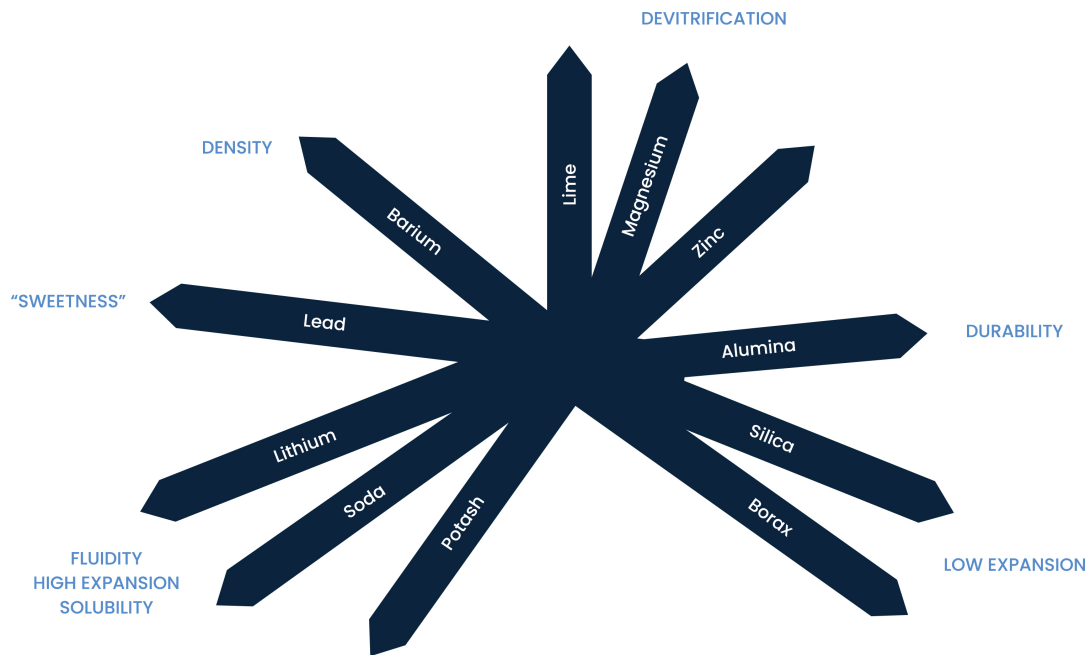


FIGURE 01.4 | Relative properties imparted by oxide ingredients. (Stone, 2010)

Of all the raw materials that are used in the glass formation, the main one is silica. This major component can be found in abundance on our planet, since it is the major constituent of sand, in many parts of the world. Additional to silica, for the manufacture of glass variants, are more oxides, which make up the batch. Despite the source of the ingredients used for the mixture, the batch materials can be categorized into five classes according to their role in the composition process of specific glass types:

- 01 Glass Former/Network Former:** It constitutes the bulk of the glass since it is the substantial component of any glass batch. Sometimes, different glass types are made up of more than one glass-forming oxide that creates the backbone of the glass network. Silicon oxide (SiO_2) is the most typical network-forming constituent, but there are more such as boric oxide (B_2O_3), germanium (GeO_2), and phosphoric oxide (P_2O_5).
- 02 Fluxes:** They are substances, usually oxides, which are added to the batch of glass in order to lower the extremely high melting point of the network former of glass within practical limits. These additives help to drop the melting point at least to 1600°C . The most commonly used fluxes for glass formation are soda (Na_2O), lead (PbO), potassium (K_2O), and lithium (Li_2O). Even if these constituents reduce the processing temperature and synchronously the manufacturing cost, the insertion of them in great proportion may cause significant demotion of glass properties.
- 03 Property Modifiers:** They are chemicals that are added in the batch in small proportions, to counter the degradation in the properties of glass. These modifiers interrupt the normal bonding, as charged ions, between glass-forming elements and oxygen to decrease the number of strong bonds and the concentration of the oxides in the glass structure, while it lowers the melting point of glass and moreover its viscosity. These substances include aluminum oxide (Al_2O_3), lime (CaO), magnesium (MgO), and others.
- 04 Colorants:** Inorganic materials are used to control the final color of glazed objects. Adding metal oxides or metal powders to molten glass can succeed in changing the color. There is a range of constituents for color alteration according to the desired color, for instance, green color is made with iron (FeO) or chromium oxide (CrO), while amber is created with combinations such iron oxide (FeO) and sulfur (SO_2), or coal (C) and sulfur (SO_2), etc.
- 05 Fining Agents:** They are referred to as chemical compounds that are added to glass-forming batches in really small amounts ($<1\text{wt}\%$), with the aim of promoting fining mechanisms of glass. This kind of

mechanism deals with the removal of the bubbles that may be formed by atmospheric gasses from the molten glass, during the time of batch melting or ingredients disintegration. The most considerable fining additives are arsenic (As) and antimony oxides (Sb_2O_3), potassium (K_2O), and sodium nitrates (NaNO_3), as well as a number of sulfates.

Some of the categorized ingredients may fall into different categories. This is related to the fact that these compounds serve diverse purposes on the batch of melting glass.

01.5 MAIN GLASS FAMILIES

According to its composition, commercial glass can be classified into a few major categories. In practice, there are various formulas of different glass typologies that actually conclude to diverse glass properties and features (Bristogianni et al. 2018). These values may slightly deflect in small ranges, considering at the end the average for the glass classification. An approximated collection of the different glass families, the chemical composition, typical remarks, and usual product applications are listed in the following table, based on the book "Unveiling the third dimension of glass" by F. Oikonomopolou (2019).



FIGURE 01.5 | Main families of commercial glass, based on (Bristogianni et al., 2018)

Soda-lime Glass

The most prevalent glass type is soda-lime-silica glass, the leader in glass manufacture since it accounts for 90% of the total output (Robertson, 2005) while reporting for hundreds of production years. The reason for its prevalence is its high workability. In contrast to pure silica, which presents an extremely high melting temperature and viscosity that is hard to work with, extra compounds have to be added to facilitate the procedure. The presence of sodium carbonate (Na_2CO_3) aims to decrease the glass-transition temperature, whilst calcium oxide (CaO), commonly called lime, operates as a stabilizer of silica to give optimum chemical durability. Nevertheless, due to its high thermal expansion, it features low resistance to sudden temperature fluctuations and it is not scratch resilient. Soda-lime articles, apart from the aforementioned characteristics, are inexpensive, chemically stable, reasonably hard, and able to be remelted several times to be formed or even recycled. All these qualities provide soda-lime glass with a broad application range, incorporating window panes, glass containers, light bulbs, and art object production.

Borosilicate Glass

Borosilicate glass accounts for a wide composition range, together with application variety. Borosilicate glass carries, apart from silica which is the major former, a minimum of 5% boric oxide (B_2O_3) and approximately 8% of other alkali oxides. It is mainly applied when efficient performance is needed for durability, chemical corrosion, and heat resistance for sudden temperature fluctuations since it retains its shape throughout these events. Due to its small thermal coefficient, it is less responsive to thermal stresses than soda-lime glass. These characteristics along with its somewhat more expensive production price,

constitute the required conditions to be useful in special chemical and thermal applications, such as laboratory equipment, ovenware (pyrex), light bulbs, and pharmaceutical implements.

Lead Glass

Lead glass, commonly called crystal, is a glass variant desirable for diverse designs due to its clarity. Typically, a crystal's calcium components are displaced by lead synthesis. Lead glass is characterized by its softness since it is more fluid and easier to work with, through a wider processing temperature range than soda-lime, placing it as the second least pricey choice. The quality of being easy to mold arises from the high percentage of lead oxide in its composition, a minimum batch of 20%, while the rest consists of roughly 60% silica and no special compounds, such as soda and potassium oxide. Lead glass has low resistance to high temperatures and as soft glass, it is vulnerable to scratching. The brilliance of its materiality and spectacular reflection relies on the fact that it possesses a high refractive index. Even if the lead is a toxic material it was often used for glassware and artifacts in the past. Thanks to its high electrical resistance properties, it is also applied for electrical devices and thermometer tubing, while the ability to absorb x-rays and the protection from their noxious radiation, whilst it maintains its optical transparency, employs it for nuclear applications.

Aluminosilicate Glass

Aluminosilicate glass took its name from the prevailing aluminum oxide (Al_2O_3) in its chemical structure. It consists of the silica former, the aluminum percentage at levels between 20-40%, and more alkaline compounds. Therefore, various typologies of Aluminosilicate glass exist, determined by their chemical compositions, with a particular focus on the oxide levels. Due to its high operating temperature, it is quite demanding to be manufactured, which leads to increased price rates. Additionally, it owes good resistance to thermal shock and tolerates temperature alterations, so it is used as a sealant for high-temperature systems such as cookware utensils, glass screens, high-temperature thermometer tubes, and sometimes in space shuttle windows. Its resistance to scratches and hard quality offer significant impact protection; making it perfect for touch screens and laminated safety glass, broadly known by the name Gorilla glass.

High Silica Glass

The term high silica simply describes the types of high-purity glass. It is composed mostly of silicon dioxide (SiO_2) and boron oxide (B_2O_3). In contrast to vitreous silica, it can be manufactured in a variety of shapes. It presents very low thermal expansion, chemical durability, and quite good optical and mechanical properties. The high operating temperature is a result of fluxing agents lacking, placing it as an expensive glass kind, which requires high energy levels and production costs for its manufacture. Its perfect image of thermal shock behavior promotes it for space vehicles, some special glassware production, and special metrology instruments.

Fused Quartz Glass

Fused Quartz glass consists of melting naturally occurring crystalline silica, such as sand or rock crystal, positing it to be the most expensive kind among the glass types. The batch is made only by pure silica in the non-crystalline state, compared to other glass categories that are made with a variety of chemical bonds, while non-silicate elements are removed from it, so as to contain very little amounts of metallic impurities. As the fusing occurs at considerably high levels, more than 1650 °C, it is really tough to be manufactured. Furthermore, this has a consequence of a very limited application field, whilst the likelihood of recycling is considerably shallow (Oikonomopoulou, 2019). Due to its extreme purity, it is distinguished by its excellent characteristics that cannot be seen in other glass types. These are the high transparency with improved optical transmission to a wider spectral range (UV and IR), durable in heat changes because of the low thermal expansion, and excellent chemical inertness. Lastly, it is suitable especially for aerospace applications and laboratory equipment for instance distillation containers for various solvents.

Glass Fibers

Glass fibers refer to groups or masses of a great number of super-thin threads made of glass material. This material is divided into two categories, based on the intended applications, which are the typical thermal-sound insulation fibers, such as wool fibers, and the not-so-usual high-value fibers used to fabricate composites or glass clothes (Shelby, 2005). The major textile grade of glass fibers is silicon oxide. However, the first category has a quite complicated structure composition with boric oxide, alkali, alkaline-earth, and alumina in small amounts, while on the other hand, the batch is composed of great concentrations of alumina. The main characteristics of this type are the lightweight material and use as thermal and sound insulators, while it is sensitive to chemical attack. The transformation temperature and the electrical

conductivity are at the same level as typical glass. Glass fibers are used in various fields such as aerospace, automobile, marine, and construction sectors.

Glass Ceramics

Glass-ceramics are partly crystallized glass, formed by controlled nucleation and heat treatment in a combination of a crystalline phase and an amorphous one. They have the benefits of glass production, together with the special properties of ceramics. Its crystallinity ranges between 30-90% and brings in a series of special characteristics such as superior resistance to thermal shock failure, great impact resistance, high strength and toughness, and low negative thermal expansion. The most common glass ceramics are based on either the lithium, sodium, or magnesium aluminosilicate systems (Shelby, 2005). With their unique properties, they possess a range of applications, including cookware, induction stoves and cooktops, advanced optics, high-temperature furnaces as insulation material, and infrared applications.

TABLE 01.2 | Approximate chemical compositions and typical applications of the different glass types, based on (Oikonomopoulou and Shand et.al).

Glass Types	Approximate Compositions	Observations	Typical Applications
Soda-lime	73% SiO ₂ 17% Na ₂ O 5% CaO 4% MgO 1% Al ₂ O ₃	Durable. Least expensive type of glass. Poor thermal resistance. Poor resistance to strong alkalis (e.g. wet cement).	1. Window panes 2. Bottles 3. Façade glass
Borosilicate	80% SiO ₂ 13% B ₂ O ₃ 4% Na ₂ O 2.3% Al ₂ O ₃ 0.1% K ₂ O	Good thermal shock and chemical resistance. More expensive than soda-lime and lead glass.	1. Laboratory glassware 2. Household ovenware 3. Lightbulbs 4. Telescope mirrors
Aluminosilicate	57% SiO ₂ 20.5% Al ₂ O ₃ 12% MgO 1% Na ₂ O 5.5% CaO	Very good thermal shock and chemical resistance. High manufacturing cost.	1. Mobile phone screens 2. Fiber glass 3. High temperature thermometers 4. Combustion tubes
Fused Silica (Quartz)	99.5% SiO ₂	Highest thermal shock and chemical resistance. Comparatively high melting point. Difficult to work with. High production cost.	1. Outer windows on space vehicles 2. Telescope mirrors
Lead Silicate	63% SiO ₂ 21% PbO 7.6% Na ₂ O 6% K ₂ O 0.3% CaO 0.2% MgO 0.2% B ₂ O ₃ 0.6% Al ₂ O ₃	Second least expensive type of glass. Softer glass compared to other types. Easy to cold-work. Poor thermal properties. Good electrical insulating properties.	1. Artistic ware 2. Neon-sign tubes 3. TV screens (CRT) 4. Absorption of X-rays (high PbO %)
High (96%) Silica	96% SiO ₂ 3% B ₂ O ₃	Very good thermal shock and chemical resistance. Meticulous manufacturing process and high production cost.	1. Furnace sight glasses 2. Outer windows on space vehicles
Glass Fibers ^a (E-glass)	55% SiO ₂ 15% Al ₂ O ₃ 7% B ₂ O ₃ 3% MgO 19% CaO 0.2% Na ₂ O 0.2% K ₂ O 0.2% Fe ₂ O ₃ 0.1% F ₂ 0.1% TiO ₂	Good thermal and sound insulators. Poor chemical resistance. Low electrical conductivity. Lightweight material.	1. Thermal/sound/electrical insulation 2. Heat/corrosion-resistant fabrics
Glass Ceramics ^b (Macor)	46% SiO ₂ 17% MgO 10% K ₂ O 16% Al ₂ O ₃ 6.5% B ₂ O ₃ 4.5% F	Semi-/Crystalline structure. Low to negative thermal expansion. Excellent mechanical properties. Very good at thermal shock. Zero porosity.	1. Cookwares and bakewares 2. Cooktops 3. Induction stoves 4. Industrial processes 5. Astronomical Telescopes

^a The glass fibers approximate composition constituents are referred to E-glass.

^b The glass ceramics approximate composition constituents are referred to Macor technical ceramic category.

TABLE 01.3 | Approximate properties of the different glass types of Table 1.2 based on (Oikonomopoulou, Shand et.al, Martlew and Shelby).

Glass Types	Means Melting Point at 10Pa.s ^a	Softening Point	Annealing Point	Strain Point	Density	Coefficient of Expansion 0 - 300°C	Young's Modulus
Lead Silicate	1200-1300	626	435	395	2850	9.1	62
Soda-lime	1350-1400	730	548	505	2460	8.5	69
Borosilicate	1450-1550	780	525	480	2230	3.4	63
Aluminosilicate	1500-1600	915	715	670	2530	4.2	87
Glass Fibers (E-glass)	>>1700 ^b	846	657	603	2620	5.4	72
High (96%) Silica	>>2000	1500	910	820	2180	0.8	67
Fused Silica	>>2000	1667	1140	1070	2200	0.55	69
Glass Ceramics	n/a ^c	n/a	n/a	n/a	2520	9.3	65

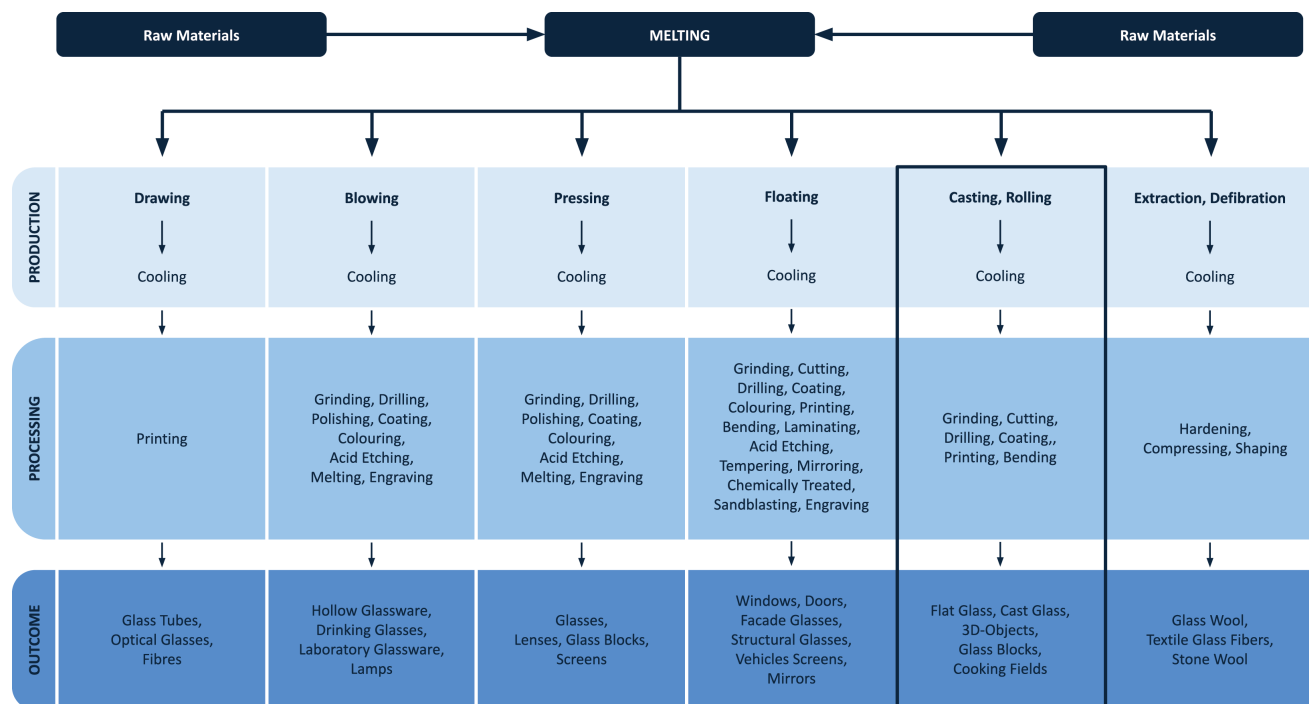
^a These values are only given as a guideline of the differences between the various glass types. In practice, for each glass type there are numerous different recipes resulting into different properties.

^b E-glass does not have a specific melting point, since it actually does not really melt, but softens instead. At the temperature above 1700°C, most of the molecules are able to circulate freely, while at the temperature of 2000°C, it begins to display degradation.

^c There is not an applicable temperature range for the melting point of glass ceramics in the literature, since it needs different temperatures on the glass-manufacturing procedure and after the glass is cooled down, different heat treatment temperature is needed for the ceramming of the glass. Upon ceramming, a much higher melting temperature than this of the original glass is applied.

01.6 GLASS PRODUCTION TECHNIQUES

Man-made glass production has been commenced and established thousands of years ago, in every aspect of life. Over this timeframe, according to the various needs that came, different production techniques were also developed and improved along with the diverse glass recipes. Today, a number of glass production methods are available, inasmuch as these kinds depend on how the glass will be exploited, which is the desired shape and the appropriate raw material batch, since different combinations may leak out different traits in the final glass output. The glass manufacturing processes are drawing, blowing, pressing, extraction, floating, and casting.

**FIGURE 01.6** | Glass Production techniques. (Haldimann et al., 2008)

This research is held within the framework of the built environment. Nowadays, glass increasingly captures the undivided attention and significance of the majority of designers, architects, and engineers, with innovative

notions and concepts being developed around the world. Advances and novelties in modern architecture are bringing more requirements not only in the glass design but also in the production methods. Within the building industry and glass applications, the most prevailing production types are floating and casting, which can be used for extended research. Nevertheless, these two processes have a major difference, since float line is a completely automated and rigid process, while casting remains rather manual (or semi-automatic) and thus presents higher flexibility. These two procedures are further explored below to clearly state the proper selection of the production technology that relies on the project application and desired geometry of the final products.

TABLE 01.4 | Overview of existing glass fabrication methods for building components and their current size limitations. (Oikonomopoulou, 2019)

Glass Process	Optical Characteristics	Main Glass Type	Standard Size [mm]	Thickness [mm]
Float	Smooth Transparent	Soda-Lime	3210 x 6000 ^a	2 - 25 mm
Cast	Smooth Transparent	Soda-Lime Borosilicate Lead	currently up to 20000 kg ^b	n/a

^a The max. panel size is continuously stretching. At present, up to 20 m long panels have been produced.

^b Based on the work of (Klein, 2015).

Float Glass

Within the field of the built environment, flat glass is utilized to encase spaces, without affecting the desire for natural light and connection to the exterior environment through crystal-clear viewing. As a consequence, glass accounts for a massive amount of applications, ranking it as the predominant glass typology of the building industry. Flat glass panes surround us constantly, whether we are aware of it or not. This outstanding domination and influence in this field is a result of the raising wish for transparency in the man-made environment.

For the manufacture of flat sheets of glass, the production techniques used were crown glass and blown cylinder sheet glass, which were the leading techniques until the end of the 1900s (Scholtens, 2019). However, both of them presented some drawbacks related to the limited panel size, a high possibility for contamination, blemish and imperfection, and surface inhomogeneity that always had a slight curl or drawing strip, so that it did not appear completely clear. Hence, in 1959 British engineer Sir Alastair Pilkington developed the float glass production line, which marks the start of modern glass production. Float line still remains the most applicable and common procedure for sheet glass, which increasingly replaced all other processes. This method in contrast to the aforementioned is respectively economical, with broad availability, immaculately smooth surface, free of air pockets, excellent visual quality and it is capable of producing glass sheets in large sizes that typically measure 6 x 3.21 meters but larger (oversized) plates can be produced as well, with the size stretching up to 20 meters long panels. (Oikonomopoulou, 2019).

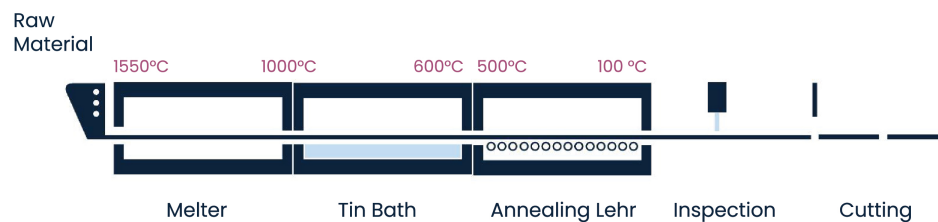


FIGURE 01.7 | Schematic illustration of the float production process by (Louter, 2011) based on (Worner et al., 2001)

The float production, which is almost like a glass river of nearly 300 meters long and unstoppably produces glass round-the-clock, starts with the batching of raw materials comprising silica sand, calcium oxide, soda, and magnesium. These are carefully measured and mixed into batches to which a proportion of recycled glass cullet is added. The latter aims to lower the melting temperature and consequently the reduction of energy consumption for the operation mechanism of the furnace. The batched primal matter is driven from a mixing silo to a fully controlled process, starting with a five-chambered furnace where it is melted at a temperature around 1450 °C. Then, the molten glass is “floated” onto a bath of molten tin at 1,000°C, forming a continuous glass ribbon of a uniform thickness between 5 to 6 mm with a perfectly flat and smooth surface. On leaving behind the bath of molten tin, the glass cools down sufficiently to 600°C where it solidifies. At that moment, it passes into the annealing Lehr, where it gradually and further cools down to

the temperature of 100°C, obviating the formation of remaining stresses. Now, the glass ribbon is hard enough and annealed, ready to be worked in further. However, once the glass has left the annealing stage, an automated process for visual flaws meticulously checks it. Finally, float glass is cut into the required sheets of various sizes that are then stored and ready to be transported.

Cast Glass

Cast glass has already been used by the 15th century BC, along with the territory of both Mesopotamia and ancient Egypt, making it one of the oldest techniques of glass formation. An ordinary method in the field of art and astronomy, but rarely exploited for architectural applications. However, its potential to enable the creation of monolithic 3-dimensional glass components with unique geometries so as to achieve dramatic architectural statements makes cast glass to be a versatile technique that is increasingly used and explored. Impressive examples of architectural concepts that use cast glass are among others the Crystal House in Amsterdam, the Atocha Memorial in Madrid, the Optical House in Hiroshima, the Futurium in Berlin, the Qaammat Pavilion in Greenland, the Crown Fountain in Chicago, and the Ice Falls in New York.

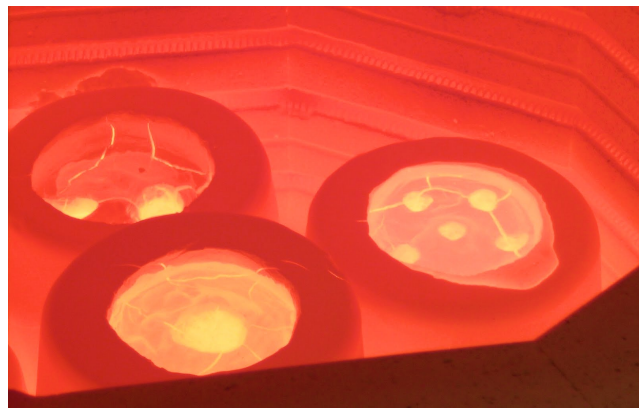


FIGURE 01.8 |

Primary casting method of glass, referred to as hot-forming (left). (Oikonomopoulou, 2019), and Secondary casting method of glass, named kiln-casting (right). (The Washington Glass School, 2010)

Generally, casting requires glass in a molten state to be poured into a mold of the demanded form or size, for the glass product to be shaped. Then, it gradually solidifies to room temperature in an annealing chamber. Along with this procedure, all the internal remaining stresses have gone, because if the whole process does not operate duly, crucial faults and stresses might turn up (Oikonomopoulou, 2019).

Cast glass is generated by two major procedures, which are primary and secondary casting. The former refers to the glass being in a state of hot liquid coming from its raw materials (sand, etc.), and then it is processed through hot-forming. At the latter, glass already in the form of cullet in the solid-state is remelted at the appropriate temperature to be liquefied to flow and shape the final glass article, a method that demands lower operating temperature and is usually made through kiln-casting. The primary difference between them is the extra infrastructure that is needed, since the first method with the aim of hot-forming demands a first oven where the molten glass is made and then a second one to be mold-poured and finally to be allowed to cool down (Bristogianni et al. 2017). Moreover, every mold must be prepared and heated at a specific temperature, since in different circumstances the temperature difference with the glass liquid is capable to cause the effect of a rough texture on the surface of the glass product.

It was already mentioned that different molds can be used in casting methods. The mold variants depend either on the used material to generate the shape matrix or the geometry of the cast product. The former is related to the thermal expansion of the used material for mold-making since different materials bear different temperature ranges over time. The latter presents the variants in mold typologies that may be permanent, if they are made with flexible material for many repetitions, or disposable, usually concerning a single or limited batch casting (Oikonomopoulou, 2019). Eventually, the final result of cast glass must undergo further elaboration to reach a sleek, glossy and clear outcome.

01.7 ANNEALING PROCESS

Like many other materials, glass presents a reaction to temperature alterations as one of the most distinct properties that it owes. Glass expands, as it heats up, and shrinks, as it cools down. Then stresses ensue from the thermal strain caused by the temperature variation within the glass. This process is mostly encountered within the glazed body and the outer surface, where exactly the highest thermal condition difference can be observed. However, as a way to alleviate stresses, which are introduced during the manufacturing, and a probable breakage of the glass even at ambient temperature, glass products should undergo through the annealing process.

Annealing is one of the most crucial phases during the generation of any glazed output, in order to ensure efficiency besides high quality. It is referred to as a controlled manner of slow-cooling heat treatment of hot glass, among a predetermined temperature gradient (Narayanaswamy, 1986). In this manner, any potential differential strain is eliminated, and the result of internal residual stresses over further cooling is impeded, while this procedure lets the surface and internal layers of glass cool uniformly for material consistency (Oikonomopoulou, 2019).

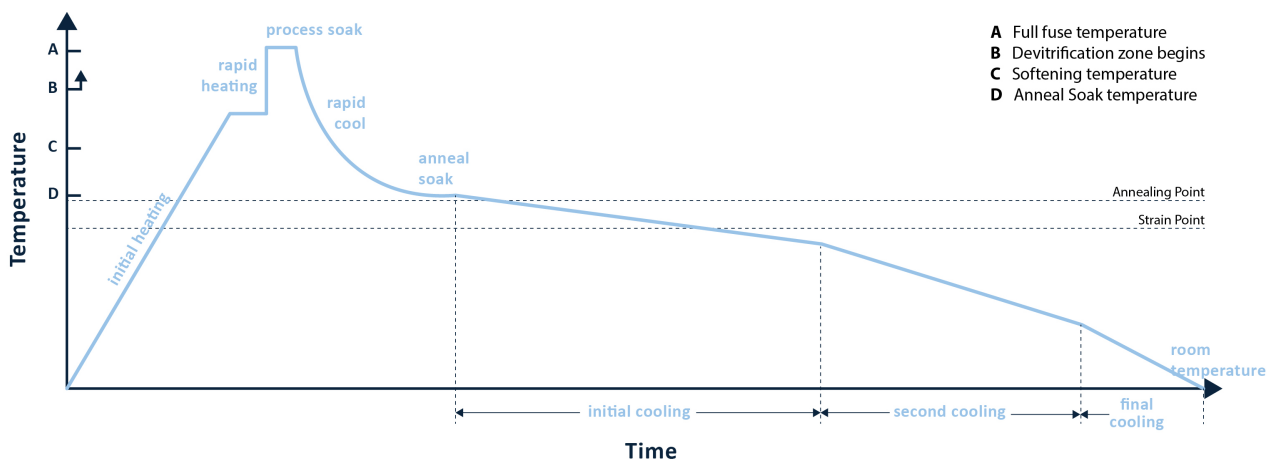


FIGURE 01.9 | Idealized time/temperature firing graph, based on (Oikonomopoulou and Bullseye Glass Co.)

To perform annealing, key processing steps should be followed. Firstly, the glass is heated up to its melting temperature, where it is sufficiently viscous, aiming to flow into the mold's area. At this point, the glass is quite soft and prepared to relieve the stains, which are situated on the inner part under a minuscule stream, with regard to the mighty stresses exerted internally on the glass structure (Shelby, 2005). As soon as the mold is filled, the glass is subjected to "quenching" to a few degrees (approximately 20°C) below its softening point (Oikonomopoulou, 2019). This causes rapid cooling to the outer surfaces of glass and lets them contract faster than the inner ones, obstructing in this manner any ordered arrangement of the atoms of the melt to form a crystalline structure. While the temperature is under the softening point of the material, its relatively low viscosity of it allows the shape of the glass to be preserved and not to occur self-weight deformation (Shand 1968). At this point, the annealing process follows. To begin with, the glass is kept at a steady temperature of the annealing point for an adequate period of time, permitting the molecular rearrangement of atoms, whilst the glass product's dimensional properties are unaltered. That aims to dismiss any existing stains, creating at the same time structural consistency. Afterward, it is cooled, until the temperature of glass reaches equilibrium, at a slow enough pace to keep the generation of remaining stresses from happening (Shand et.al, 1958). In essence, glass cooling takes place between the aforementioned annealing point and the strain point, known as transition temperature, a sufficiently significant phase of the cooling procedure. In the former, the stresses occur within a few minutes, although in the latter it requires several hours (Vogel, 1994). As the glassware cools down between these key stages, the atomic structure becomes rigid. Consequently, under the strain point, the stresses are inadequate to relax in time and are deemed permanent (Oikonomopoulou, 2019). Finally, the glass body temperature is then able to cool at a faster rate than room temperature, yet reasonably slow (Shand et.al, 1958). When cooling happens in a gradual manner, the atoms are capable of relaxing and the output lacks weak points. Concluding in an unstressed, well-annealed glazed product, avoiding vulnerability to fracturing or shattering, in response to prevent it from any minor mechanical or thermal shock that the finished glass could be subjected to.

Throughout the annealing range, the temperature variation, in the warmest along with the coolest segments of the glazed output, defines to a great extent the magnitude of the resulting internal stresses (Oikonomopoulou, 2019). In consideration of this fact to ensure maximum stress removal, there is a large relation between various factors, such as the glass composition, the coefficient of thermal expansion, the product's size, shape, the thickness of section and design, the total quantity of surfaces exposed to cooling and the amount of residual stress required. Moreover, the kiln design itself (heating means, size, geometry, etc.) and the existence of other thermal bodies in the kiln region could also play an extra influence factor in the annealing process (Oikonomopoulou et al., 2017). For instance, small and simple geometries objects have a consequent annealing process to the manufacturing one, while complex and relatively larger products regularly require attentive annealing treatment. Accordingly, glass outputs with round or ellipsoid shapes and equally distributed volume are easier for the prevention of residual stresses, compared to pointed edges and forms of irregular mass design, where such stresses are probable to focus in specific areas arising from heterogeneous shrinkage (Oikonomopoulou, 2019).

Nevertheless, the factor that possesses the most notable repercussion on the time, which is requisite for glass annealing, is the mass of the glazed elements. According to Oikonomopoulou et al. (2018), “the larger the component, the exponentially longer the annealing time”. A characteristic example of this argument constitutes the manufacture of cast glass components in a block-shaped form that is intended for the Crystal House building face envelope in Amsterdam. The production of a brick with dimensions of 65-210-105mm and a corresponding weight of 3.6 kilograms demands an annealing time period of 8 hours, compared to a larger block of 65-210-210mm and the doubled weight of the aforementioned sample, which requires a timespan considerable bigger fluctuating roughly to 37 hours. To sum up, the annealing of glass is critical to its durability. Consequently, every different product design stands in need of a unique annealing schedule, so the temperature is distinct to each of them.

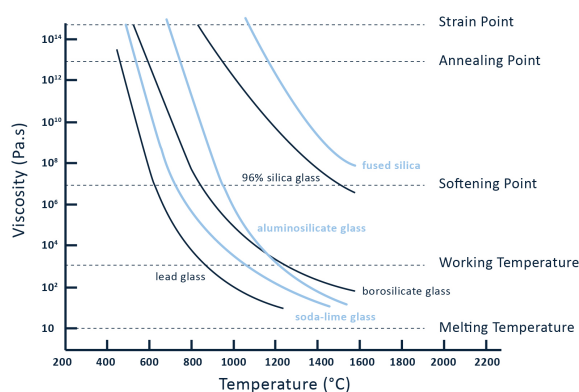


FIGURE 01.10 | Approximate viscosities versus temperature curves plot for the most characteristic glass families. (Shand et al., 1958)

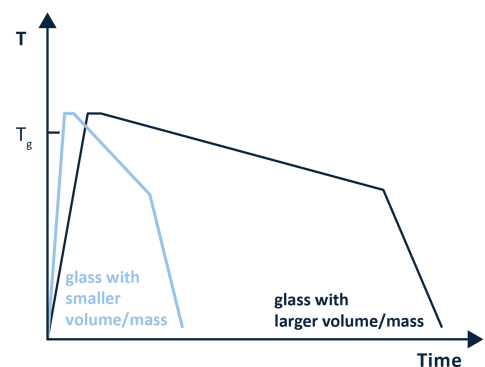


FIGURE 01.11 | Schematic representation of the annealing temperature as a function of time for glasses of different volumes. (Schott, 2004)

01.8 CONCLUSION

Glass could be characterized as a versatile material. In recent times, it has experienced a broad innovative boost, even though it has been used for thousands of years. Its presence in all sorts of everyday life in various applications puts it in a very ordinary position. Hardly any other material, that is exploited not only in our everyday environment but also in the built one, could sufficiently meet the current extensive usage of glass. An existence, so ordinary that we infrequently notice, since glass is a material that has always fascinated everyone.

This chapter has sought to provide a complete overview of the theoretical background of glass technology. The information that is presented covers every aspect of it. Glass is known as a hard but at the same time vulnerable material to breakage, which in its usual appearance is transparent or translucent. The precise composition of it may diversify to meet particular requirements, according to where it is applied. However, the most frequently used variety of glass is comprised of silica sand, soda ash, and limestone, produced by fusion and rapid cooling of the molten glass in such a manner to prevent the ordering of atoms into a visible crystalline formation.

Glass, like any other material, possesses some unique characteristics. Disparate families may present dissimilarities between one or even more properties that carry, depending on independent variables of their chemical constitution that attach diverse characteristics to the product result. According to the various needs that came, different production techniques were developed likewise along with the diverse glass recipes, since individual combinations may leak out different traits in the final glass output. The most prevailing methods are floating and casting of glass, two processes with exceptional divergent manufacture stages.

Another crucial production phase of any glass output generation is annealing. A process, which assists in the alleviation of stresses that are introduced during manufacturing, in order to ensure efficient and high-quality products. In consideration of this fact, to ensure maximum stress removal through annealing, there is a large relation between various factors with mainly the glass product' mass and shape, resulting in that different objects' design is linked with a separate annealing schedule to each of them. To determine the unique temperature range that each glass should be undergone, a qualitative evaluation of strains should be held to ensure their strength and reliability.

Hence, the review of the all aforementioned literature operates as a rulebook to understand glass technology. Consequently, selecting the proper type of glass for a particular application equates to comprehending all of the probable combinations that glass variants belong. These rely on the project application, design and experimental observations.

02 | GLASS RECYCLING

02.1 GLASS RECYCLABILITY/CIRCULARITY

In view of the continuous growth of the worldwide population, the economic expansion and goods production have been disengaged from the efficient exploitation of natural resources. At the moment, it remains an unsolved problem, with major concerns from the whole ecosystem. It is about time to move towards a circular economy with the main objective of the extension of products and materials service-life that are currently landfilled, in order to assist in waste depletion.

In 2020, the global glass manufacturing market reached a volume of 35.85 million tons, corresponding to USD 228.7 billion (Glass Alliance, 2021), including every production segment; packaging, construction, telecommunication, electronics, automotive, and transportation. That year, 2.01 billion tons of municipal solid waste were disposed of on a global scale, from which approximately 100 million is referred to as glass (Statista, 2021). Less than one-third got recycled, while the rest were buried in landfills. Glass recycling may be challenging, due to some intrinsic materials or chemical characteristics, but not impossible. Already, the glass industry is making efforts, in cooperation with manufacturers and governing bodies, to boost and improve these recycling rates, recognizing the benefits of glass recycling that can succeed in the target of energy and resource consumption.

Glass is a completely sustainable material, which can be refillable, reusable, and of course perpetually recyclable. A source that owes an absolute recycling ability to be converted into available material, since it can be melted down over and over again, and turned into new products without any loss of its standard quality. However, the theory does not always correspond with practice. Given the huge glass manufacturing volume in the world, the lack of proper recycling policy, the big contrast of recycling rates per region and per glass application sector, the variants in glass batch's recipe, and the risk of contamination, it is still a long way off. These reasons conclude that it is required to explore and map too many alternative recycling paths, which may be very expensive and unproductive (Oikonomopoulou, 2019). Only in the case of food and beverage glass containers, the recycling rates are compensatory, especially in examples such as Europe's, where the average collection of glass containers climbed to the record rate of 78%, in 2019 (FEVE, 2021).

02.2 RECYCLING LOOPS

When it comes to speaking about the future of a material or product, we just refer to the term recycling. However, not every recycling loop is equal to the other, since three types are more or less liable for replenishing the quality degree of the matter in question. These three types are recycling meaning to keep it on the same level, downcycling lowering the quality (open-loop), and upcycling to raise the quality (close-loop). Further exploration of the term distinguishes the difference between them. Generally speaking, all of them share the common term "cycling" which expresses the flow of things into a circle. Although, not each of these processes is circular since the Circular Economy begins again as it ends. Accordingly, glass circularity, which is a matter of debate in the current research, is an idea that its direction is to close the life-cycle of glass, following the circular economy.



FIGURE 01.12 | The Recycling logos.

Recycling

The recycling method refers to the process of converting material and product wastes into a new one, sustaining the properties in their original state without significant degradation. Actually, it reduces a product down to its composing materials towards producing something new out of this material, putting it back into the same life cycle, exactly to the same product. For instance, glass containers are products easily recyclable, as they can be recycled again and again into the same object, while the resulting material will still be of equal value. Essentially during this loop, there are moments that a significant amount of recycling is downcycled, as certain materials result in inferior quality.

Downcycling

Downcycling is a method that delays the disposal of waste. It transforms manufactured products and spent materials into both new raw ones, ready to be exploited in the manufacturing process as inputs, and to waste products or as fuel sources for a completely different production procedure of less value than it originally was. In other words, downcycling can be considered as an open-loop approach where materials going through recycling will be used for alternative destinations from their former to a completely new material, which can be used as an input into another manufacturing process. For instance, glass waste is mostly used in concrete mixtures to replace natural aggregates, especially when it contains contamination, it is not well recycled, providing that it is risky to damage the recycling facilities, and as a result, it is often downcycled instead. Eventually, a part of the matter of recycling has to drop out of the recycling loop and wind up as disposal waste or be burned.

The mix-up of one product through heat, chemical reactions, or physical crushing with various types of similar or dissimilar materials makes up and alters the initial characteristics and results in its degradation. Usually, recycling programs are typically open-loop processes.

Upcycling

Upcycling is focused on supply chain sustainability. Generally, it is associated with the procedure that waste is collected, recycled, and generated into new products perceived to be of higher value or quality than the one they came from without any degradation or waste sent to the landfill. Upcycling could happen either in an open or a closed loop. For the latter, the manufacturing process is usually designed with recycling in mind, but it is a more restorative and regenerative method to keep materials at their highest utility and quality as well. This process aims to minimize the environment's damage and discourages natural resource depletion, helping all over to reduce the carbon footprint and finally to manage corporate sustainability inventiveness. Ideally, upcycling does not generate any waste at all, while the closed-loop is related to the fact that recycled products remain in the circular life cycle as the more sustainable approach.

Regardless of the fact that some recycling loops maintain their original state more of the material's quality compared to others, eventually, all methods aim to extend the material's service life in one or another way. This concludes in limiting the amount of virgin raw materials processed in new products and a delay to end up in a landfill. However, we need to keep in mind that, each of these recycling methods is radically different in its approach and impact on the underlying raw materials; consequently it is crucial to always choose the most sustainable possible option.

02.3 BENEFITS OF GLASS RECYCLING

Glass recycling procedures contain a wide number of actions, especially when glass upcycling is achieved, which can be more or less assimilated as beneficial with the most efficient results. Glass recycling transforms the production industry to its maximum productivity with minimum wasted effort and it provides notable environmental advantages. These can be presented as air pollution reduction, used energy savings, furnace conservation, shortening the amount of required raw material, logistics optimization, and glass waste mitigation.

The glass production from raw material requires really high heat rates to melt down the batch mixture, which is approximately 1450 °C. Consequently, this process consumes a really large amount of energy, especially during the melting phase as high temperatures are reached in the furnace. This energy utilization corresponds to the highest emissions rates. Along this production line, carbonates are decomposed and set free CO₂ pollutants as hazardous waste products released into the atmosphere. According to the EU average, a tonne of recycled glass is able to prevent 670 kg of carbon emissions, equal to a decrease of 20% in air infection and 40 to 50% in water pollution (FEVE, 2016). Another example presents that a relative 10% of the cullet added in the glass mixture

lowers the particulates by a total of 5%, equal to 8%, nitrogen oxide by 4%, and sulfur oxides by 10% (Larsen et al., 2009).

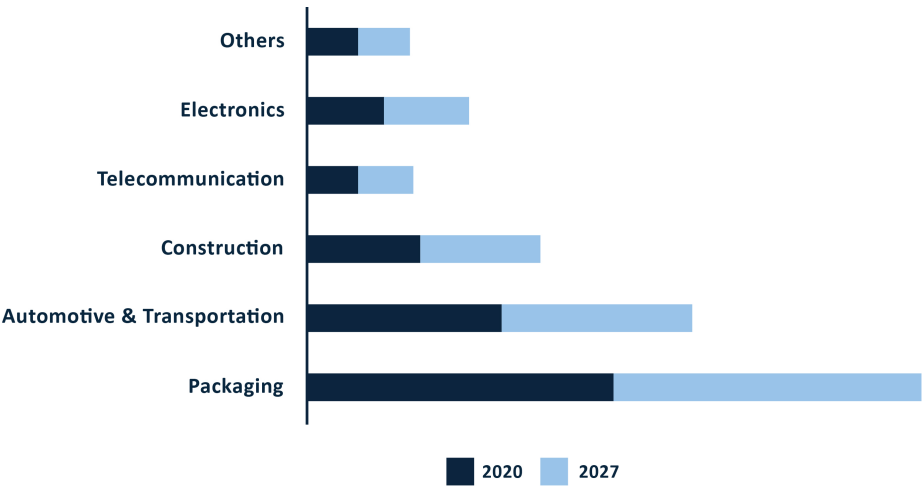


FIGURE 01.13 | Global glass manufacturing market by sector (USD Million). (Gminsights)

The most important environmental benefit deriving from the return of the cullet to the glass production line is that it drops the energy consumption. Cullet in comparison to raw materials possesses a lower melting point. When recycled glass pieces are inserted in closed-loop cycles of glassmaking, a 10% addition of recycled glass cullet is able to yield energy savings of 3% (FEVE, 2016). The use of cullet also aids in decreasing the batch-free time by both lowering the number of infusible materials and by supplying extra liquid all over the fusion (Lebullenger et al., 2019). Additionally, this process extends the service life of the furnace, since including cullet in the manufacturing batch makes it less corrosive and it operates in lower temperatures than with plain raw material in the batch, dropping it by approximately 200°C.

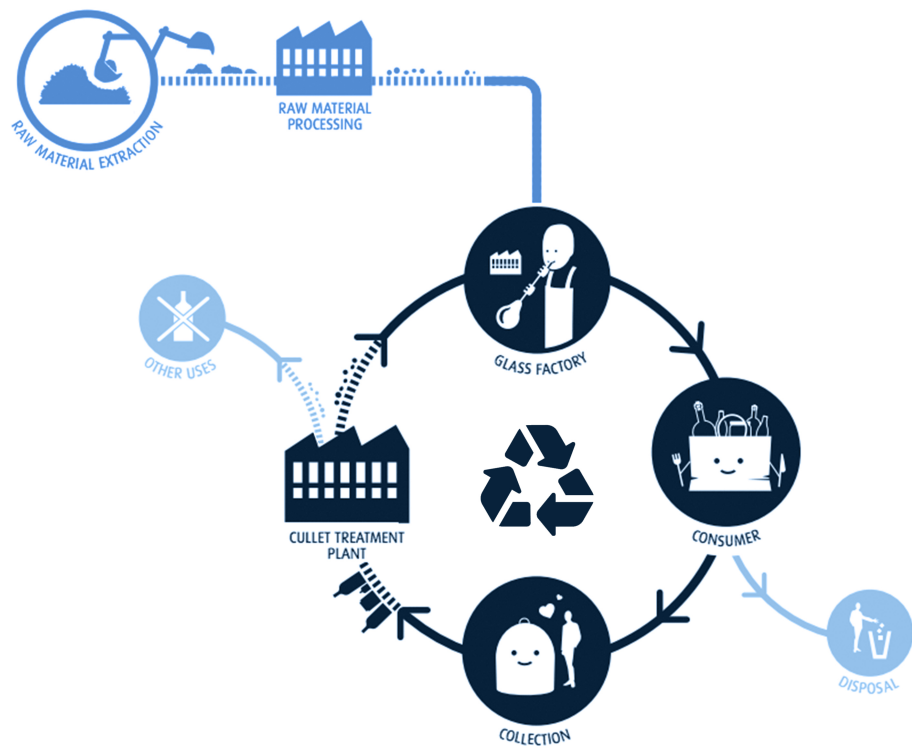


FIGURE 01.14 | Benefits of glass recycling on CO₂ emissions in a closed-loop system. (FEVE)

The use of recycled cullet for the production of glass also assists in the reduction of raw material extraction. This addition of crushed glass into small pieces is used as a substitute in the production line, meaning that new raw material is not needed in the process, preserving the natural resources with minimal use. For each kg of cullet used in the replacement of the raw material, there is a saving of 1.2 kg of unprocessed materials. Nevertheless,

apart from the raw material extracted from the earth's crust, the acquisition of it actually consumes really high amounts of energy. The major source is fossil fuels such as coal and gas, which are coming from the natural deposit, and moreover, they emit immense amounts of greenhouse gasses. To an extent of it, glass recycling optimizes logistics, thus the carbon footprint connected to transportation, since recycled glass comes from local collection points, near manufacturing plants (Lebullenger et al., 2019). Glass recycling brings a volume reduction in glass waste ending up in the landfills. Compared to other materials, glass does not chemically react with other substances, so it is insoluble, and not able to incur decomposition another important fact is that it does not leak any poisonous substances to pass to the soil and groundwater (Dyer, 2014). However, a glazed product, exposed to the environment, needs more than 4000 years to decompose (FEVE, 2016), so glass waste covers space in landfills. Additionally, glass recycling operates as a closed loop, without generating any by-products or waste. In many regions around the planet, landfill space is a part of environmental importance at a premium, and limiting waste disposition is considered an important step in moving toward efficient and sustainable use of land. However, glass waste can also be used for incineration. Inherently, glass is clearly a noncombustible material, so it cannot totally be destroyed.

Glass recycling, despite its environmental advantages, presents some other benefits linked to society and the economy. It is a responsible and measurable action, which must be also held with the assistance of the consumers to help the environment protection. Of course, this is a process where glass is collected and recycled locally, so the gas emissions related to transportation create a very limited impact on the whole life-cycle assessment. The fact that recycling takes place locally supporting local and rural industry, gives also opportunities for new employment positions in collection schemes and cullet treatment centers to be opened. Finally, recycling glass aids to reduce the manufacturing costs from the reclaimed materials, instead of getting raw material.

02.4 HISTORY OF GLASS RECYCLING

Glass recycling is a significant part of glass history and at the same time a very crucial subject in the field of academic research. As it is already mentioned in a previous chapter related to glass history, while Egyptians, Syrians, or possibly Mesopotamians incidentally invented the glass production techniques around 5000 BC as a by-product of metalworking, prehistoric people have been exploiting naturally occurring obsidian as a useful tool of their everyday life since the Stone Age. However, there is not any clue if these premature civilizations ever tried to recycle glass objects. Evidence arose from the Parthenon site, that ancient Greeks certainly thought of methods and ideas to reuse glass remnants with the aid of cast glass as a surface for board games (FSWASTE, 2017).

Since the first extended glass manufacture, the reuse of pristine glass objects became a routine practice. The initial start of glass recycling history is traced back to the later Roman Empire and the earlier days of the Byzantine, where they explored the reusability and recyclability of glass by crumbling and remelting it over and over again without lowering its initial virtual quality. Written sources in poetry indicate evidence of glass recycling during the Roman Empire, where the glassmakers of that period did not have the theoretical and practical understanding to re-melt the cullet in a batch, limiting their skills in the fusion method of recreating broken pieces of glass into new useful products (Cosyns, 2019). During archeological excavations in the ancient city of Sagalassos, in the territory of the Byzantine Empire, fuel ash slag and kiln fragments from approximately 330 AD were discovered, pointing out glass recycling (Degryse et al., 2006). These efforts on recycling led them to evolve a product much cheaper than the one that is made from new raw material and additionally less energy was needed for the reason that the glass cullet decreased the operating temperature. Around the 1st century, written sources validate the extension of glass recycling in the Western Empire thanks to the trade and some years later in eastern territories.

It is believed that in the Middle Ages glassworkers who created their artwork on demand, fashioning beakers, beads, and other decorative items and stained glass in religious buildings, originated mainly from recycling pre-existing old items fallen into disrepair. During the Victorian Era, with the move of rural society to an industrial one and towns became cities, poverty came into people's life. For their survival, citizens more than ever had to recycle for a few pence discarded items out of necessity (FSWASTE, 2017).

However, in the modern world, glass recycling was triggered on a major scale during World War II, driven by hardship related to the shortage of basic commodities. Just like other materials and products, glass production demands energy and raw material consumption for the fabrication and transportation of goods, while it emits

CO₂ that deteriorates the greenhouse effect, the public awareness of environmental degradation was flourishing during that period. After all, glass recycling became the norm until the 1970s, as a vital cog in the industrial wheel. Beverage companies started to comprehend the significance of re-utilization and promoted a small financial reward to the consumers for returning their used containers, relying on reusing them, or manufacturing new bottles from scratch. Nevertheless, this effort was limited only to a certain kind of glass container, which shares the same glass composition, and no other materials for different purposes, in order to be remelted and reformed into a new product that is the same as before.

By now, even if there are many types of glass products, only a mature glass industry has been established for post-consumer containers, such as bottles or jars. It is widely known that glass free of pollutants is an indefinitely recyclable material without losing any of its qualities, because of its chemical structure. Apart from the containers, the vast majority of all the other everyday glass products are either down-cycled to a low-value application or are sent and disappear into the landfill. Consequently, glass waste still remains a significant and unresolved problem to be tackled.

02.5 GLASS WASTE TYPES

The various applications for commercial glass demand different chemical structures of the desired products. Generally speaking, glass-manufacturing derivatives are really diverse. It provides numerous glass products of different compositions and production techniques, ranging from small glass ornaments to huge flat glass panels for the built environment. The link point among these diverse production sectors is that they all have to proceed to batch melting through a furnace for the glass generation. On the contrary, the proportion and composition of raw material, the size, and type of the furnace and the production line, the demand for energy, the combusted fuel, the operating time frame of melting and annealing, and finally the cullet size to be used in the batch composition sufficiently differ from the one industry to another.

Glass waste can be firstly divided into two major categories, pre-, and post-consumer glass waste. The pre-consumer glass waste is generated during the production procedure of glass, before even the products reach the consumer, and are generated exclusively during the industrial operation. This part represents roughly 25% of glass waste in Europe. On the other hand, post-consumer glass waste is produced after the customers use the goods, referring to the remaining 75% (FEVE). The primary difference presented between them is that the former may not require any action to go back into the production line, compared to the latter that it will appropriate degrees of sorting, collection, cleaning, treatment, and quality control for contamination so as to proceed back in the recycling loop. According to the existing glass recycling industry, post-consumer glass waste could be briefly divided into three parts, classified by their disposition (Bristogianni, 2019).

- the **post-consumer containers/packaging**, such as bottles or jars
- glass coming from the **Construction & Demolition**, such as flat glass and window glass panels, and the **automotive industry**
- other **unsolved waste glass**, for instance, glass from electrical appliances

On account of glass products, commercial glass waste is typically classified into eight broad sectors of the glass manufacturing industry, based on a study held by Telesilla Bristogianni (2018). This clustering is conducted between similar chemical compounds, setting the guidelines on what way the waste cullet should be handled resulting in the final glass product. Identical glass wastes are capable to be combined, inasmuch they share the working and annealing temperature range, the easiness of crystallization, and the coefficient of thermal expansion (Bristogianni et al., 2018). Thus, the mechanical, optical, and thermal properties of recycled glass products can be predicted.

- **Soda-lime:** This family is the most common type of glass in the world, prevailing in the glass industry, with a percentage of roughly 80% of the total glass production (Lebullenger et al., 2019), whilst includes subcategories with products of similar principal constituents, and manufacturing methods. In this falls the automated blown, the mouth-blown and the float glass derivatives.
- **Soda-potash lime Silica:** Similar to lead glass, potash gives better brilliance and optical quality to the product with much more weight, perfect to be used for lens production.
- **Lead Crystal:** Due to the presence of lead oxide, this glass is heavier than others with a special shiny look and transparency, due to being highly refractive. A material, less brittle than others and soft in order to be

easier cut. It is the perfect high-quality glass to be used in glassware, cut glass, bulbs, lenses, and prisms. However, this glass possesses potential health risks since it is referred to as toxic.

- **Lead-free Crystal (Alkali-barium Silicate):** It is an alternative to the toxic lead crystal, by replacing it in the batch with barium oxide, zinc oxide, or potassium oxide. Due to its hardness, it is ideal for fine engraving with a clarity corresponding to lead glass. The major difference is its weight and the glow when it is cut.
- **Borosilicate:** It is widely known as Pyrex glass, however, modern laboratories also use this type for glassware. Moreover, it is used for packaging medicines and drugs due to its excellent chemical resistance, and for cookware, microwave, ovens, and semiconductors for the good resistance to thermal and electrical shock.
- **Alkali-aluminosilicate:** This family owes good resistance to thermal shock and tolerating temperature alterations, so it is used as a sealant for high-temperature systems, especially for screens of devices, and as screen protection, referred to as Gorilla glass.
- **Ceramics:** Glass-ceramic materials share many properties with both glasses and ceramics, containing both non-crystalline and crystalline structures. As a material has become extremely useful for countertop cooking and industrial processes.
- **Glass fibers:** It is used for insulation, filtering, and firestop applications.

02.6 GLASS WASTE MANAGEMENT

Every material, product, and service has a degree of impact on the natural ecosystem. This impact is linked to the raw material extraction from the Earth's crust, just like silica sand for glass manufacturing, while energy is needed for the product fabrication, distribution to the consumers, use, and finally disposal at the landfill. Following the waste hierarchy for glass recycling, a circular economy thinking is generated leading to identifying the proper environmental options for the most efficient outcomes and less detrimental to the ecosystem.

The built environment always possesses an essential role in the global economy and it could easily constitute the motive force for sustainable innovations and developments nowadays. Consequently, it triggers an ongoing transition from a linear system of glass life-cycle to a circular one, as the most efficient use of glass waste by converting them into newly glass outputs, creating a global phenomenon, as to link welfare to healthy and environmentally sustainable solutions.

The concept of round flows firstly appeared in 1966 in one of the books by Kenneth E. Boulding, who drew the significance of the relationship between economic development and ecological demotion through a "cyclical" model of production (Blewitt, 2015). However, a more specific description was introduced by scholars from Pearce and Turner in 1996, depicting the economic model as an engine, which receives waste at extraction, production, and consumption stages and converts them to imports to be exploited under a loop (Pearce et al, 1990). Additionally in 2010, the Ellen MacArthur Foundation (EMF) presented a complete concept of Circular Economy, via continuous efforts to inspire the world to rethink, redesign and create a positive future (Nobre et al, 2021), as a big idea in need, to face the climate change and create a more efficient and resilient future for business, society and nature. This closed-loop model is expressed through simple means from the European Parliament, as followed:

"The Circular Economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing, and recycling existing materials and products as long as possible. In this way, the life cycle of products is extended."

The term Circular Economy is also referred to as «Circularity» or «CE» by EMF and it is further explained as "an industrial system that is restorative or regenerative by intention and design", adding at the same time its intentions to change the end-of-life status "towards the use of renewable energy, which eliminates the use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems and, within this, business models" (EMF, 2013). Consistently, there are a number of various definitions that try to explain the term Circularity, which became an object of extensive research through the years until today.

These statements entail the fact of an incessant relation of values from both the economical and ecological side of materials and in extent the products, which retreat into different cycles due to the various paths of closed loops that they follow. These paths lead to CE strategy targets to reduce waste to a minimum, by keeping the products that reach the end-of-life within a circular loop, which offers them the contingent to capture the lost

value from glass waste recycling. They also invent the proper circumstances for the efficient reuse of the material, economizing natural resources, energy, and carbon dioxide contaminants. The procedure of reusing glass products or transforming glass waste into cullet prepared for recycling is characterized as a waste reclamation operation and it constitutes a subject to waste management.

The waste hierarchy is referred to as an evaluation tool establishing a preference ranking on program priorities based on sustainability. It actually sets the basic concepts and definitions related to waste management, whilst it expresses the awareness on how to manage waste, from the very beginning and not to the end-of-pipe solutions. The management of glass waste aids to generate the amount of hazardous environmental conflict, impeding the greenhouse effect from CO₂ release, poisonous pollutants, unreasonable energy consumption, and natural resources depletion.

According to the Waste Framework Directive, this concept lays down a few initial principles of waste control. It actually set some required limits in order for waste to be managed without endangering human health and harming the environment, risking water, air, soil, plants, or animals contamination. Simultaneously, it is in charge of protecting ecosystems from nuisance through noise or odors and the countryside or places of special interest (European Commission).

The framework is constructed from the most to the least preferred choice, according to which is the best for the environment.



FIGURE 01.15 | Waste Management Diagram. (ARUP)

- **Prevention:** When action must be taken, waste prevention is in the first place. This is equal to less material used in the design and fabrication process, and selecting sustainable materials to be utilized for a longer period of time. Consequently, this concludes to less waste at landfill sites.
- **Preparing for re-use:** When waste is generated, the hierarchy designates products and materials for reuse extending their service life. Checking, cleaning, repairing, or refurbishing products or parts of them, could play a remarkable role in the amount of waste output.
- **Recycling:** Recycling is a key component of waste reduction and the most sustainable action when it comes to waste refusal to landfills. Turns waste into a new material or product, and the number of raw materials required decreases significantly.
- **Recovery:** Next preferable choice, for non-recyclable waste, is to produce power in the form of “waste to energy” or other types of materials. This method aims to decrease the dependence on nonrenewable fuels and limit carbon dioxide emissions.
- **Disposal:** This is the least sustainable option in the hierarchy and our last resort is landfill and incineration when waste cannot be exploited in any other aforementioned way.



FIGURE 01.16 | The 3R's logos. (VOY)

Waste hierarchy concept includes the 3Rs initiative (reduce, reuse, recycle), offering ecological choices to deal with the increasing waste derivation and its associated influence on the natural ecosystem, human health, society, and economy. This would be the foundation to build a sound-material-cycle society through the effective use of natural stock and materialism, emerging as a potential key action to create better management of resources and waste in contemplation of undertaking global problems. For the aforementioned challenges, three main principles are based on a circular model for the transformation to a more sustainable future, driven by design:

- Waste and pollution elimination
- Materials and products extension of useful life (circulated with the highest value)
- Nature's regeneration

At its core, a circular economy model has the intention of designing out waste. More specifically, the concept of the first principle suggests the minimization of poisonous effects on the environment, asking businesses and by extension their economic activities, to rethink the whole supply chain to reduce the natural damage that pollutes air, land, and water. If this would happen from the primary stages of product development, a huge amount of greenhouse emissions released into the natural ecosystem would have been confined. As far as the second principle is concerned, it aims to reimagine an economy that does not exploit finite resources but instead of that, it creates the loops by reusing, remanufacturing, and recycling materials and products. Additionally, products and materials must be designed to last more and further to be optimized for disassembly and reuse to be comfortable to handle, transform and renew them. Main priority is to utilize a concept that positively impacts the economy and the environment. Finally, the third one refers to the regrowth and regeneration of the natural systems, improving the environment, since it enhances the natural capital and the creation of the requisite conditions. This last principle actually constitutes the fundamental concept of circularity (EMF, 2013).

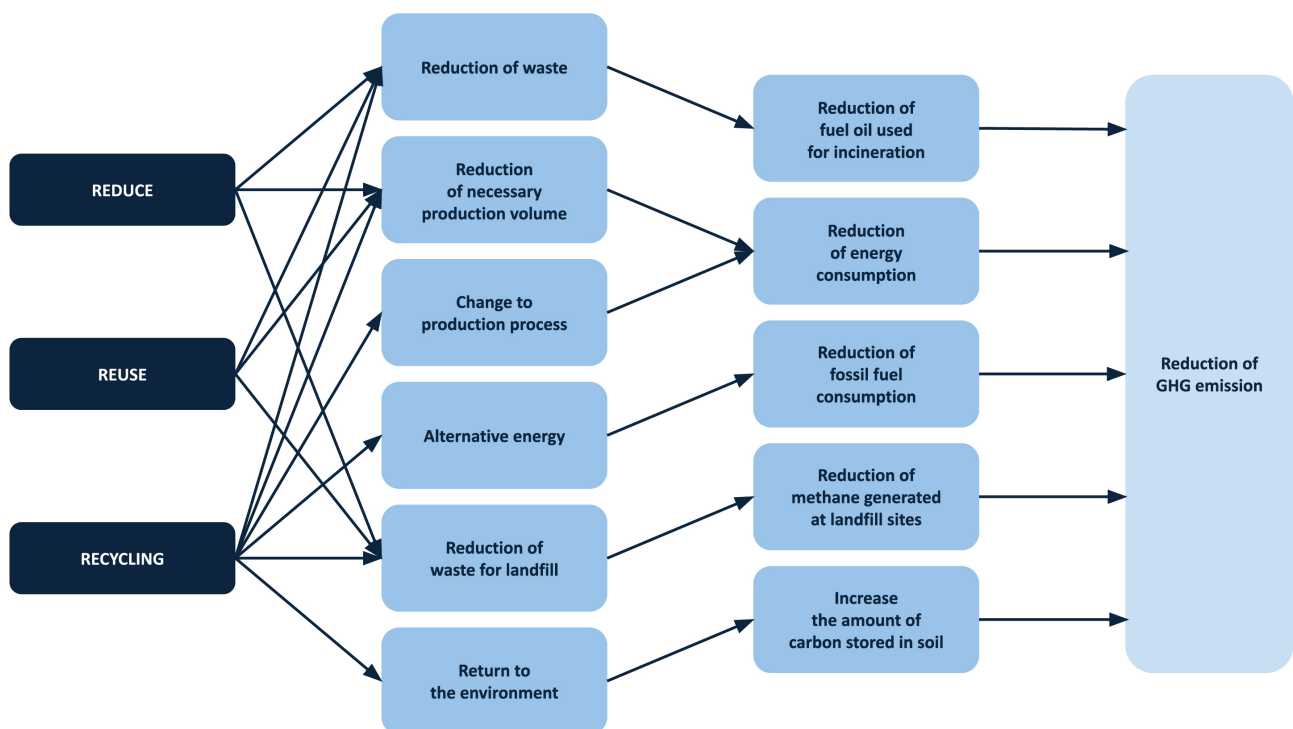


FIGURE 01.17 | The 3Rs approach and its impact on greenhouse gas emission. (Lebullenger et al., 2019)

02.7 CURRENT GLASS RECYCLING PROCESSES

Glass has long been leading the way in circularity. Made either from raw material found in nature or recycled glass cullet. It is totally recyclable, as long as it remains relatively pure since it maintains its intrinsic properties regardless of the number that it is converted into reusable material. By adding glass waste back into the manufacturing line, a closed-loop recycling approach is achieved. However, this is not always the case.

Glass Container Industry

In practice, the upcycling method mainly exists in the case of soda-lime post-consumer containers of the glass industry. Glass packaging is Europe’s most recycled material (FEVE). Thanks to the recycled food and beverage packaging industry, which operates as a well-functioning Circular Economy. This is also reflected in the latest rate of glass packaging collection in Europe, reaching a record of 78% in 2019, with a growth of 2% compared to a year earlier (FEVE, 2021).

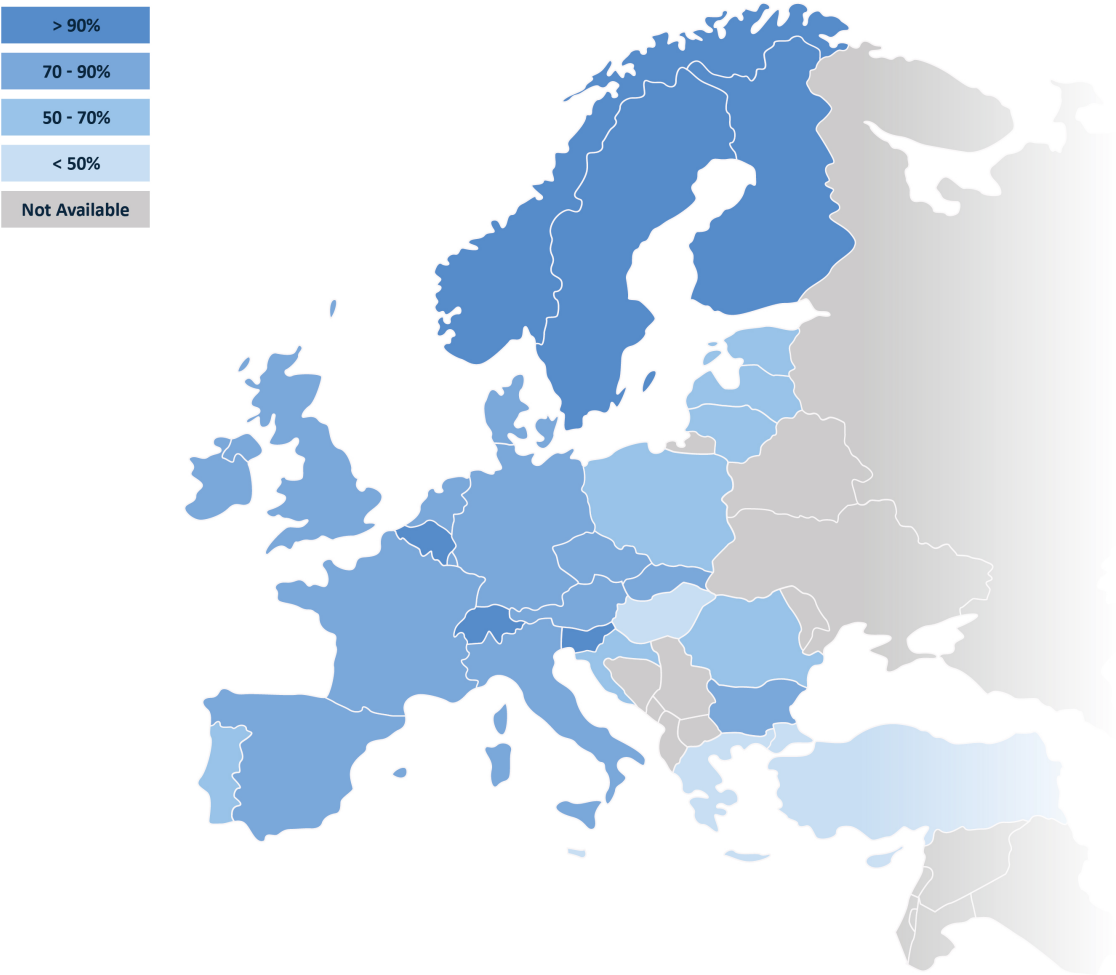


FIGURE 01.18 | Container glass collection for recycling in Europe, based on (Close the Glass Loop, 2020).

This percentage of glass containers is either reused or recycled. The former concerns the collection, sorting, sterilizing, and reusing the glass containers, leading to the use of much less energy for either extracting raw materials or recycling them in order to manufacture a new one. Refillable containers, whose recycling rate fluctuates between 12-20 trips, as long as it passes the spectrometer test on the inspection/wash line, will demand approximately 90% less energy in comparison with the one-way glass products (Ellen MacArthur Foundation). When the glass product reaches the end of its service life, it is smashed up, melted, and reformed into new containers, as recycled.

The recycled glass cullet used in the industry’s furnace presents a remarkable saving amount for both energy consumption and CO₂ emissions. On the whole, the addition of cullet in the production of glass containers is able to reduce by 3% the energy requirements and emit 5% fewer greenhouse gasses, for every 10% increment of melting cullet in the batch, instead of using exclusively natural resources. Expressed as a proportion, an example to assimilate the capability of recycled cullet in the production is that reprocessing only cullet by replacing completely virgin material, the carbon dioxide emissions are cut by approximately 58%, comparatively of a scenario that there is not any exploitation of recycled glass waste (FEVE). Notwithstanding the above-mentioned occasion, the cullet ending up in the production loop constitutes the average batch of 52% of glass container production (FEVE, 2021). This number is equal to about 30 billion glass packaging, which is going back to the closed bottle-to-bottle loop at one of the 160 plants in Europe.

Glass container industry intends to raise the glass content to the manufacture in the frame of a close-loop economy, by saving more and more glass in advance. In 2019, 78% of the post-consumer containers are picked up for recycling throughout the European territory. With an increased glass-recycling trend, the new EU 2030 recycling targets and the UN Sustainable Development Goals set by the European Union will be a step closer with the commitment of citizens. Consequently, the glass packaging industry is the perfect candidate to fit satisfactorily into the current and future ambitions for a circular economy.

Responsible manufacture and consumption (SDG 12) will achieve results with significant social advantages and secure economic growth, but most importantly it is reliable for the environmental benefits of the value chain. Considering glass recycling enables the reduction of ecological footprint (SDG 13) by saving energy and raw materials, it maintains and opens locally new job positions in the glass-recycling sector, whilst glass plants distribute their 50% of glass production within 300km and 70% of the recycled cullet travel, not as much as 300km. Glass industry assists to erect a recycling-based society with the key factor to limit discarded waste and transform the as valued resources.

Float Glass Industry

It is obvious that at present, float glass manufacture is a linear process. Despite the infinitely recyclability of thin-walled glass sheets, post-consumer waste of such a category is rarely recycled into new glass material or products. On the contrary, it is principally crushed together with other building materials and then they are either sent to the landfill for disposal and be destroyed by burning or they are downcycled together with other mineral waste in lower-quality products, for instance as aggregate applications on the concrete mixture for civil works. As stated by the Commission's report on the Thematic Strategy on the Prevention and Recycling of Waste, waste derived from the construction and demolition sector vary between 510 to 970 million tons per year, while it is estimated that glass waste is less than 1% of the total amount (European Commission, 2011). Even if this number of end-of-life glass sounds unimportant, the whole portion of such generated glass waste is not, as glass is predestined for closed-loop recycling, and considering all the different materials that exist in the built environment.

Most of the thin-walled glass used in the built environment could be collected, dismantled, and recycled by closing a circular loop when placing it back on the production line. However, many obstacles rest in front of the circular life of float glass. First and foremost is the absence of in-depth research about dependable facts and figures about the quantities of float glass reaching end-of-life. Secondly, a record of all the current practices relating to sorting, collection, and recycling would be helpful to understand the scale of the recycling challenge in order to study in-depth the best approach. Finally, a mapping of all the obstacles to the transformation of the float glass industry in a circular economy is discussed in the following chapter. Yet, this is a challenging matter in practice. Furthermore, these barriers further include the challenge of dismantling especially in the case of IGUs, rendering the whole procedure cost-inefficient and time-demanding; the strict quality standards of the float line in recycled cullet acceptance both in terms of visual performance, especially on the assumption of colored cullet, and in terms of contamination rate, which occupies much lower acceptable proportions compared to the glass packaging industry.

The float glass industry is eager to support and shift to a circular economy, expanding the availability of high-quality recycled cullet in its fabrication procedure. Already, the float glass industry adds into the glass batch up to 25% cullet together with the mineral ingredients. This will benefit the industry to save both raw material and energy, and simultaneously it aims in the efforts for protection to the natural environment. An interesting example is that of Vlakglas Recycling Nederland founded in 2002, a company that is active in waste sheet glass recycling. The company gathered one billion metric kilos of architectural glass in fourteen years, and one of its aims is to achieve a 20% return back in the manufacturing line of float glass waste (Vlakglas Recycling Nederland). The whole effort assists the EU sustainability and low carbon agendas, while it enhances the competitiveness of EU-based industries (Glass for Europe). At the same time, it contributes towards the future of sustainability and the long-term health of the environment.

The recycling that occurs in the flat glass industry faces a major obstacle, which is referred to as the high-quality requirements for cullet. Within the float line, three distinguished sources of cullet are highlighted, depending on which phase of the glass life-cycle is refused, namely internal, pre-consumer, and post-consumer cullet. Each of these categories is analyzed further in the next chapter. In spite of that, not every glass panel coming from the construction and demolition sector will be acceptable for passing immediately back to the production. The vast majority of recycled glass used back in the sheet-glassmaking is originating from internal offcuts in the plant itself and they have not yet been delivered to the user. This grade has never been gone from the industrial facilities and in essence, it is instantly recycled on the site. Due to

research progress on the float plants, more types of cullet can get back into the manufacturing loop. Saint-Gobain is the leader of flat glass recycling with an acceptance rate currently climbing to 40% recycled content out of the total batch (referred to as specific glazed product circumstances), together even with cullet that is not supplied by the company but in conformity with their eligibility criteria (Saint-Gobain).

Apart from the cullet origin and certainly the glass recipe compatibility, color contamination makes up a matter under the settlement. In an effort to secure a fixed tint and limit the risk of having inhomogeneous float glass outputs, which are related mainly to the optical quality rather than the mechanical one, every product of the float line gives permission to receive specific rates of color contamination. In every recycling location, the sorting of the cullet becomes according to the cullet substructure's color and glass type. This service assists to operate the reinserting of the recycled glass waste straightforwardly to the manufacturing line to a certain extent as to gain the ultimate glass product without any variation to the existing float line or quality demotion.

All in all, cullet recycling is the perfect candidate to conduce to the establishment of a circular economy. It is a very promising manner not only to meet the market's demands and adapt to legal obligations but mainly creates a significant act of preserving the environment and the natural resources. Even if the whole procedure to secure high-quality cullet is long and requires strenuous effort, it is able in European level operations to deliver roughly 300.000 tonnes of unprocessed material per annum, which is equal to economizing 70.000 metric tonnes of greenhouse emissions (European Commission). However, all the aforementioned cases, linked to the composition of glass cullet, indicate why the float industry mainly relies on the recycling of internal glass cullet, where the degree of contamination is predictable to ensure the desirable glass result.

TABLE 01.5 | Saint-Gobain cullet eligibility criteria. (Saint-Gobain)

✓	Saint-Gobain admits the following types of cullet:		
	Only cullet from flat glass used in the construction and the automotive industry	Decorative glass such mirrors and lacquered glass in limited amounts in the production mix	Black enamelled glass only from Saint-Gobain Sekurit factories
	Laminated glass only if it is made up of one or two standard Polyvinyl Butyral sheets (after special reprocessing)	Coated glass made of magnetron and pyrolytic	Coloured in the mass glass including mixed colour glass if the mix is known and homogeneous

Other Glass Industries

Taking into consideration the recycling loop of other sources of glass wastes apart from the aforementioned, the ambitions of a circular economy is absent. Glass products such as the electrical and electronic equipment and devices' parts, laboratory glassware, glass windows of vehicles, kitchenware, and many others, besides that are not proved to be reused in one or another way, they are also most unlikely to be converted into new materials as well. Contemporary technological efforts are attempted to cut down the contamination, which is crucial in glass applications, or to separate them from any adhesives of coatings. In spite of that, it still needs much more effort or skill to accomplish the extended exploitation of such kinds of glass waste.

TABLE 01.6 | EU-27 statistics on glass production, generated glass waste, collected and finally recycled in 2007. (Vietez et al., 2011)

Glass Type (by industry)	Glass Production	Glass Waste Generation	Glass Waste Collection	Recycled Waste Glass
Glass Packaging	21 Mt	17 Mt	11 Mt	8 Mt
Float Glass	9.5 Mt	5.1 Mt	2.9 Mt	2.9 Mt
Domestic Glass	1.5 Mt	0.8 Mt	0.5 Mt	0.5 Mt
Mineral Wool	3.7 Mt	2 Mt	n/a	n/a
Glass Fibers	0.7 Mt	0.4 Mt	n/a	n/a
Special Glass	1 Mt	0.5 Mt	0.45 Mt	0.4 Mt
TOTAL	37.4 Mt	25.8 Mt	14.85 Mt	11.8 Mt

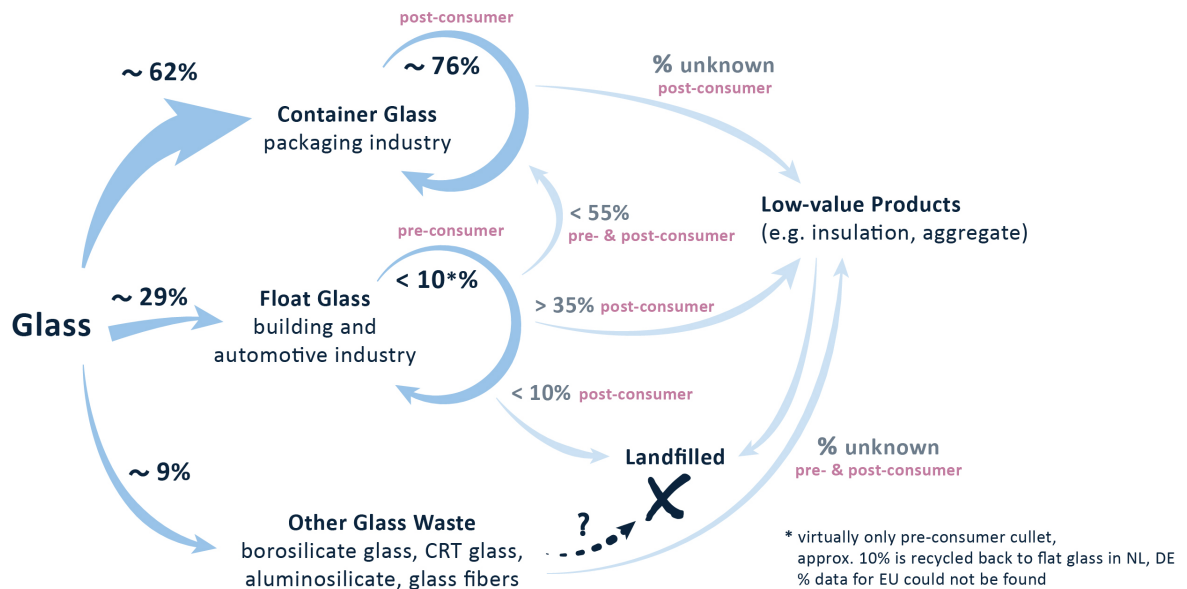


FIGURE 01.19 | Illustration by (Bristogianni and Oikonomopoulou, 2022) of the production and recycling of glass cullet in EU28 in 2017 based on approximate numbers as provided by (Rose, Nothacker 2019; Hestin et al. 2016).

02.8 GLASS PACKAGING INDUSTRY & FLOAT LINE

Circular models and sustainable approaches are continuously influencing the way of thinking, manufacturing, and techniques in the glassmaking industry. Glass material, due to its ability to be endlessly recycled, has the ideal prospect to lead in the transition efforts to a low-carbon and resource-conscious environment. Although this notion has long been utilized in the glass packaging industry, as a successful closed-loop, the case is not the same for the float glass industry which occupies a more complicated place.

TABLE 01.7 | Main differences between the glass packaging industry and the float line.

	Packaging Industry	Float Line
Well-organized Collection System	✓	✗
Mono-material	✓	✗
Loose Cullet Acceptance rules	✓	✗
Effortless Recycling Processing	✓	✗
Cost-efficient Recycling Process	✓	✗
No Disassembly Needed	✓	✗

But what is the difference between these two glass industries? As container glass recycling is concerned, whether the cullet is applied, as a reusable product, or as a recyclable matter, the collection and recycling system for container glass owns an unquestionable successful narrative especially in Europe, presenting significant-high recycling trends. The aforementioned issues are from the fact that bottles and jars are constituting just from glass, as mono-material. Even glass packaging from different suppliers follows more or less the same recipe with small fluctuations, so the industry knows what to expect and the contamination rate is predictable. On the other hand, cullet coming from thin-walled glass reaches recycling facilities in a wide form variation, considering its application. That is not only referred to as the production way of glass if it is formed via float line or casting, but the cullet usually carries contamination related to the secondary processing, such as coatings, glass lamination, ceramic printed parts, wired glass, and metallic edge sealing and plastics that

remnants from the insulated glass units. The aforementioned elements complicate and grow the challenges all the more for the sorting and cleaning procedure of glass waste and drop the probability of the cullet being recycled.

TABLE 01.8 | Allowable percentage of color contamination of recycled cullet, based on (Vieitez et al., 2011; MRA Consulting Group, 2021).

Input Cullet \ Product Output	Glass Container Industry			Float Line	
	Clear (flint)	Green	Brown (amber)	Clear (flint) ^a	Lightly Tinted
Clear	> 95%	< 15%	< 10%	-	< 5%
Green	< 1%	> 70%	< 10%	-	
Brown	< 5%	< 15%	> 85%	-	

^a The float glass industry does not accept cullet with color contamination due to the risk of jeopardizing the quality standards and optical hue that has set in every specific production line.

Theoretically, glazed products could be fully made from pure recycled cullet, being equivalent quality to those made entirely of raw material. However, the next problematic contaminant that differentiates the success between the two glass industries is color contamination. Generally speaking, there are four main tints on the cullet, categorized into flint or clear, green, brown or amber, and mixed one, which is related to commercial color requirements. Due to the fact that recycled glass retains its color, these hues must be separated by the recyclers in order to meet the market's needs. To manufacture various glass products, there are different needs to achieve the perfect color consistency, varying according to the desired output standards by the manufacturer, within and between the production that runs. Determined by the kind of product, container or sheet glass, and the color being produced – these display implications for cullet usage. The most demanding requirements are applied by the float line, which invests in the optical quality of the product which is mostly flint glass. On the other hand, the packaging industry can ensure higher capacity in color contamination on the different colors that are applied in the products.

Even if color sorting technology for cullet has made considerable improvements over the past years, this kind of contamination of post-consumer glass waste is inevitable. The float line case and its acceptance of recycled glass back to the close-loop requires precise control of the available cullet, which may result in a preference for more unprocessed material. For this reason, there is greater tolerance for colored glass packaging, considering at the same time that generating for instance brown glass still demands particularly fine control of the composition that may introduce any impact on the color.

TABLE 01.9 | Maximum acceptable levels of glass contamination. (GTS, 2007)

Contamination	Flat Glass maximum (ppm)	Container Glass maximum (ppm)
Ferrous Metals (cutting blades etc.)	None (if <0,5 g, only max. 2 g/t)	50
Non-ferrous Metals (space bars, drink cans and lead glass)	None (if <0,1 g, only max. 0.5 g/t)	20
Inorganic Materials (stones, ceramics, porcelain etc.)	None (if <0,2 g, acceptable)	20
Organic Materials (foils, plastic, paper, wood etc.)	None (if <2g, max 45 g/t)	3000

To an extent, owing to the case that post-consumer flat glass is not made up just from glass compared to container products, glass industries rely on what recycled cullet is accessible and ready for use at a practicable cost. Getting cullet in a form that is pure, furnace-ready normally involves a lot of processing. In theory, the mono-material packaging really easily can be added in the form of cullet to the production line again, as its composition is almost identical to the original product. Contrariwise, this method is applied to the flat glass industry only to the off-cuts that come off at the cold end of the production line, such as in quality testing or cutting phases, and to the pre-consumer glass in case-specific, for instance after a drilling or known coating is deposited. However, this is not any more an option for thin-walled glass coming from the construction and demolition sector, related to external post-consumer glass. This cullet may carry an extended and unknown variety of extra materials and substances, ranging from PVB foils and liquid crystal layers to contaminants such

as ceramics, stones, and plastics related to the improper collection of the building wastes on-site (Bergmann, 2020). Consequently, usually this heavily modified sheet glass demands greater effort and processing in order to recover as pure cullet, making the whole procedure more high-priced. An additional consideration influencing the price of cullet recapturing from waste is the various glass composition and color tints, which alter from one producer to another. Supplemental color separation of the cullet of an existing mono-material stream attaches an extra amount to the operational expenses of 10-15%, equal to 17-24 euros for every tonne insertion compared to mixed cullet sorting (WRAP, 2007).

According to a survey held by Glass for Europe in 2020, it is evaluated that technical, infrastructural, and economic status considerably confine the expected exploitation of cullet into the loop of float glass making to a maximum of 37%. When the separation of glass is too complicated or even costly, the recyclers dispatch the whole stream to be refused to the fields. In comparison to packaging glass, C&D glass waste pushes the final cost even higher, intending to meet the narrower quality needs.

All in all, cullet originating from a floating line possesses a way more limited rate of reclaiming, due to the greater quality requirements, resulting in almost half the load of the glazed products to be either downcycled or disposed to the fields (Vieitez et al., 2011). Float glass presents high expectations in the absence of any contamination in cullet, in order not to jeopardize the production, which is able to guide in inclusions and discoloration on the final product. On the contrary, the glass container industry with less strict rules and a more organized recycling system develops a more successful route. Contamination remains the greatest technical challenge to overcome to profit from the higher availability of high-quality cullet for the remelt process of glassmaking (DeBrincat et al., 2019). This stresses the significance of organizing and developing an alternative glass-recycling process for the cullet coming from the construction and demolition region, intending to accommodate all the specifications of the flat glass industry. Moving onward, it is deemed necessary, as the grade of cullet rises, to create further evolution in technology to grant the lower value cullet to be processed and cleaned to a rate that is permitted by the thin-walled glass manufacture.

02.9 BENEFITS - PROBLEMS & LIMITATIONS

Sustainability and circular economy are more and more influencing the manufacturing methods in glass production. Glass cullet constitutes a valid and efficient alternative to be used as raw material in glassmaking. Moving towards a more circular economy could deliver a series of operational and strategic advantages, carrying at the same time various potentials within the economical, business, social and environmental framework (McKinsey, 2016).

Benefits

One of the main priorities of circularity in the glass fabrication sector is to shorten as much as possible the greenhouse gas emissions to give a positive outcome to the ecosystems that are hosted by our planet. Currently, the production of materials and products we use every day accounts for 45% of the total CO₂ emissions (European Parliament, 2018).

The mitigation of such emissions and the extensive exploitation of raw materials help in the fight for natural world protection. Recycled glass decreases the greenhouse gasses on-air and the water pollutants by approximately 20% and 40% respectively. If cullet recycling is done on a large scale, then an even raised profit is achieved, as for every metric tonne of cullet added to the batch, a reduction of a maximum of 300kg emissions is delivered (DeBrincat et al., 2019). Thereafter, limiting industrial poisonous effects benefits not merely the environment but as well the entire ecosystem. As stated by the European Green Deal, the circular development is capable of significantly immersing in half the carbon dioxide emissions by 2030 in comparison to the gas outflow levels of 2018 (European Commission, 2014).

But how could circularity be beneficial in this reduction? The CE model promotes the use of renewable energy consumption that proves to be less hazardous than fossil fuels, while the reusing and dematerialization of materials and products demand less energy for the manufacturing process. Moreover, the cullet melts at a lower temperature than its raw material ingredients, resulting in less energy usage. As it is stated by British Glass, a tonne of exploited cullet economizes 300kWh of power (Glass Technology Services, 2008). According to ARUP's research, which was held on the embodied energy on recycled glass with miscellaneous content, it is observed a decline from about 14MJ and 13.2MJ to 12MJ for each kilogram of thin-walled glass with respectively 10%, 35%, and 70% recycled waste glass used in its content (DeBrincat et al., 2019).

Next on the list of environmental benefits is the preservation of a healthy and resilient ecosystem. Recycling glass saves on the need to acquire more grist and primal matter, which is extracted by the Earth's crust, in order to generate new glass outputs. Preserving in this way the available natural resources. This effort also aims the protection the terrain, conserving the unique landscape and the aesthetic value of the natural world. Extracting sand and using heavy machinery for glassmaking has negative consequences through modification of soil, noise, and harmness to the biodiversity. Consequently, glass recycling assists as a conditioner for balanced ecosystems (EMF, 2015). Related to this, a circular economy aims for the favorable management of land use, soil, water, and air from the negative externalities and the contamination that is occurred. Moreover, the waste does not occupy any space on the field if the cullet is recycled. A properly made recycling process based on the business-as-usual scenario could keep away from the disposal of roughly 900.000 tonnes of architectural glass waste annually. What is more, the extraction of 1.23 million tonnes of organic matter is avoided, mainly constituting from silica sand, reducing at the same time the CO₂ release by 200.000 tonnes each year (Hestin et al., 2016).

The surge in revenues from circular activities, along with the lower price in production of products and materials to be more functional, simply disassembled and of course, reused, has the force to influence the GDP value and therefore boost economic growth (McKinsey, 2017). Additionally, CE in the glass industry has the potential to lead to a higher amount of material savings up to 70% (EMF, 2015), seeing that the raw material is not the primary ingredient in the manufacturing process, lowering the material needs, as it leaves out the disposal face.

This development can also bring greater local employment in entry-level and semi-skilled jobs, creating new work positions. It is predicted that 50,000 new jobs could be generated in the UK, 54,000 in the Netherlands, and approximately 700,000 jobs in the EU alone by 2030 (Kalmykova et al, 2018). These will be connected to the creation of new opportunities and services referred to recycling and repairing practices, innovative products, and materials design related to positions for designers and engineers to create lasting and effectively disassembled objects, and therefore increasing trend in new business models. In this new circular sphere, profit opportunities may come to create circumstances for a new market model of lower input costs with waste and energy shortages and the safety lock of supply flow. This innovative market will disconnect companies from their dependence on the volatility of raw materials, since the inputs will be issued from reusable and recycled sources, turning them into more resistant and prepared to deal with unexpected changes, related to increased climate change events.

Circularity's concept seems to foster stronger bonds between the businesses and the clients, giving the former the chance to acquire knowledge of their customer's working patterns through continuous interaction with them. This will also improve the satisfaction and loyalty between them and contribute to achieving product and service development to suit clients better. In a market where suppliers remain responsible and consistent for a longer period, communicating well and understanding the customers' preferences and needs is more important than ever. Finally, consumers will also be provided with more durable and innovative products that will increase their quality of life and save them money in the long term.

Implementing the model of the circular economy may present various benefits for the environment, economy, businesses, and society, as it is already elaborated. Despite that, it also displays some significant obstacles as restrictive events that express the reason why this circularity model in glass manufacture has been expanding so hesitantly and slowly, and many times, issuing from the near-complete lack of flat glass recycling stream, the glass waste has reached their end of life in the landfills.

Problems & Limitations

There are major challenges to glass recycling linked with many obstacles and limitations, making it really difficult especially for the float glass industry. Flat glass cullets are possibly be reused to a limited degree and when value standards are high. Generally speaking, there are some main obstacles in the recycling of float glass connected to the collection system, glass contamination, production process, and legislation.

A proper system of flat glass recycling schemes must be developed. Nowadays, glass sheet waste has a low market value because of the absence of a properly organized dismantle, collection, and treatment system to make what would be a valuable glass-making raw material, without any technical issues. This is happening owing to the requirement of synergies and breakthrough technologies to be addressed as this system to be properly organized. Also, the lack of initial financing support does not help the establishment of a recycling system that requires infrastructure and management schemes. The economic barriers that

are formed to the performance of the circular economy concept are associated with the traditional system of economy. Starting with, most of the current businesses operate under the mentality of a linear approach and it is difficult to invest and evolve their work into a new system. Apart from this, most professionals and workers are only qualified with their knowledge, skills, and references that are limited. The offer of circular goods is not competitive, in contrast to the prices of raw ones, so this is the reason for the low demand for such products and materials. Moreover, there are not any taxes added to the price of raw materials, resulting from social and environmental externalities, placing nature and well-being underprivileged financial market signals.

The obstacles to Circular Economy development in glass manufacture are mostly connected to the establishment and operation of the traditional economic system and the governed legislations. The enactment of legislation about the float glass circular economy would further reinforce the organizing of the recycling system. The current world's economy is supplied from the demand of the linear model and it is not ready to be considered with circular entrepreneurship, keeping at bay the existing situation. This is followed by the fact that modern circular trade markets may be provoking to perform and evolve because of regulations, making it harder to build new alliances for closed-loop innovations. Moreover, the majority of the glass companies focus on short-term value creation dedicated to the altar of money, while the circular economy stands by a long-term value creation strategy. Consequently, regulatory instruments and initiatives will aim to be activated in a coordinated manner to provide incentives for the recycling of C&D glass. An appropriate policy would assist to promote and encourage the collection and recycling of glass cullet.

Nowadays, the competence to recuperate glass materials and correlated advantages linked to the natural ecosystem protection, as a design activity, should be of primary importance that is not frequently considered. The most glazed panels implemented in the building envelope are made out as hermetically sealed insulating glass units (IGU), admitted as one of the most challenging barriers, since any of their components are not capable of being fully separated for reuse or recycling (Babic et al., 2021). Moreover, the procedure to yield the cullet from an IGU is cost, energy, and time associated, making it not worth to be dismantled. Consequently, to achieve efficiency as the different parts of an IGU to be reused, the disassembly of such a system should be set up as a standard practice across the industrial market.

To the extent of the IGU and the glass waste recycling in general, the biggest challenges arise when the glass cullet is contaminated. This kind of impurity or external body in the glass structure is undesired in glass manufacture since it is crucial for the glassmaking to cause problems to the desired strength and quality of the end product. Contaminants exist in various forms, so the risk of having even a tiny proportion of contamination that impair the output is considerably large. One impurity might mean that tens of meters of the glass must be defused (Geboes, 2020), so only pure cullet is accepted.

Glass waste remains a noteworthy problem, which continues to exist unresolved, while contamination remains the dominant practical obstacle in cullet recycling. Contamination can be subdivided into two subcategories: the material contaminants that may be non-glass materials and glass fragments of different compositions, and the color one. The former may be metal pieces, stones, ceramics, organic waste such as food leftovers, plastics and textiles, and hazardous chemical remnants. Upon melting, such parts might not liquify completely, relying on their size. In the example of glass panels, the contamination is referred to the treatments that this product may carry, such as laminations, adhesives, tints, and coatings, which must be removed usually through a manual process. The cullet of dissimilar composition refers to different compounds that glass can be constituting, making it challenging to be mixed as a consequence of alterations in thermal expansion coefficient, and melting and annealing schedule. In a float line production that consists of soda-lime glass, borosilicate or high silica glass are unwanted, since they owe higher melting points and properties in general. Even in a lead glass that has a lower melting point than soda-lime, toxic lead particles will be added to the glass production batch. Consequently, all of them are possible to stimulate undesirable inclusions in the glass efficiency. The latter is also associated with the thickness of thin-walled glass and the contamination rate that is capable of tolerating, as contamination plays the role of stress concentrator, a crucial factor in glass breakage. Lastly, related to the optical quality control of the float glass production line, to produce clear glass only fragments of specific color rates are permitted for a homogenous raw material. Glass cullets of different colors from the standard one, can be reported for the optical status of the end product. Clear glass is more prone to color contamination, especially to amber or green cullet coming from a bottle package.

Float line is a completely automated process. Production of thin-walled glass is not flexible, since it follows a specific recipe of sheet generation, which is really difficult to change. A characteristic example is the switch of float glass thickness. When production is a sheet of 4 mm thick, an alteration to 5mm distance has to grow gradually. Therefore, the glass that is manufactured during this time is worthless, the same as the spent energy to be generated, owing to the thickness of the flat glass that varies between this one millimeter (Geboes, 2020).

Apparently, barriers to the Circular Economy expand in more different perspectives such as societal, structural, operational, attitudinal, and technological. Difficulties of dealing with and staying in control of the circular value chain, the lack of knowledge on efficient and sustainable matters, the aversion to risk, and the effort and time of redesigning and re-defining products, systems, and services consist only of some of the related obstacles of the aforementioned categories.

Even if the circular economy is still in its infancy in the glass sector and especially in the float line, switching from the current linear model of the economy to a circular one becomes the biggest and most radical challenge for business models, presented in the 21st century. The advantages, disadvantages, viability, and limitations of the circular approach in glassmaking should be discussed in detail to comprehend every aspect in order for a properly made strategy to be elaborated. This set the foundations for the execution and effective performance of the operational system, which would display a sustainable business scenario for the recycling of every grade of glass waste.

02.10 EXPERIMENTAL RESEARCH ON CASTING GLASS WASTE BY TU DELFT

Following the extended explanation of the unsolved problem of glass waste and existing data on recyclability and management, it is assumed essentially important to review current research and experiments. This assists to lay down the foundations to comprehend and explore further the potential prospects of unexplored float glass waste compositions in terms of recycled cullet resources. The existing applications and revealing evidence in published experimental work outline the prospective guidelines that could be followed to investigate the potentialities of such waste. Accordingly, obtaining insight into the different float glass cullet and production method is used as assistance in selecting the optimum glass recipes and processes on the firing schedules.



FIGURE 01.20 | Re³ Glass Project's recycled components variations. (Oikonomopoulou, 2019)

Since 2017 in TU Delft, a lot of research has been held in glass recycling in an effort to enable the circular use of glass waste and its potentials. Recovering discarded glass in cast glass products opens new paths to reintroduce such waste back to the supply chain, as a closed-loop approach. Concerning glass recycling experiments, considerable work has been presented through master theses, publications and scientific papers by the students and research group of TU Delft, activating on Glass & Transparency including architectural and sustainable glass.

Pioneering experimental research has been conducted on the project «Re³ Glass» by Telesilla Bristogianni and Faidra Oikonomopoulou. Their work regarding the design and development of structural, dry-assembled interlocking glass members further concentrates on following the so-called waste hierarchy strategy of REduce, REuse and REcycle (Bristogianni et al., 2019). As far as the first step is concerned, the concept employs recycled glass waste in order to form through casting the 3-dimensional components, allowing the toleration of higher degree of contamination and impurities due to its wider section, in comparison to the thin-walled flat glass, without necessarily compromising the product's mechanical or aesthetical characteristics.



FIGURE 01.21 | Re³ Glass Project's commercial glass products (left) converted into recycled bone-capsule interlocking elements (right). (Bristogianni et al., 2019)

Previous research on the aforementioned project presents a great amount of promising investigational works published. These either validated the contingent of Re3 Glass piece-by-piece or introduced promising mixtures of unexploited glass waste.

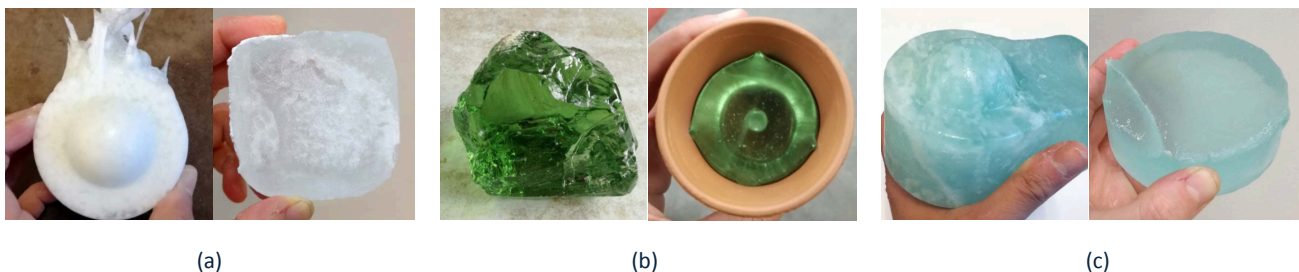


FIGURE 01.22 |

- (a) PPG Starphire (extra-clear float glass) kiln-cast at 860°C and mechanically quenched (left) and at 1.200°C with top surface crystallization (right).
 (b) PPG furnace clean up waste green glass before (left) and after casting at 860°C (right).
 (c) PPG furnace from float production furnace clean up aquamarine cast at 860°C fully crystallized (left) and result at 1.200°C (right).
 (Bristogianni et al., 2018)

In the first place, extensive research has been conducted by Bristogianni et al. (2018) on a variety of glass waste coming from several families that were introduced back to glassmaking. This effort indicates the recycling capability of those glass compositions linked to common objects, that are currently deposited into the fields, while at the same time signaling any constraints on fulfilling the principles for structural components. Testing materials from beer bottles and window panels with PVB to mobile screens and oven doors, introduce new opportunities and alternatives for the recycling of such waste. These various sources were firstly examined through test melting for their viscosity in working temperatures between 860°C and not above 1200°C. With the method of kiln-casting and hot-pouring at different firing schedules, the glass samples have been firstly formed starting with the lowest temperature for energy efficiency, taking into account the glass waste's attempt at crystallization. In the final results generated by the experimental research, cases on cast homogeneity, crystallization formation, color alterations, and probable impurities and faults caused by the presence of any contamination were evaluated. The outcome of these first explorations, it is evident that the greater the working temperature is set, the smaller crystallization is formed under the top surface of the sample (Telesilla

Bristogianni et al., 2018). The analysis also showed the different kinds of glass waste, in order to be properly recycled to produce glass components, seeking extra exploration in terms of heating temperature and annealing treatment to meet the most appropriate outcomes.

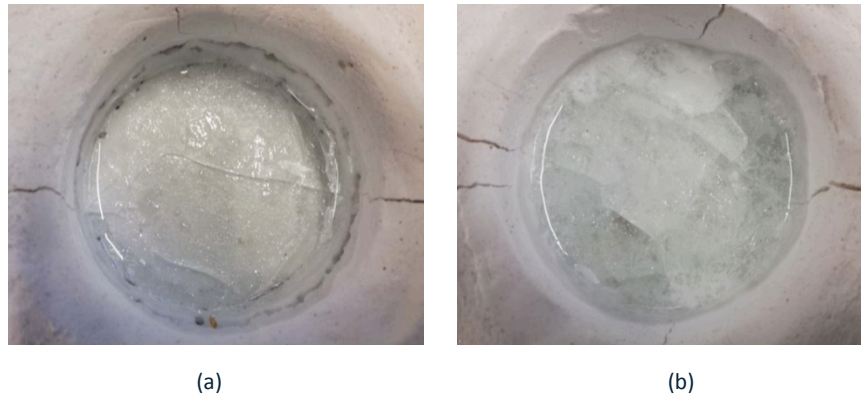


FIGURE 01.23 |

- (a) Lead crystal and float glass combination, fired at 3 hours at the maximum temperature of 1250°C and the abrupt cooling results in a very transparent glass body with cracks formation, which corresponds to those found in the mold.
 (b) Borosilicate and soda-lime-silica glass combination, fired at 1250°C and annealing at 570°C, giving the result of a transparent bubbled body with crystallization at the mold's walls and cracks, corresponding to the mold's one.
 (Bristogianni et al., 2018)

Moreover, initially tested combinations of matching glass recipes of different everyday products that are mixed together, present a certain interest. As part of a realistic case scenario, where the separation of the different wastes could be avoided, it is possible to promote a procedure that activates their closed-loop recycling. In this way, their physical properties could be merged, concluding in the improvement of the complete behavior of the final glass output. These samples were tested at higher temperatures from 900°C to 1250°C, in order to prevent any cracking or breakage on the glass object, as a result of cooling and annealing rates. Moreover, further exploration of the cullet size is needed, as the mixing in small shards was not the most suitable means to achieve a satisfying homogenization inside the melt, while a force generation in the body of the object and the mold's surfaces was observed. Examining the glass cullet in the form of fine powder could be proved as a better way of dealing with the difficulties of the experimentation with recycled glass mixtures.

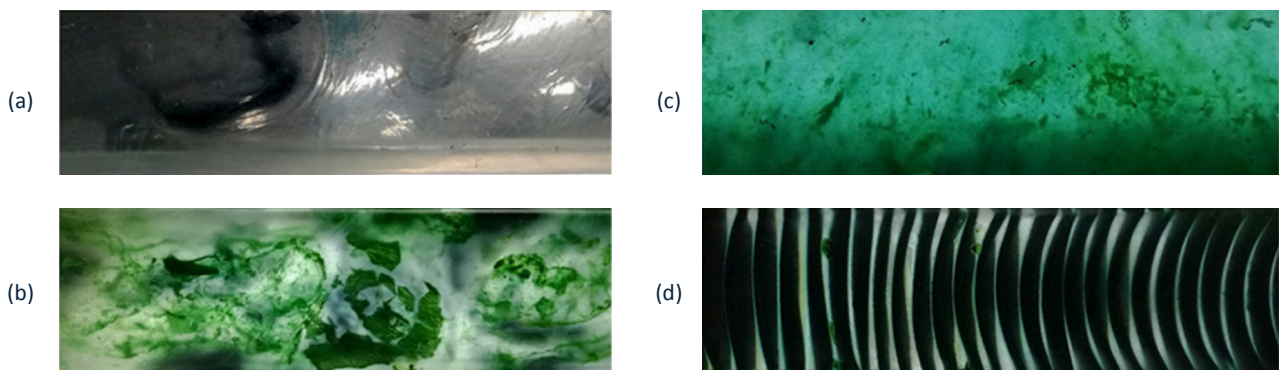


FIGURE 01.24 |

- (a) Combo of float glass (soda-lime-silica glass) with contamination tested at 1120°C, presenting heavily cords of light blue hue with color streaks, while ¼ of the specimen fractured due to the presence of glass-ceramic content in the cullet.
 (b) Oven doors (soda-lime-silica glass) tested at 1120°C, with color streaks, coating residue, and occasional surface flaws by mold contamination.
 (c) Car windshields (soda-lime-silica glass) tested at 1120°C, with color streaks, bubbles, stones, and coating residue.
 (d) Enamel float glass (soda-lime-silica glass) tested at 1120°C and positioned in 60 vertical layers, with remnants of the vertical layers of the coating.
 (Bristogianni et al., 2020)

Another noteworthy research has recently explored further the potentialities of recovering non-recyclable silicate glass by Bristogianni et al. (2020). In this work, the casting parameters are evaluated, along with the probable faults that may occur in the glass specimens, owing to the contamination that the cullet is caring for, in defining the flexural strength, Young's modulus, and the strength-limiting defect. The main objective is to provide insight and extend data on previous research into the result of the casting parameters on the recycled products' strength, and to estimate the reasonable plausibility of using commercial waste glass for the generation of certain load-bearing elements. This work studies several glass types under the form of cullet into the same mixture, with the most common contaminants to be coatings (soft, hard, mirror, enamel, frit), glasses

from various manufacturers with alternative color tints, and contamination related to the collection and sorting process. Therefore, the specific experimentation on the samples is differentiated from the previous one since a relatively low working temperature is used on the firing, fluctuating between 820°C and 1120°C.

The outcome of the research was that a meticulous sorting of the waste glass in the recycling station is able to provide a really promising casting result. However, identified impurity of glass, such as coatings and traces of organic contaminants and metals are endured by the glass network, whilst glass ceramics and glass types with considerable compositional alteration lead to cracking or breakage of the outputs on the cooling stage. Moreover, some glass recipes that have lower liquidus points enable lower working temperatures. Such circumstances on recycled-glass production limit the existence of sintering blemishes, apparent bubble formation, and stone configuration caused by the mold.

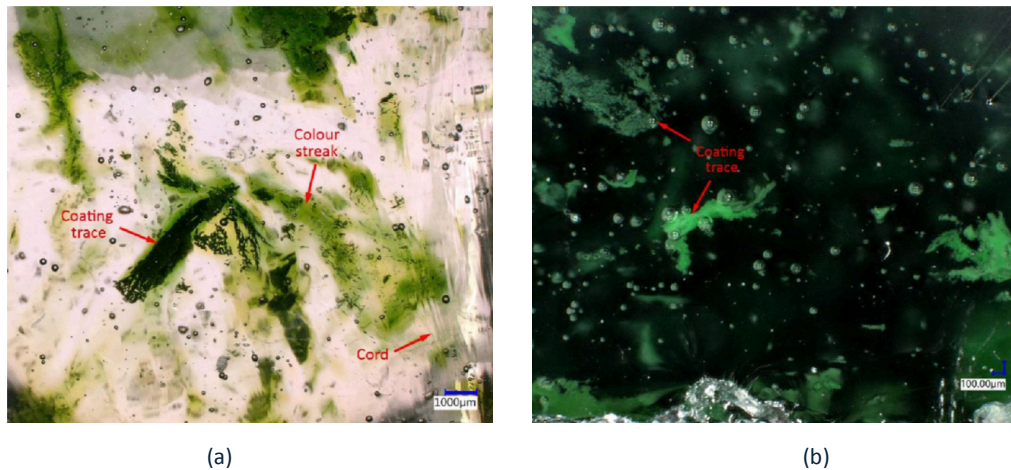


FIGURE 01.25 |

(a) Microscope image of the oven doors sample tested at 1120°C, with flat crystalline inclusions, cord, color streak by coating residue and bubbles, (b) Microscope image of the Car windshields tested at 1120°C, with flat crystalline inclusions and bubbles. (Bristogianni et al., 2020)

Anagni et al. (2020) examine even further in their scientific paperwork, possible combinations for glass waste between dissimilar glass families. Each type of glass was broken or grinded in the form of either shards or powder, for different mixtures to compose the cast glass elements for certain structural applications at temperatures of 970°C, 1120°C, and 1200°C. The various attempts have been performed denoting the possibilities of some compositions and providing the guidelines for an upcoming examination. Besides that, the developing research aims to provide light and knowledge on enabling different scenarios of a more sustainable approach for these widely-used material waste in certain applications. Her work proves that Soda-lime-silica glass and lead-crystal glass mixture are unveiled to be the most adaptable formula with all the necessary physical and mechanical properties of such a needed glass unit to be met. Whilst, she draws conclusions that cullet powdering is influenced by the formation of faults related to stones and metal contamination originating from the grinding machine.



FIGURE 01.26 |

(a) Soda-lime with lead-crystal glass melted at 970°C in the form of powder, presenting a high bubble level and considerable contamination, (b) Soda-lime with lead-crystal glass melted at 1120°C in the form of powder, presenting considerable bubble level of small sizes and contamination, (c) Soda-lime with lead-crystal glass melted at 1120°C in the form of cullet, presenting negligible bubble level of small sizes and low contamination. (Anagni et al., 2020)

The most recent work on glass recycling by Bristogianni and Oikonomopoulou (TU Delft) is involved in the walk-in installation with the name of “Transparent Things”, located in the Gernheim Glasswork LWL Industrial museum’s outdoor facilities. A project initially assisted by Michel Melenhorst, professor of Contextual Design at the TH OWL, and the participation of a group of international young people studying at Technische Hochschule Ostwestfalen-Lippe, who were also supported by advice and the work of the two scientists from TU Delft, as part of Re3 Glass Project.

This time the concept in the installation of “Transparent Things” is referred to as an artistic experiment for the fabrication of recycled and reusable cast glass elements for architectural applications in the form of thick-walled tiles. The main consideration of the concept is sustainability and the circular model within the scope of the climate crisis, and the limits of thoughtless goods consumption and waste generation. For the production of the components, in-house discarded glass waste was considered after cleaning, crushing in cullet, and remelted under a firing schedule on a kiln, since glass recycling is constituted by a multi-stage procedure. In the project, twelve colorful panes were formed by the team of students, while additional eight panes were fabricated in TU Delft’s facilities out of flat glass waste coming from cars and monitors sheets.

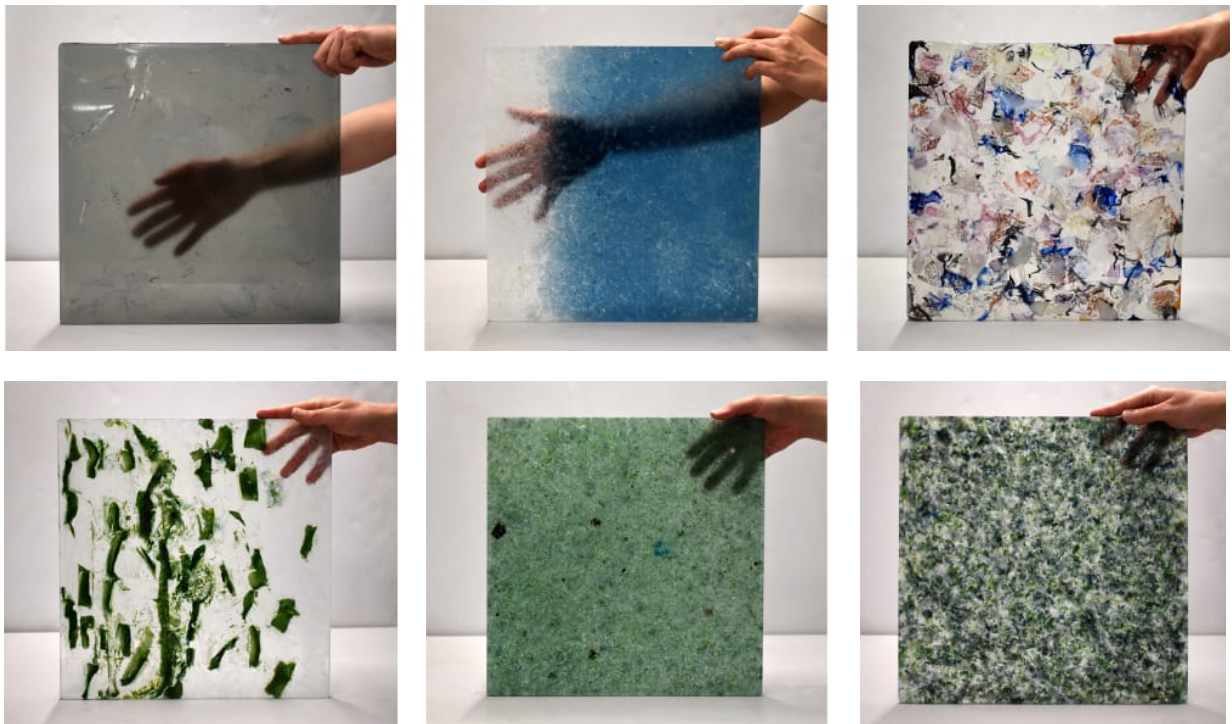


FIGURE 01.27 |

Transparent tiles out of glass waste, part of Re3 Glass Project. Image credits: Oikonomopoulou & Bristogianni, 2022.

02.11 CONCLUSION

Given the continuous growth of the worldwide population, human activity has been disconnected from the natural environment, causing detrimental damage to it. More than ever, it is deemed necessary to move towards a more sustainable way of life. Glass is an inert material, indefinitely recyclable and capable to maintain its properties, independently the number that is remelted and reformed into a new product. Using recycled glass to make new products generates remarkable energy and CO₂ savings, and it contributes to creating a circular economy. This places it as one of the most sustainable materials, nominating it as an excellent candidate in the transition efforts to a low-carbon environment.

According to the existing glass recycling industry, the types of glass wastes can be briefly divided into three major families, categorized by their disposition: the post-consumer containers, the C&D glass, and all the other unsolved glass waste. Apparently, it is not obvious to talk about glass recycling glass packaging, when it is proven that a mature closed-loop recycling procedure for glass bottles is already working really well, especially in Europe. However, this is not always the case. Depending on the degree of purity achieved in the processing of cullets from waste glass recycling, barriers come to the complete return of all recovered glass to glassmaking,

since not all qualities are accepted back in the recycling loop. Unfortunately, the vast majority of all the other everyday glass products are either down-cycled to low-value applications or are sent and disappear into the landfill.

Among the various glass waste, a great proportion of float glass remains unexploited. Even if these flat glass cullets are of high quality, they are thrown away, occupying valuable land. This large quantity of non-recycling glass category indicates that there is a large potential for upgrading the glass recycling process. To significantly drop the environmental impact, the conventional life-cycle of the flat glass must evolve into a circular life cycle. This report reviews the existing linear float line procedure and proposes a circular concept for the end-of-life of post-consumer thin-walled glass materials, coming from the construction and demolition sector, through recycling at a high level, back to the glass-making loop. In the flat glass industry, soda-lime glass is used, so other types of glasses are not included in this research as their contribution to the problem of glass waste is negligible.

Small efforts have been made for the recycling of such glass waste, but ambitious. Thus, major challenges, related to the whole life circle of glass, create various limitations and obstacles to be tackled and to develop a circular system of flat glass recycling. Arup already studied the part of prevention and preparing for re-use stages of glass waste hierarchy. The current report aims to map the whole system's viability, concentrating mainly on the recycling phase for the strategic development of the operational system.

Finally, the cast glass method is going to be explored for the manufacture of a glazed component. An interesting method, which is a more flexible process with small-scale production, minimizing logistical and environmental costs of waste collection and transportation. Moreover, it is able to produce glass from recycled waste cullet with bigger thickness, which actually can tolerate more contamination and impurity rates than thin-walled glass.

03 | CONSTRUCTION & DEMOLITION GLASS WASTE

03.1 C&D WASTE

The built environment makes up one of the industrial sections with the highest utilization of energy demand, exploitation of natural resources, and waste generation, causing environmental pressure generated by the construction and demolition sector. This consideration places it, as a substantial field, where sustainable approaches such as reuse and recycling have to take ambitious and pioneering actions. In the European Union, buildings figure to be an elementary source of more than a third of all waste produced (European Commission, 2011). Sizable quantities of various materials and products in the C&D sector and extended construction areas represent the ideal and inviting circumstances, where recycled materials could be exploited in a circular economy. Over and above that, the EU already sets rules and targets in order to make certain this waste is handled in a way that preserves the natural world and circularity is promoted.

“Construction and Demolition (C&D) materials consist of the debris generated during the construction, renovation and demolition of buildings, roads, and bridges. ”

(EPA)

This kind of waste is coming from buildings and civil-engineering works erection but mainly from the demolition, destruction, and renovation activities in the construction field. It frames a large diversity of waste, including bulky and heavy materials and products such as concrete, bricks, clay tiles, steel, gypsums, metals, glass, wood products, rocks, plastic, and salvaged building components among other doors, windows, and plumbing fixtures. Additionally, C&D debris may accommodate minor proportions of hazardous solvents and asbestos, being risky to hinder the recycling process.

Construction and demolition materials constitute a significant waste stream and regardless of their contingents to be recycled, their mass quantities are either landfilled or diverted to a “next use” market, for instance, aggregate, soil amendment, fuels, and compost. Generally, different stages of refusal, recovery and recycling of building waste have been achieved beyond European countries. Some members’ efforts are crowned with success, while others are in vain, with trends spanning from less than 10% to over 90%. A European approach has been made to include and improve the sustainable concept in the man-made environment. Accordingly, a common language of standards and rules have been enacted namely “Waste Framework Directive” in 2008 and “Construction and Demolition Waste Management Protocol and Guidelines” in 2018. These tools have set milestone objectives with the matter of greatest importance the waste stream management towards a circular economy.

Specifically, in the Netherlands a major campaign has been launched in 2016, to drive to a fully circular Dutch economy by 2050. For Dutch, the building sector constitutes a significant part of their financial system. Annually, this sector demands half of the total raw resources of the Netherlands with 40% of carbon dioxide release, whilst 23 million tons are referred to as waste of which almost the majority is directed to another use, mainly as aggregate (Schuttelaar et al., 2018). In response to that, specified Agendas set goals for a completely circular C&D industry by 2050, which will tackle the environmental, economic, and societal challenges.

03.2 C&D GLASS WASTE

Looking at the world of construction, glass panes are all the time used material for façade applications in transparent surfaces, such as curtain wall components, windows, glazed doors, or sometimes roofs and floors, produced by the float line. These sheet glasses account for 30% of the whole production of the glass industry in Europe produced by seven factories that represent one of the biggest manufacturers along with China and North America across the globe (Hestin et al., 2016). Seeing the building field as its leading market, with daily production capacities of 850 tons of melted glass (Glass Alliance, 2021). However, the continuously increasing trend in the architectural and engineering field towards wider applications of glass surfaces and demand for transparency in the building facades has spread the need for float glass generation.

Several activities of the building sector, primarily the demolition and renovation operations, when taking place post-consumer glass wastes are generated. By improving the properties of glass panels, in order to influence the solar energy transmittance and to extend the total energy performance of a structure, the significance of thin-walled glass technology is growing in both the building erection and renovation field. In an effort to fulfill the

contemporary energy standards, the replacement of the old single-glazed panels with a new one with double or triple glazing, extra coatings, and gasses in the gaps for higher efficiency, has turned out to be a common practical intervention the time being. Consequently, the aforementioned activity implies that a big amount of end-of-life sheet glass is generated. Each year, this output of C&D glass debris equates to almost 40 million tons only in European territory and much of this is landfilled or recovered, with the latter being the most usual option with an average rate of 82% (Hestin et al., 2016). All things considered, the growing energy requirements along with the mean service-life of a glass panel, which is estimated at 25 years, a notable rise in such waste is predicted over the forthcoming years (DeBrincat et al., 2018).

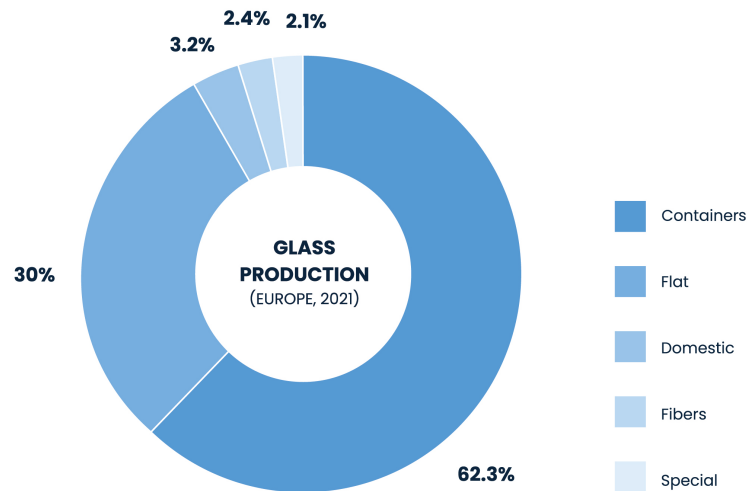


FIGURE 01.28 | Production Share and Evolution within GAE Sectors (in million tons). (GAE members, 2021)

For the time being, several directions and operations have been planned aiming to handle the current situation of waste, including glass coming from the C&D sector. Targets have been set focusing on a more sustainable world, where the linear economy in the material management must be displaced by a circular approach. Glass waste carries a reasonable amount of high quality and prospects for reuse and recycling. The benefits are proven when in a furnace the melting of one tone cullet preserves 1.2 tons of organic matter with 70% made up from sand extracted from the Earth's crust, while energy savings related to the melting stage stand at 2-3%, equal to a reduction of one-third tons of greenhouse gasses. However, the ecological impact of treating C&D cullet highly rests on the covered distance for cullet collection and distribution.

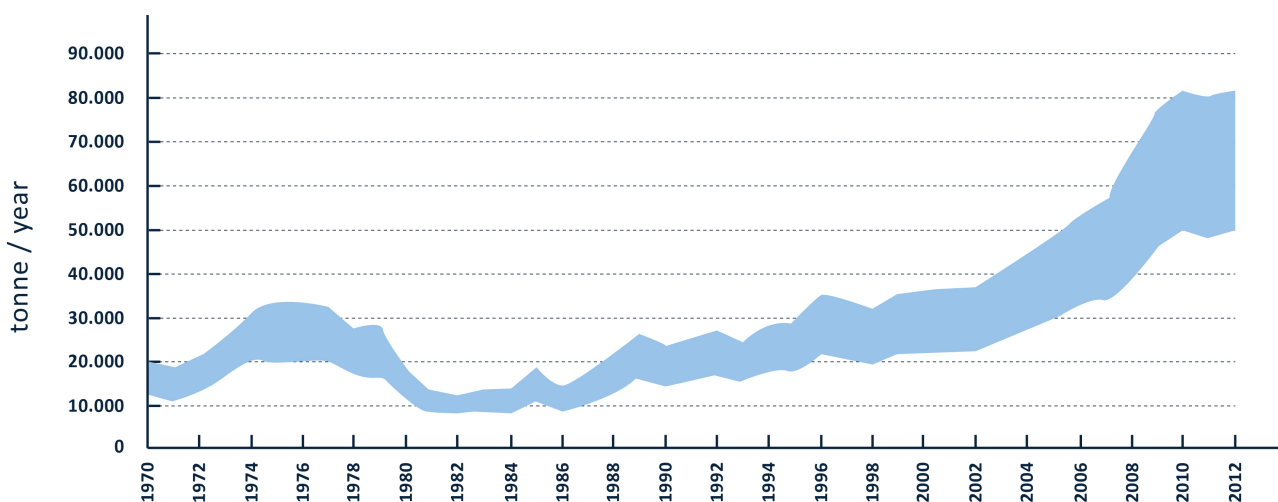


FIGURE 01.29 | Overview of the growth in consumption of flat glass in the construction sector from 1970 to 2012. The graph takes into account an error deviation of 25% of the calculated rate (Dubois, et al., 2013).

03.3 GLASS CULLET

As a resistant material, glass can be recycled indefinitely. Glass recycling is the processing of waste glass into useful materials and products, which are formed into cullet to be suitable for reforming. Cullet can be considerably serviceable among others in the mitigation of consumed power in the time of melting procedure in the float line production.

“As cullet is referred the glass that is broken or refused, usually added to new material to facilitate melting in making glass.”

(Merriam Webster Dictionary)

Nevertheless, thin-walled glass cullet comes from two categories, highlighting the notable quality difference that is distinguished between them.

- **Internal Cullet:** It includes discarded pre-consumer glass cullet that is generated at the cold end of the production. They are tracked during the quality control or remnants and offcuts on cutting or prestressing processing in the float line operation stages during the manufacturing process. Impurities detected by the quality check are owed to transition phases of product changes, for instance, thickness heterogeneity and color flaws. Internal cullet is not regarded as waste, due to its high quality ready to be inserted into the furnace, as it is very similar to the original glass panes. Inasmuch, it is pure and contamination-free from the moment that it has not been in touch with other substances, so it does not require any activity to be cleaned or treated.
- **External Cullet:** Both pre and post-consumer external cullet are referred to as waste, as they have reached their end-of-life and have been collected and reprocessed with the intention of recycling. Lacking its whole service-life characteristics and their exact composition, this kind of cullet is difficult to be completely specified. For the aforementioned reason, the probability of containing any contamination qualifies as lower value glass waste, compared to the internal type. Consequently, if the purification of the external cullet with the removal of contamination is possible, then the cullet typically can be mixed with the batch. An exceptional event is the issue of color contamination that different glasses own from their various production lines, displaying implications for cullet utilization. Each and every flat glass industry and line sets specific limits on color contaminants' presence, in order not to jeopardize changing the tint of its glass. On the other hand, if the quality is defined as too poor, it is not sufficient to be used, so it is landfilled or recovered.
 - **Pre-consumer:** It refers to the glass waste derived from external industrial sources, which is related to the glass processing that the glass panel has been gone through (cutting, drilling, etc.).
 - **Post-consumer:** It contains cullet from post-consumer glass waste coming from the construction and demolition sector.

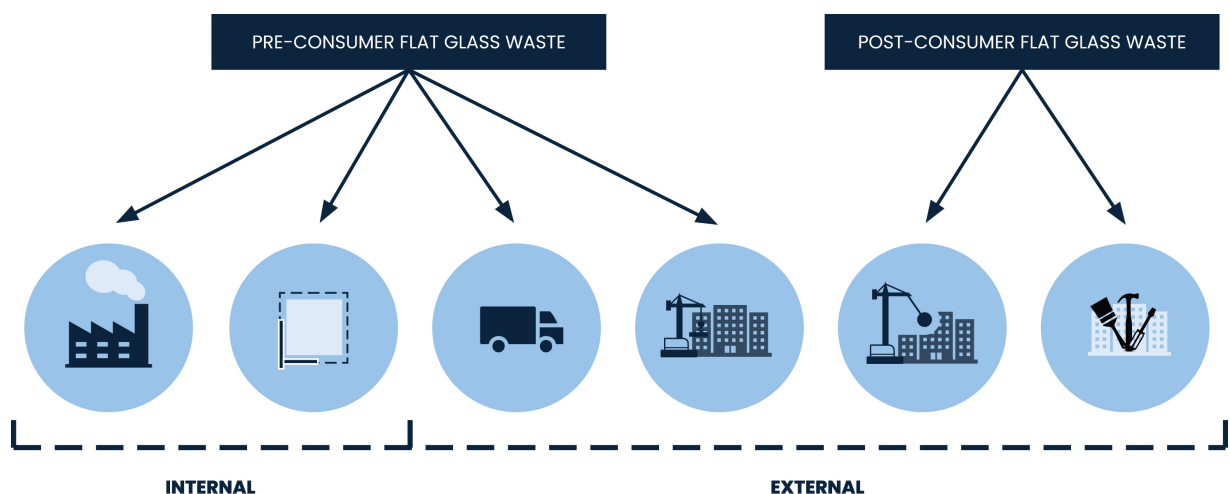


FIGURE 01.30 | Flat glass waste classification. (Geboes, 2020)

When glass cullet is included in a batch, the first thing that becomes clear is that they are extremely useful as a valid substitution for silica sand. Cullet addition on the float line production is already a standard industrial

practice since most of the glass manufacturers add a small proportion to the glass recipe. This cullet originates mainly from pre-consumer glass as by-products of breakage or offcuts of the processing, as it is practically an internal recycling process. A percentage that fluctuates from 10 to 40 percent of the total batch, with an average number of 20-25% (ARUP), results in saving energy and extraction of new raw materials.

In order to validate the quality of the cullet, even if it is internal or external, a “Quality protocol for flat glass” was released. Criteria, about if the glass cullet is no longer waste and it is ready for a new introduction into the float glass production, are clarified (WRAP/EA, 2008). The fact of the procedure is that the level of quality for waste cullet of glass panes production is 20 times thorough compared to the post-consumer container industry (Vieitez et al., 2011). In accordance with the standard guidelines, there are several requirements to be met relegated in composition, particle size, and contamination.

Composition

In order to, a proportion of cullet to be utilized back in the float glass production line, its origin and composition should be known and be compatible with the following guidelines:

- *Clear soda lime silica window glass.*
- *Less than 5% lightly tinted flat glass (bronze, green, blue, and gray).*
- *Flat glass with highly transparent thermal insulating coatings (e.g. ClimaGuard, K glass, Planitherm)*

Moreover, any proportion of cullet corresponded with the forthcoming types is not authorized to insert into the production process. Diverse glass types, even in minor quantities in the same recycling stream, cause changes in the glass fluid’s viscosity in the furnace during the melting process. Additionally, glass tends to preserve its color.

TABLE 01.10 | Glass Categories not accepted by the float glass industry. (GTS, 2007)

X	Not accepted glass types		
	Container glass	Borosilicate glass (e.g. Pyrex, Borofloat, labware, cookware)	Dark tinted glass
	Laminated glass	Fire resistant laminates (e.g. Pyrodur, Pyrostop, Pyroguard)	Lead glass
	Glass ceramics (e.g. Robax, Ceran)	Heat resistant glass	Printed glass (with ceramic inks)
	Windscreens or antenna glass	Mirrored glass (some manufacturers accept low levels of <0.8%)	Wired glass (any type)

Particle Size

The cullet must be of a specific size since it carries implications for the material handling on the production site. It is a really notable guideline of the industry, as the cullet must be kept to a minimum, since airborne dust problems may occur. Additionally, large glass fragments probably create occlusions in the cullet transmission system. The limits on the size of the cullet are as stated in the following table.

TABLE 01.11 | Cullet particle size eligibility criteria. (GTS, 2007)

✓	Acceptable Particle Size		
	Sizes smaller than 4mm are eligible at a rate of 5%	Sizes smaller than 6mm are eligible at a rate of 15%	Maximum fragment area should not exceed 100 cm ²

On top of that, the particle size assists in a more convenient way as contingent contamination can be detected through the routinely and careful examination of the allocation phase of the cullet to the manufacturer’s place.

Contamination

As it is already mentioned, the glass cullet must be purified and free of any impurities caused by extrinsic materials or substances, since glass pollutants are unwelcome for further utilization of the cullet. If flat glass waste is not carefully collected and on the contrary, it is combined with other building debris, a great

concentration of contamination may jeopardize the glass product output and not only (Dubois, et al., 2013).

However, even negligible levels of pollutants and off-target compositions on glass cullet may expose the glass production line to irreparable risks. Firstly, impurities are able to cause undesirable flaws in the new glass products, resulting in aesthetic imperfections or even worse fragilities that may drive the glass product to breakage during production or later on along its service life. For instance, particles of CSP, glass ceramics, and nickel matter should be strictly kept away from the cullet stream, inasmuch as they possess a higher melting point than glass elements, introducing defects in the final glass object. Secondly, reinjecting an amount of contaminated cullet in the furnace is able to lead to damage, reducing the oven's lifespan. In the long run, such an omission could come up with high finance charges on the production line (Saint-Gobain). Moreover, since contaminants are able to influence the materials' composition during manufacture, it is really probable to generate unforeseen and inadmissible chemical reactions. That entails the induction of Volatile Organic Compounds (VOC) emissions maximum restrictions, that are strictly enacted and the glass industry should be compiled accordingly (Saint-Gobain).

TABLE 01.12 | Maximum acceptable levels of glass contamination in the glass industry. (GTS, 2007)

Contamination	Particle weight/size	Flat Glass maximum (ppm)	Container Glass maximum (ppm)	Technical Glass maximum (ppm)
Ferrous Metals (cutting blades etc.)	< 0,5 g	None (if <0,5 g, only max. 2 g/t)	50	10
Non-ferrous Metals (space bars, drink cans and lead glass)	< 0,1 g	None (if <0,1 g, only max. 0.5 g/t)	20	20
Nickel-containing steels or alloys (grinding equipment etc.)	-	None	n/a	n/a
Inorganic Materials (stones, ceramics, porcelain etc.)	> 0,2 mm	None (if <0,2 g, acceptable)	20	20
Organic Materials (foils, plastic, paper, wood etc.)	> 2 g	None (if <2g, max 45 g/t)	3000	3000

Recycled cullet could easily not be given the appropriate observation that deserves. Thereafter, it is really crucial for the quality of glass to be specified and controlled at the source, since prevention may be salutary. Subsequently, the float glass industry accepts exemplary levels of contamination, as to prevent such jeopardy.



FIGURE 01.31 | Main risks presented when cullet is used in glass production. (Saint-Gobain)

03.4 GLASS TRANSFORMATION & POST-PROCESSING

The glass products coming from the flat glass industry, after the primary generation method, undergo secondary processing according to the consumer's needs. Post-processing methods influence to a great extent the ultimate behavior of the glass product, particularly in the output of the float line. A number of techniques affect the mechanical properties of the products, while others the optical characteristics. This transformation is held either by glass manufacturers or by other companies, where the glass is cut and treated to the desired forms and sizes and is modified to the final output (Dubois, et al., 2013).

The flat glass industry has a wide range of thin-walled glass applications, accordingly the panes are converted into curtain wall components, windows, doors, floor panels, and many other examples. Each of these unique products demands additional treatments that may essentially vary between them, containing an ample field of attainable processes. The following techniques coincide to alter the properties of a glass sheet's inner or outer layers according to each process, providing specific properties. The understanding of these methods will aim to comprehend all the probable barriers to glass cullet recycling potential, which may be the response of the

vulnerable parts where defects and impurities affect the mechanical strength of glass and the whole performance.

- **Tinted glass:** Body tinted flat glass is manufactured by receiving a special color blend. Throughout the float line, the batch is obtained by adding colorants, referred to as really small quantities of metal oxides to the thin-walled glass constitution, to produce various specific colours. The tint on the glass is homogeneous along with the total thickness of the pane. These color additions do not influence the standard properties of glass, except for alterations in the transmission of solar energy.
- **Lacquered Glass:** A type of glass, also known as back-painted glass, that is produced by attaching a lacquer coating on the one surface of sheet glass and subjecting it to dry heat to harden in an oven. It also assists the lacquer to join accurately with the panel in order to obtain a smooth finish. This layer supplies the glass with an opaque appearance with any desired coloration.
- **Cutting & Shaping:** Mainly designated as the first step of flat glass secondary processing. The glass panes are cut to the desired size or form proceeding to the edge working. This method is achieved through the weakening of glass chemical bonds, alongside a score-line that makes it susceptible of cutting up in that border by putting in controlled force.
- **Drilling:** It is a typical process happening before any other treatment that may affect the glass surface. A procedure of hole generation with various sizes and cross-sections.
- **Coating:** Glass coatings are very fine layers of metal, which are applied to the glass surface. These layers can be added to the glass during the float line procedure or just after the processing of cutting, forming, and drilling. This differentiation between them is referred to sequentially as online and offline coating. The addition of coatings on the glass surface is applied for various reasons and they are able to modify and improve properties such as control of solar gains, thermal performance, visual appearance (colored coating), and optical output.
- **Laminating:** Laminated glass is produced by bonding together two or more glass sheets with suitable interlayers, mainly polyvinyl butyral (PVB) or ethylene-vinyl acetate (EVA), to create a sandwich under heat and pressure (DeBrincat & Babic, 2018). Accordingly, laminated safety glass is formed with safety on impact, enhancing post-breakage performances to decrease the risk of injuries upon glass breakage. Simultaneously, the fire resistance is raised and properties such as acoustic control and thermal insulation are improved. Finally, it is characterized by the stiffness and load-bearing capacity of structural glass applications. Laminated glass is typically applied in facade elements, thicker glass units, skylight glazing, safety glazing, and cantilevering balustrading. Even if it looks like monolithic glasses, they perform considerably different compared to them (ARUP).
- **Printing:** Glass sheets can be further processed with the printing of repetitive patterns and colored textures for aesthetic, shading, and privacy needs. Ceramic enamel frits are applied on panes surfaces, containing finely ground glass mixed together with inorganic pigments to produce the covetable color result. Actually, the glass with the ceramic patterns is heated in the furnace at temperatures exceeding 600°C, in order for the frit to be fused into the compositions of the glass and become an integral part of it. The ceramic coating is almost as hard and tough as the glass itself, with highly weather-resistant and UV protection able to maintain its patterns without fading.
- **Heat treating:** When glass panes need extra durability for safety reasons, the pre-coated glass undergoes a heat treatment. Essentially, this is referred to as heat strengthening or toughening (known as tempering). These processes tend to alter the glass surface's properties as the resistance to stresses is raised. This increase used to be two times the strength of the annealed glass for heat strengthening and four to five times more for toughening, because the glass cools rapidly, whilst when it breaks it crumbles in dices.
- **Chemically treated:** It is applied when extra strengthening is necessary. Chemically strengthening is a result of the post-production chemically process, where the sheet of glass is placed in a salt bath at a temperature of 300°C. The process happens by giving sodium ions and receiving potassium ions as an exchange method that leads to the growth of glass strength. Typically, it reaches six to eight times the float glass levels, while it is not deemed as safety glass from the moment that it shatters in a similar way as float

glass. This process is applied when thermally toughened processes are not available, such as gravity bent glass with unconventional formats and to the common trademark of Gorilla glass.

- **Insulated glass units:** The insulated glass is made usually by double or triple glazed panels separated by a spacer to create a hermetically sealed gap. The glass option relies on the structural requirements which can be either annealed glass or safety glass, related to tempered, heat, or chemically strengthened and laminated. A design with exceptional performance, a thermal insulator, and a format with great solar control to achieve the optimum energy efficiency in order to reduce building energy.

TABLE 01.13 | Glass processing effects on glass recyclability ^a, based on (ARUP).

Glass Process	Acceptability for Recycling in Float Line	Notes / Comments
Annealed Glass	Yes	Readily recyclable
Tinted Glass	Yes	Readily recyclable
Coating (Hard or Soft)	Yes	No effect on recyclability
Lacquered Glass	Yes	No effect on recyclability
Cutting and Edge Processing	Yes	No effect on recyclability
Drilling	Yes	No effect on recyclability
Laminating	Limited	Current methodology for delaminating decreases quality. Requires improved delamination processes to ensure stays in closed cycle level. Current acceptance refers more the laminated glass to be used to produce container glass or mineral wool
Ceramic Printing and Fritting	No	Current methodology does not allow the removal of the ceramic printed layer on the glass and further the acceptance of the cullet for recycling.
Heat Strengthen	Yes	No effect on recyclability
Toughened (or Tempered)	Yes	No effect on recyclability
Chemically Strengthened	Yes	No effect on recyclability
Heat Soak tested	Yes	No effect on recyclability
Insulated Glass Unit	Yes	Requires proper removal of the metallic spacer bars and edge seals, presenting limitations on processing of individual glass panes.
Glass Ceramics	No	No acceptable by the industry, because of other different composition of glass.
Mesh Glass	No	No acceptable by the industry because of the presence of the wired metal mesh interlayer which is laminated in between the sheets of glass.
Low Iron Glass	Yes	Specifying low iron glass may require float manufacturers to reduce the recycled glass content to ensure a clear product is achieved. Further discussion with glass supplier on a project basis is required.

^a The current table indicates only if any of the glass processes enables the recycling of the cullet without affecting the standard characteristics of glass. It does not negotiate the acceptance rate by the float glass industry or the introduced challenges on their recyclability.

Different treatments that float glass is subjected to may affect contamination. These implications provide some challenges in the recycling process, bothering the upcycling for this glass type. One of the most challenging barriers at the moment is the laminated glass. The glasses and interlayers have to be separated, in order for the extrinsic material from the glass to be removed. This separation process can be made into different methods. The first one is by a machine that crumbles small particles of the glass and separates them. A procedure not acceptable to the float glass industry, due to the probable external materials existence, but it may be worthy for the packaging industry. The second method is not that common and widespread. Due to it, a system, developed by the Australian company “Delam”, delaminates glass sandwiches with the aim of heat, time, and steam on panels sizes up to 1.8 by 3.5 meters, regardless if they are flat or curved products (Delaminating Resources, 2013).

An extra obstacle in the recycling of float glass is related to its thickness (Vlaskglas Nederlands). Laminated glass until 30mm can be transformed into cullet with the present machine's infrastructure, since larger thicknesses can lead to harm to the metal blade, which is used on the glass smashing system, and metal fragments can pollute the cullet.

Glass coatings could be referred to as contamination. Instead of that, they are not damaged and they proceed to recycle. Along with the remelting phase of glass, the high temperature of the furnace is enough to burn and destroy them (DeBrincat & Babic, 2018). Respectively, any heat-treating of glass is not detrimental to the ability of glass products to get into the recycling loop according to a study that was held by TU Delft on the chemically treated Gorilla glass (Bristogianni et al., 2018).

The printing glass with enamel frits is not allowed in the recycling loop. This is happening due to the presence of ceramic elements that are fused into the glass composition since they are compatible with the rest of the recipe of glass to be melted. On the other hand, the main problem of IGU is disassembly. Its compact design leads to extra complications while it is dismantled and favors contamination on the glass, especially by metal pieces from the spacers. Consequently, the procedure of purifying, cleaning, and shortening the glass is quite expensive, sometimes more than purchasing a new unit.

Finally, the most common obstacle in flat glass recycling is color contamination. Every float line possesses its characteristic color tint for each of its products. To generate various glass products, there are different demands to meet the perfect color consistency, varying according to the desired output standards by the manufacturer, within and between the lines that run. Consequently, such production does not easily accept external cullet, since it risks altering the hue of its glass, displaying. Another reason for the rejection of such cullet is that the float line has to invest in the optical quality of its products.

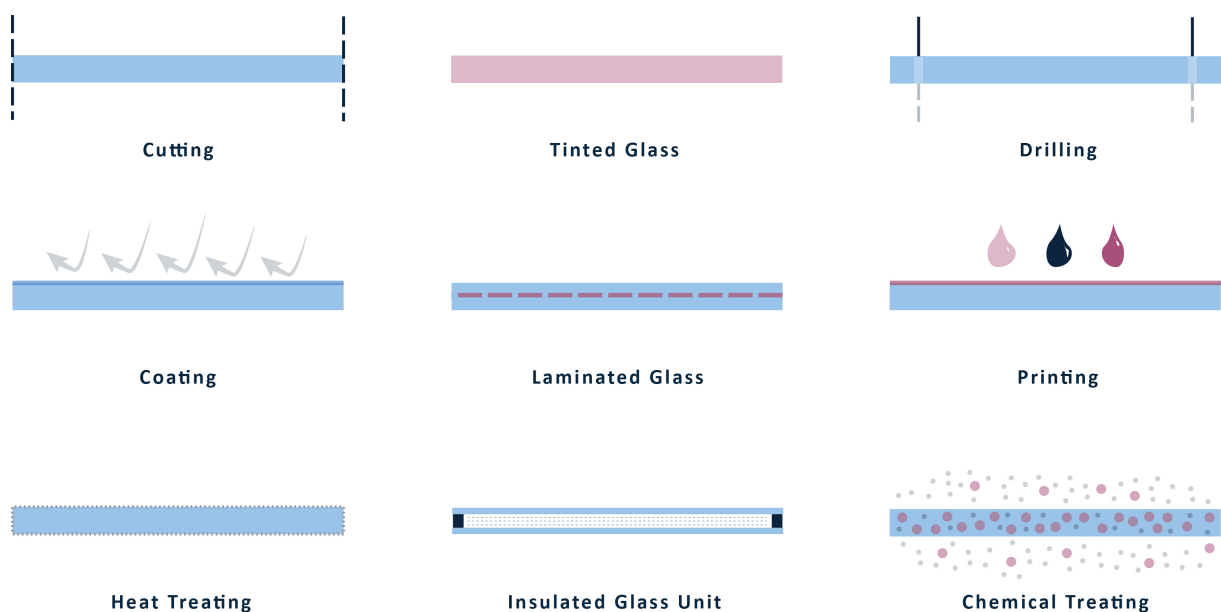


FIGURE 01.32 | Float Glass treatment techniques.

03.5 CULLET CLASSIFICATION

Glass could be considered unique, due to its recyclability. However, not all diverse glass systems, which are removed from the built environment, meet the standards to be welcomed back to the melting furnaces of the float industry. Once coating, lamination, printing, and other processing methods have been a part of the glass cullet, the recycling process is not anymore so straightforward. Only the cullet that meets the value levels of the European directive 2008/98/EC is able to proceed in the recycling and not to be assumed as waste (Saint-Gobain). According to this guideline, glass manufacturers have found three main qualities of categorization of glass fragments, corresponding to the degree of contamination (ARUP).

CLASS A: It contains a completely pure cullet, with zero contamination, due to the high-quality demands of the float line. This type is ready to be transferred immediately to the industry into the melting furnace without any purification processing. This type can be met specifically on the pre-consumer internal glass cullet, but there are ambitions for post-consumer cullet from the current C&D stock to be part of this grade.

CLASS B: It is alternatively referred to as mixed cullet that there is a chance to carry some pollutants. For instance parts of coated glass or laminated glass that are really challenging the interlayer to be entirely extorted through the specific delamination process. The current typology usually becomes part of other glass recipes, such as in glass packaging or glass fibers.

CLASS C: It includes cullets, which are contaminated with materials and substances completely undesirable in the glass recycling loop since they are not proper for remelting. Usually, in the glass mix, there may exist parts of ceramic fritted glass, glass with different compositions, and metallic articles such as IGU spacer bars. The most common use of such grades is to be exploited as aggregate.

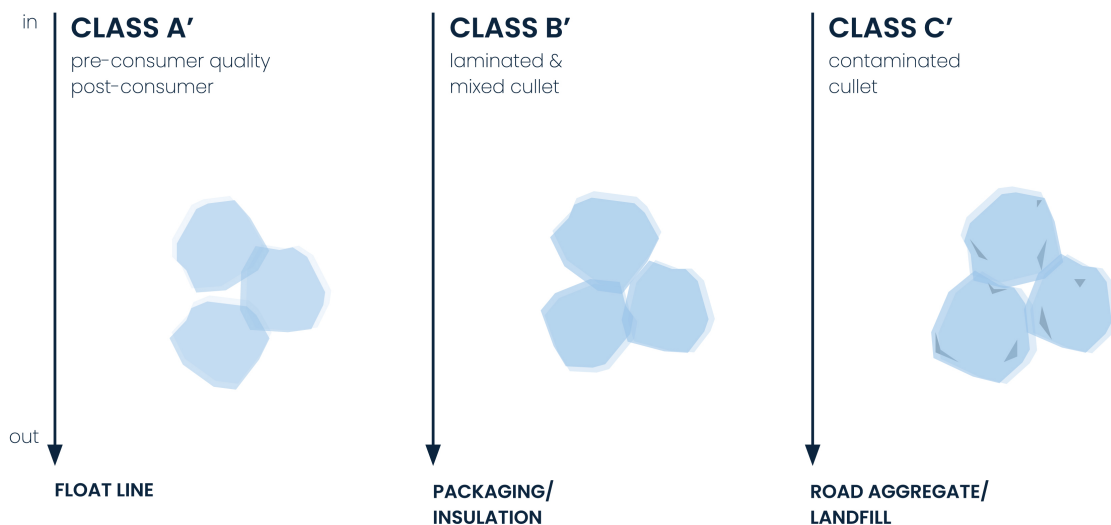


FIGURE 01.33 | Glass cullet grade classification according to contamination rate. (ARUP)

Main challenge of these grades is to be reintegrated into the recycling loop with the aim of a closed economy concept. Consequently, a way must be introduced to either develop a technology that sorts and purifies the cullets making them available for recycling and reuse in the float line or a new strategy to be found as the cullet to be reoriented into the built environment as a high-quality material or product. Both of these options will increase the utilization of the recycled cullet from the glass industry.

03.6 C&D GLASS WASTE TREATMENT

In C&D glass recycling, the biggest technical barrier is contamination. If a strategy is found, the availability of high-quality cullet will be raised, therefore the glass goes back into the melting procedure of the automated float industry. Certainly, not all the quantity of architectural glass cullet will be directly moved into the furnace. The increasingly high standards of glass quality by the companies make the proportion to be exploited really limited. Thus, getting the cullet into the float line totally demands a lot of processing.

Considering the struggle of guaranteeing the glass fragments' origin and value, it totally needs a well-oiled recycling series of actions. At the moment, there are not many systems that let the gathering, sorting, and cleaning of glass cullet successfully. Numbers indicate that in Europe only one quarter, of the whole raw material used for glassmaking, is recycled cullet. Studies show that 37% of cullets could be exploited if there were not obstacles related to financial, technical, and infrastructural aspects (Glass for Europe, 2020).

As it is previously mentioned, glass is a material 100% ready to be recycled, without any quality degradation. This expresses the fact that in theory float glass waste is suitable to be exploited as valuable source matter

either in float line or glass packaging and other technical glass objects, as the ideal example of the circular economy model.

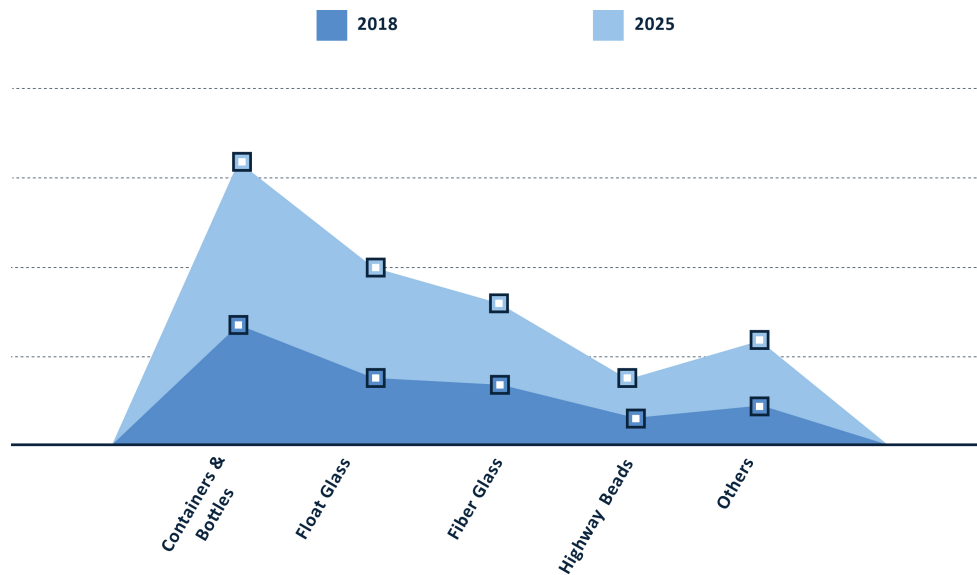


FIGURE 01.34 | Global recycling glass market growth predictions per sector (Ayushi et al., 2019).

However, this is not a simple case and in order for any type of glass to be used in the production, the batch has to undergo several elaboration phases to remove as much as possible the contamination. When the end-of-life is reached, glass waste is collected into temporary containers in construction and demolition places and at drop-off points. Clearly, it is crucial how the glass is collected. The glass waste should be clean, an indication that is needed to recycle, if it is not reverently gathered as separate flow from other waste it is really probable to be contaminated and then has to be disposed of as common waste without any treatment. This is a consequence of the high rate of foreign matter in the batch.



FIGURE 01.35 | Double glazed units removed from tertiary buildings awaiting recycling process. (DeBrincat et al., 2018)



FIGURE 01.36 | Mixed float glass on the recycling process. (Maltha Groep BV, & Vlakglas Recycling Nederland, 2017)

Just after the collection phase, the waste sheet glass is then transported by trucks to qualified glass recycling plants. Then, a first primary inspection process is carried out by trained staff members in order to check the level of contamination in the volume of the glass waste. According to Vlakglas Recycling company, the discarded and collected thin-walled architectural glass is referred to by 90% as post-consumer use, and practically on all occasions, the glass cullet is contaminated with extra incorporated elements on its surface. Consequently, to proceed with the recycling of any glass waste faultlessly, the entrant flow is necessary to meet a series of acceptance terms, as guidelines, where the permitted kind and the degree of impurities in the glass waste are specified. In different cases, determined by the grade of pollution, every waste stream is categorized differently, for example as C&D waste or bulk one, and dismissed as adequate (Maltha). That stage is known as sorting. This can also comprise segregating certain glass species together with detaching the most apparent contamination,

for instance, stones and plastics. A first separation of color is possible as well, which is originated by numerous added ingredients that the mix of them should be avoided, especially on the occasion of float glass production.

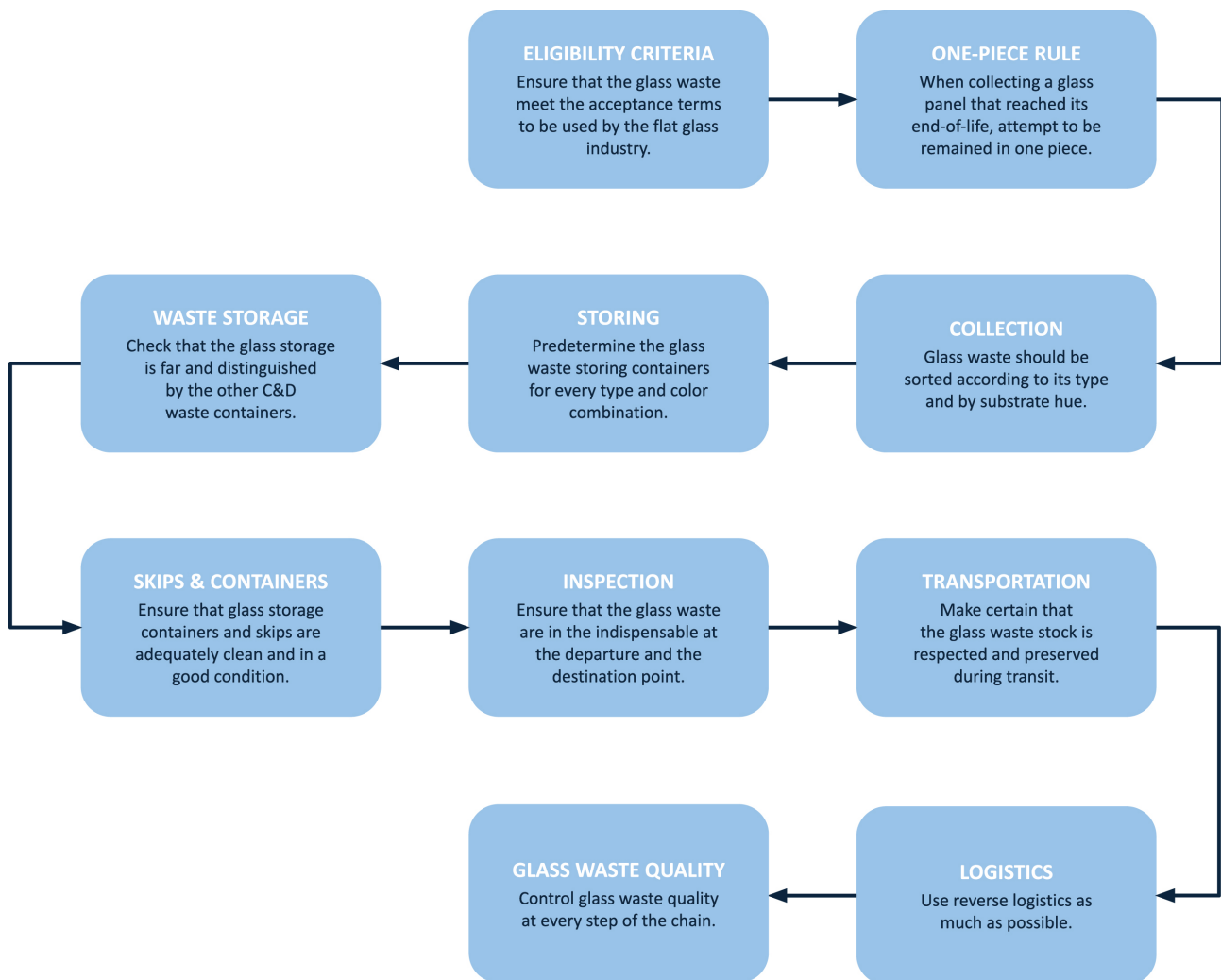


FIGURE 01.37 | Major rules to achieving perfect glass waste collection, based on (Saint-Gobain)

The following step is the breaking stage, where the sorted glass is then crushed into smaller sizes. A smashing system of hammers or metal blades spins around an axis, which generates the small fragments and automatically pulverizes the glass waste. In order to avoid these particles getting airborne, some water is added or misted to prevent this to happen. At that time, magnetic separators remove any metallic element included in the batch, and then the broken glass goes through trommel screens where the cullet is divided accordingly. Simultaneously, a fan pushes out remnants of plastic or textiles. When these major processes are carried out, an optical sorting inspects the cleaning and sorting result until now and if the matter of glass is sufficiently clean (JRC, 2011).

Differently, the three last steps of crushing, sorting, and sieving are gone over and over, as a test-and-repeat loop, till getting as far as reaching the indispensable result. The final inspection sorts and classifies the glass pieces in accordance with their size, since different final uses of the recycled glass require different dimensions, with the purpose that each grade will be guided and distributed to particular industries (RTS, 2021). Finally, a mechanical and manual check ensures that certain qualifying conditions are fulfilled in order to have the cullet, as the outcome of the float glass waste that is ready to be remelted.

To sum up, the quality and value of glass waste is hence on the whole designated by its level of purity. Complete and well-organized collection process and appropriate waste partition in agreement with the acceptance conditions are therefore definitely worthwhile to lead towards a closed-loop concept of the flat glass industry.

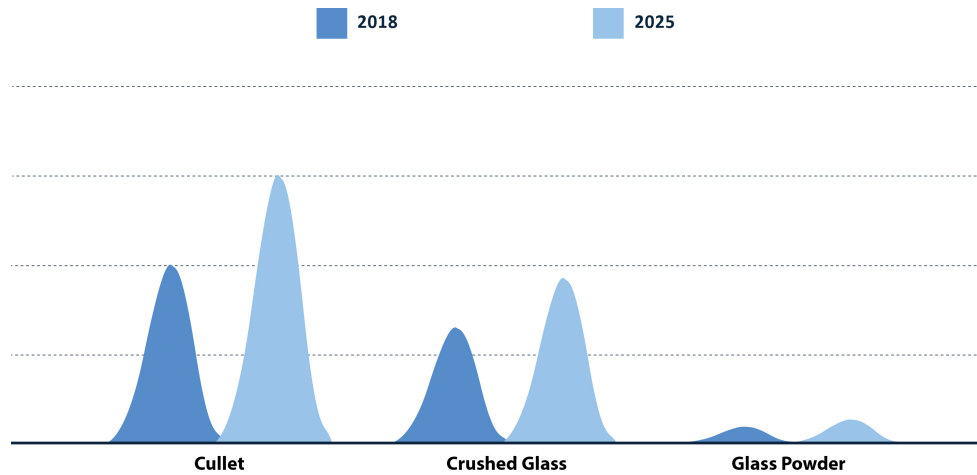


FIGURE 01.38 | Global recycling glass market growth predictions per recycling outcome (Ayushi et al., 2019).

03.7 SERVICE LIFE & END-OF-LIFE OF GLASS UNITS

Service life of glass units in any application in the man-made environment is related to the lifetime of both the glass pane and the supportive frame.

Generally, the estimated lifespan of insulated glass units can reach 25 years (DeBrincat & Babic, 2018). This limit is placed because of the obvious demotion of the materials that the unit consists of, such as the polymer edge seals. Due to the pure condition of any material, the IGU's performance plunges, so the replacement is inevitable, even if the other materials themselves, such as glass panes, have not reached the end-of-life. On the other hand, the frame's material varies, consequently their service-life, which usually stands up to 60 years (DeBrincat & Babic, 2018). For instance, wooden frame components can be serviceable for approximately a period of up to 20 years with regular upkeep, but some professionals estimate it to live more than 40 years. Aluminum-framed members are incredibly strong and durable, and with attentive maintenance, they are able to last almost half a century, while PVC frame elements' life cycle is considerably lower, ranging between 15 and 20 years.

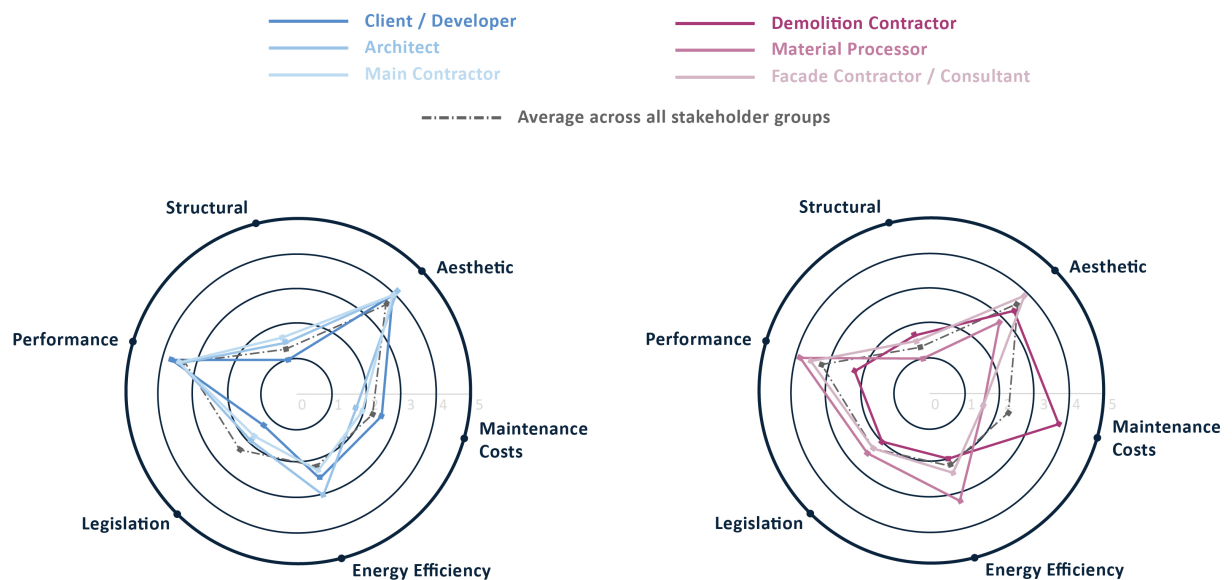


FIGURE 01.39 | Weighted ranking of typical reasons for facade replacement (Hartwell et al., 2019)

Over time, the need for more glazing unit replacements in the building sector raises. This is happening on account of buildings demolition, or facades renovation for aesthetic or performance occasions, regardless of the technical service life of the glass pane or frame.

When the glass panes reach their end-of-life, they are classified into six major waste stages in accordance with the life cycle when it is manufactured.

- **Manufacture:** It brings waste during production, for instance, offcuts or quality rejections.
- **Glass processing:** It generates waste through the processing and treating of sheet glass, such as cutting and drilling.
- **Transportation:** Due to unexpected damage or breakage.
- **Construction:** Referring to the waste generated during the placement of the glass products.
- **Demolition:** When the functional or technical lifespan of the whole building arrives.
- **Renovation:** When the functional or technical life cycle of only the glass products is reached.

(Geboes, 2020)

04.8 CONCLUSION

The growth of the C&D glass recycling industry requires a new network to be developed, associated with circularity. Today, we are far away from a well-organized system, such as the packaging recycling loop, where almost all the glass cullet is turned into valuable and reusable material. This is mainly related to firstly the challenges of architectural glass separation from extrinsic materials and substances and secondly the lack of sufficient machinery to decontaminate the glass sheets coming from the building envelope. These block the use of glass cullets, owing to the high-quality requirements of the industry.

The float glass industry has classified the glass cullet into three grades according to its purity. Class A' is already used by the industry back in the float line. However, the challenge is to put back into the recycling loop the remaining two grades. The current research will investigate the feasibility of upcycling these cullet qualities, by creating testifications on recycling glass panels, made by C&D glass, with the aim of casting method. This method is more flexible than the float line, while the practicability to cast components with higher thickness than the traditional thin-walled glass, gives the opportunity to the product to tolerate any contamination that purity grade of class B' and C' may carry.

The testification is going to start with the exploration of a composite glass by both grades. This sandwich glass will have in the middle the cullet class C which is referred to as the lowest quality, whilst cullet class B will be placed on the surfaces, creating advantage tensile strength, which is transferred on the surfaces. Simultaneously, a glass panel will be created by cullet class B to check also its feasibility. Both of these will be tested at different temperatures, for their fluidity, homogeneity and compatibility to be elaborated for the optimal result in the different compositions and the proper strength of the product. Moreover, experimentation could be made on the products performance.

04 | LITERATURE REVIEW CONCLUSIONS

Hardly any other material, that is exploited not only in every short of daily life but also in scientific and technological aspects, could sufficiently meet the current usage and broad innovative boost of glass. An existence, so unique and versatile, since glass is a material that has always fascinated everyone and has been used in numerous applications. However, the precise composition of glass may diversify to meet particular requirements, according to where it is applied. These dissimilar recipes attach different features to glass objects, and divided them into various glass families, depending on the desired result. In consequence, distinct glass production techniques are also developed, with the most common methods being glass floating and casting, since individual combinations may leak out in different traits of the glass output.

Given the continuous growth of the world's population and its demands have also spread the need for glass material production, which continues to ascend. The intense industrial manufacture of glass derives a high volume of embodied energy and generates a significant amount of glass waste. Two factors that cause a detrimental impact on the ecosystem, unveil the disconnection between human activity and the natural environment. More than ever, it is deemed necessary to move towards a more sustainable way of life.

Even if the glass is a material readily recyclable in theory, and the recycling of it has been conducted since its discovery, a small proportion of glass waste is recycled at the moment. Using recycled glass to make new products present many benefits since saves remarkable energy, and mitigates CO₂ emissions and natural resources exploitation, contributing to the participation in a circular economy.

The aforementioned observations from the literature review operate as a rulebook for the selection of the focus in the current thesis. Comprehending all of the probable parameters, a further explanation of the coming decision-making is explained. These rely on the final project objectives and experimental findings for the fabrication of a recycled cast glass panel, made from construction and demolition waste, to be achieved.

The Center of attention of this graduation studio is the distinct group of **architectural float glass, coming mainly from the C&D sector**. A great proportion of glass waste among post-consumer glass packaging and other special and unsolved glass waste remains unexploited. Generally, the continuously increasing trend in the architectural and engineering field towards wider applications of glass surfaces and demand for transparency in the building envelopes has spread the need for float glass production and the replacement of the older ones, which implies the causing of considerable thin-walled glass waste mainly discarded at their end-of-life or down-recycled, pointing out the large potential in upgrading the glass recycling process. This depends on firstly the degree of purity achieved in the processing of cullets from waste glass recycling, related to foreign material attached to them or the compositional variations since not all qualities are accepted back in the recycling loop, secondly the barriers on the rigid flow stream of the automated float line, which operates under default recipe to fulfill all the requirements of the final result on the float glass, and lastly the lack of a properly organized system of flat waste collection.

As it is mentioned, glass material with the ability to be endlessly recycled has the ideal prospect to lead in the transition efforts to a low-carbon and resource-conscious environment. Although this notion has long been utilized in the glass packaging industry, as a successful closed-loop, the case is not the same for the float glass industry which occupies a more complicated place. This large quantity of non-recycling glass category, remaining unexploited after its end-of-life, indicates that there is a large potential for upgrading the glass recycling process. The differences between these two industries are numerous. As container glass recycling is concerned, whether the cullet is applied, as a reusable product, or as a recyclable matter, the collection and recycling system for container glass possesses high recycling trends. The aforementioned issues are from the fact that glass packages are constituting just from glass. Even though glass packaging from different suppliers follows more or less the same recipe with small discrepancies, the industry is aware of what to predict. On the other hand, cullet coming from thin-walled glass reaches recycling facilities in a wide form variation, considering its application and the various processes that glass undergoes, regardless of the glass forming method. These complicate and grow the challenges all the more for the sorting and cleaning procedure of glass waste and drop the probability of the cullet being accepted back to the glassmaking, while extra costs for the yield of pure cullet are added.

All the aforementioned facts complicate and grow the challenges all the more for the sorting and cleaning procedure of such glass waste compared to glass containers, and moreover, their introduction back to the float line, dropping the probability of cullet to be recycled. Small efforts have been made for the recycling of such glass waste, but ambitious. Thus, this thesis project selects the challenging and unexplored float glass recycling,

mainly used for architectural purposes, coming from the construction and demolition sector, since additionally there is not any research specifically directed to this glass waste type.

As it is obvious, the use of recycled cullet with diverse compositions or contamination could lead to crucial risks in the total production line of flat glass. These could jeopardize not only the quality of the final glass production, but also it risks the whole industrial process and facilities and it may lead to unwanted atmospheric emissions.

To overcome most of the aforementioned probabilities, the **cast glass method** will be explored for the manufacture of the glazed component. An interesting method that enables the fabrication of monolithic glass components with higher thickness than conventional flat glass. Owing to this monolithic nature, panels out of cast glass are allowed to carry more contamination and flaws than a sheet of thin-walled glass, barren of jeopardizing the strength or optical quality. Further, glass casting is a non-automated small-scale technique, which affords opportunities for experimentation in the firing schedule and glass formulas (Oikonomopoulou, 2019). This technology could be a favorable solution and promising strategy for transcending the main barriers of C&D cullet refusal, owing to either impurities or different glass synthesis. Recovering discarded glass in cast glass products opens new paths to reintroduce such waste back to the supply chain, as a closed-loop approach.

The float glass industry has classified the glass cullet into three grades according to its purity. Even if, the class A' grade is already utilized by the industry back in the float line in small proportions, the major challenge is considered to reintroduce into the recycling loop the remaining two grades. In this thesis, the **selected purity grades of the cullet are class B' and C'**, of defined composition and contamination rate cullet mainly coming from the external stage of pre-consumer glass, and the mixed one of undefined origin coming from post-consumer use, respectively. Grasping the challenge to use this discarded or downcycled valuable cullet.

The following firing experimentation is divided into different firing stages, intending to discover if recycling flat glass is in fact feasible in practice. A variety of materials, purity grades, combinations, and compositions will be tested to introduce a thick-walled glass panel, which allows tolerating a higher degree of contaminants unaccompanied from any critical compromise to the object's properties. To recycle float glass waste, knowledge should be gained on the fluidity and mixability, since not all of the sheet glass products have exactly the same chemical composition, due to fluctuations in the recipe and have undergone post-processing, and on top of that the contamination that is carried. As a consequence, this could jeopardize the potentiality of successful glass melting and the generation of a homogenous thick-walled glass end-product.

Throughout the experimental research, a **strategic approach to the fabrication of a composite panel** of the selected purity grades of glass will be attempted for the generation of the translucent result. This composite-sandwich glass will have in the middle the cullet class C which is referred to as low-quality since contaminants' rate is not possible to be counted, whilst cullet class B will be placed on the surfaces where the contamination rate is defined, creating an advantage tensile strength, which is transferred on the surfaces. This firing setup will test the compatibility between the different cullet qualities to be elaborated for the optimal result in the different compositions and the proper strength of the product.

Grasping the boundaries of glass recycling, which has been continuously stretching, only some primary attempts have been made from previous experimental work in the recent years by the architects, and engineers of TU Delft, unveiling the ambitious potential of glass upcycling for the building sector. These studies concentrate either on the mechanical properties of recycled glass samples, the fabrication of 3-dimensional strong glass components or glass panels emphasizing the aesthetic result always with the method of recycled glass casting. Nevertheless, a consistent analysis on C&D waste has not been done so far!

Identifying the existing research gaps, the focus of this thesis is the proper mapping of the current situation of glass recycling, and the identification of the most promising glass C&D waste through experimental research by contacting melting test to understand the most promising streams as it is already explained above and tools that have not been utilized before. The experimental analysis of the new concept concentrates on the development of the composite panel and the thermal shock testing in uneven temperatures, as the strength of recycled glass has already been investigated previously in order to evaluate how such glass behaves. Additionally, the whole embodied energy of this new concept will be assessed for further analysis and understanding of the whole effectiveness of the proposed supply chain of this novel recycling method, which is carried out for the first time.

For the time being, it is obvious that a linear flat glass waste chain incurs, so the need to switch towards a circular life-cycle of such waste is rising. The growing interest, in this transition to closed-loop recycling, can be also seen and encouraged by float glass industries and different actors in the whole construction sector. These

new building components can be introduced by means of closed-loop alternatives that extend the service life of these products, establishing at the same time the foundation for a circular life-cycle of architectural glass. However, to comprehend totally how this upcycling method could be performed, first and foremost it is crucial to identify all the recycling obstacles that rest on the conventional life-cycle of C&D glass and must be overcome, creating a **C&D glass recycling mapping**.

Thus, to evaluate the glass panel's performance under utmost temperature fluctuations, a **thermal shock test** will be held for the first time in such a glass waste target. The thermal failure of a glass element, either hot-cold or cold-hot, responds as an outcome to uneven temperature alterations across different zones of the object since, under the effect of solar radiation, favorable conditions are created for the generation of tensile stresses causing failure to glass, such as cracking or breakage, under certain exceptional values. In the contents of my experimental research that refers to a product introduced for the building envelope and could be exposed in weather conditions, the application of thermal loads is deemed as a requisite verification of the recycled panel to imitate any failure caused by a thermal shock in practice.

Finally, **LCA analysis** will be performed about the embodied energy that the recycled panel possesses, identifying as well the gaps in the existing data and pinpointing the steps where most energy savings can be achieved. Thus, an idealized life-cycle will be taken into account exploring the potentialities and environmental impact as an upcycling approach within theoretical and practical strategies.

02 | TOWARDS A CIRCULAR LIFE-CYCLE

01 | CURRENT LINEAR APPROACH

01.1 LINEAR ECONOMY MODEL

What will it need to be transferred from a throwaway model into one that regenerates nature and prevents natural resources? The circular economy model is rapidly becoming a guiding force in every aspect of life, business, and government level as well. In order to understand why it is so important and necessary, it is needful to comprehend the fundamental differences between a linear and circular economy.

Unfortunately, today we serve and act on an economic system with a “take, use, dispose” mentality and as a result, the majority of these used products are mainly disposed of and end up in the landfill. This kind of economy, which is widespread across the world, removes and exploits raw materials from the Earth, using them to create new products to be sold and used only once until they have reached the end of their useful life. This is the so-called linear economy:

“A model that natural resources are turned into products, which ultimately destined to become waste, because of the way they have been designed and manufactured.”

But what is the biggest issue the current linear economy faces? Of course, waste, related either to material or energy one, results in much consumption. To explain it simply, this system and its predisposition towards unstoppable wasting of valuable materials is a notable problem in question on a planet with confined resources. It does not consider the notion of environmental preservation; risking draining all of the planet's pores and simultaneously contaminating it irreversibly. In Europe, the most recent report, which was held in 2018 by Eurostat showed total waste, was approximately 2 million megatons produced by every economic activity and household, whilst 38,5% of the whole amount of all municipal waste generated was disposed into the landfill (Eurostat, 2021). Nevertheless, the refused materials reflect a multidimensional impact on the environment. This impact is first and foremost related to further negative results since methane emissions are produced from organic waste putrefying the soil and the atmosphere (Nordal et al, 2020). On top of that, the continuous disposal of waste creates extra demands for raw pores to be extracted from the finite resources stock and additional energy so that fresh stuff be manufactured. Unfortunately, the most disappointing part is that it emboldens a culture of reckless consumption, ignoring the acquired value of the materials and products that reached the end-of-life, driving on environmental degradation.

All the former facts compose the increasing acknowledgment of an urgent occasion to shield and protect the planet's finite resources and reduce emissions. These reasons led the way to a global movement towards a circular economy, an essential gesture for the environment. Circularity is evident throughout nature, maintaining balanced ecosystems, suitable not only for human life but also for every kind of lifeform. Our planet operates in a fully circular manner, only since the rise of intricate living civilizations and systems has this equilibrium been unsettled. As opposed to that, the closed-loop model aims to mimic Earth's natural cycles by applying corresponding propositions, where waste materials, products, and energy become input for other processes through waste valorization.

Circularity serves the belief that it is possible to reach high levels of sustainability without diminishing the profitability of the business or decreasing the number of available materials, products, and services. In essence, it aims for higher pores exploitation, and circular resource flows, by recovering to the fullest extent and limiting waste generation and pollution through substantial design. Besides that, it seeks to indemnify the impact right at the beginning of the making procedure of the consumption products or materials, instead of behindhand when the end may be unavoidable. Literally, it provides a systematic switch that alters the whole economic thinking and attempts to mitigate the damage.

01.2 PROCESS MAPPING & LIMITATIONS

Sufficiently, an in-depth study is appropriate to comprehend the current barriers to C&D glass recycling in order to create a closed-loop procedure. These barriers are linked to each phase that constructs the linear economy of float glass production.

Natural deposit is commonly classified into renewable and nonrenewable resources. Raw material, which is an essential part of glass recipe, falls into the second category of unreplenishable pores. The reckless use can lead to the source depletion of silica sand. Every year, approximately 40 billion tons of sand and gravel are extracted from the Earth's crust (Saint-Gobain). A demand that surged 20 folds in the last centuries, due to the increased requirements mainly in the construction field. Apart from that, soil exportation has detrimental results on biodiversity. This process modifies and disturbs the soil's particular ecosystem due to the use of heavy machinery, noise generation, and stirring of its structure. Of course, these activities require high-energy utilization, with extended carbon dioxide emission for the equipment's function and raw material transportation to the industry.

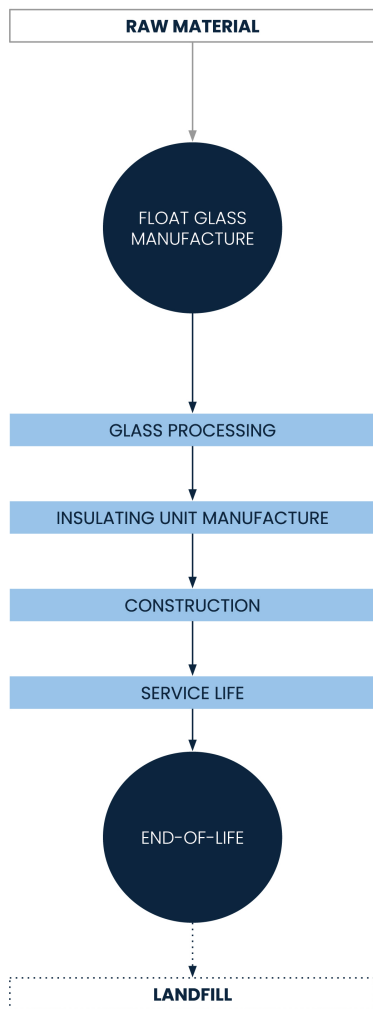


FIGURE 02.1 |
Current open-loop glass recycling.

Next is the float glass manufactured by the fully automated industry, which was patented by Sir Alastair Pilkington in 1959 and continues to exist the same. An energy-intensive process, which operates 24 hours a day and 365 days per year, is unstoppable for 10 to 15 years, on the melting temperature of a batch at 1550°C, completely made up from raw material. This continued operation of the furnace to be heated both by electricity or gas combustion generated immense quantities of CO₂. The presence of cullet could aid in the dropping of the temperature. Subsequently, the quantities of gas emissions decrease, since the cullet is already decarbonated and it does not demand the same level of energy. However, the reintroduction of recycling glass back into the loop, as it is already mentioned, is not that flexible due to the strict standards of contamination existence, which is able to compromise the strength and visual result of flat glass manufacture. Each float line operates under its own recipe; to prevent any contamination typically does not accept external cullets even if it is completely purified, as it can affect for instance color contamination, and result in a different hue at the end product. A change in the batch owing to pollutants would result in the discard and loss of up to 7 days of production for successfully altering the material composition in the continuous ribbon (Oikonomopoulou, 2019).

When the float glass is formed, it passes in the phase of secondary processing and treating. This phase includes a wide range of possible procedures, which actually create limitations and obstacles to the recyclability of the product. These procedures and barriers with their extended explanation can be found in the first chapter in paragraph 04.4, while they can be held either by the production industry or by the glazing unit manufacturer, according to the client's needs and requirements. Additionally, to the possible secondary processes, the assembly of IGU consists of a mixture of materials and components fixed together, as a monstrous hybrid, which is not economically feasible to salvage the raw material easily and completely after the end-of-life.

A major part that creates the technical barriers to materials and product reuse is the design approach that lacks compatibility and disassembly provision. This makes it really challenging when the product's end-of-life arrives, related to the removal, deconstruction, handling, transportation, and storage difficulties of the cullet. Additionally, the low market value and the absence of an organized and developed system to collect and recycle architectural flat glass makes it even more challenging.

Finally, the current regulatory framework does not provide incentives for the recycling of C&D glass. The latest update for specific legislation and measurements for glass recycling exists since the EU Landfill Directive of 1999 (Glass for Europe). Glass is a cheap material to be landfilled, rather than to be recycled, so there is not a favor for the emergency of C&D glass recycling. The need to revise the EU policy instruments deemed necessary, in order to promote the collection and recycling of building glass under encouraging conditions.

Even though it is eager to support and organize the development of end-of-life architectural glass, sorting, and recycling, there are several additional reasons that it does not happen (Hartwell et al., 2019). This is related to the lack of compatibility between recycled material and the new one, whilst adequate supply usually is missing. All the aforementioned reinforce the fear of the industry for failure or the recycling process.

02 | CIRCULAR MODEL

02.1 PROPOSALS FOR A CLOSED-LOOP PROCESS

The increased attention paid to the built environment's efficiency, and the prevention and sustainable use of natural resources have raised awareness of the potential of the construction and demolition sector. This could create a significant key strategy, addressing the challenges of energy, climate change, and resource efficiency. Flat glass constitutes an important material in a man-made environment and can help if end-of-life management is improved. For this reason, the float glass industry is willing and keen to increase the quantity of recycled glass in its production processes.

Sustainability begins with development, and for the C&D glass cullet, there is a need for a more resource-efficient and circular industry economy, through a closed-loop recycling procedure. Such efforts commence with a top-to-bottom study of float glass products' life-cycle, in order to acknowledge the vulnerable points for improvement. Consequently, this upgrade must be tackled through the different schemes of glass cullet life.

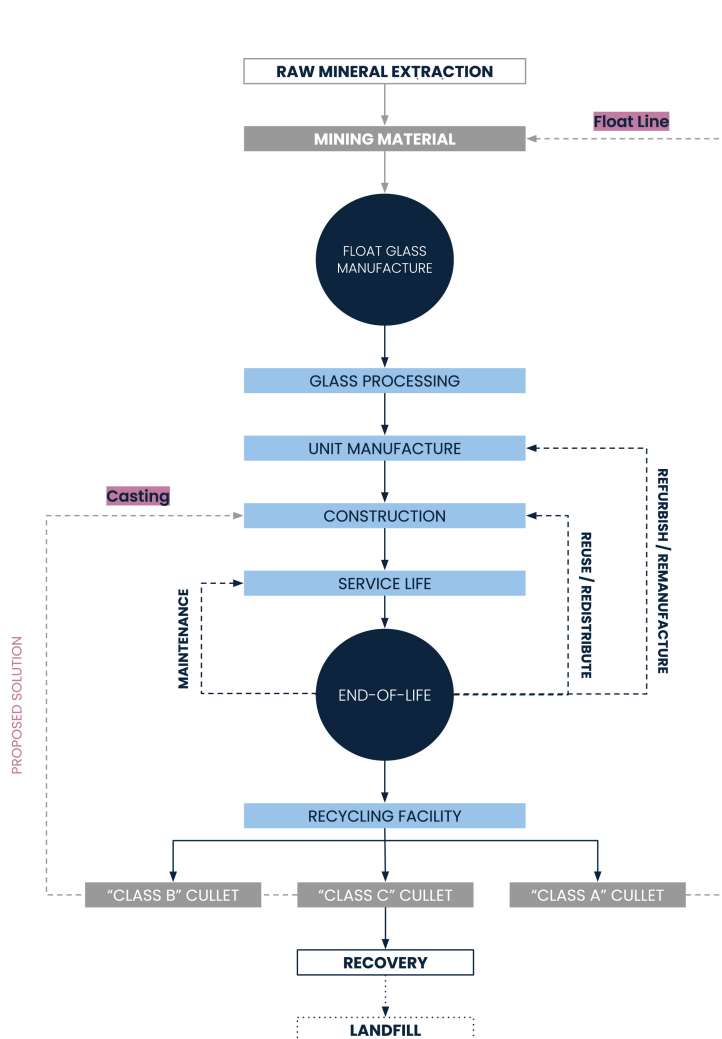


FIGURE 02.2 |

Proposed open-loop glass recycling.

Awareness

First and foremost, a crucial role plays the awareness and education of the consumers, in order to desire, buy and consume in a "green" way. As this to happen, relevant legislation must be established, whilst building standards and contract awards, such as BREEAM certification, should be updated to give greater emphasis on the reuse and recycling of existing C&D glass stock. The estimation of embodied energy of the new recycling products through the life cycle assessment could be tangible proof compared to the existing situation of float glass production. All this must happen within the framework of a common language in the whole world of the float glass industry since right now the low-making significantly differs between them.

Motivation

Motivation about C&D glass recycling could play an important role in the purpose of a closed-loop creation. As it was previously mentioned, consumers should desire "green", so they need to have accessibility to "green" companies. The latter will stand in need of adequate financial support to operate sustainably. Initial financing would trigger their circular action, as to set up the infrastructure and management schemes. Moreover, the deployment of new technologies and infrastructure should be supported by existing initiatives at the EU or worldwide level, both on the processing and product sides. Eventually, the collection and

recycling of end-of-life glazing should represent a valuable business opportunity to be developed across the flat glass industry.

Design & Manufacture

Design and specifications for glazing facade units must follow guidance adopting circular economy principles, in order to maximize the potential of reuse and recycling of these products. The design phase should be organized according to the compatibility of the glazing goods, as well as to the feasibility of a

proper dismantle method. Accordingly, the design could assist to avoid complicated deconstruction processes without the deleterious contamination of the glass cullet. Apart from that, the new design approach should use only the indispensable materials in the manufacture of the products, as they need to be durable in order to have a longer service and lifespan. Moreover, the maintenance of the glass unit should be considered.

If the problem of C&D glass recycling is tackled from the root, then it will experience several benefits. The recycling glass cullet, which is acceptable from the flat glass industry, will be increased, while the raw material demands will dropdown. Accordingly, the carbon intensity of flat glass manufacturing will fall. Finally, beneficial could be counted the use of other glassmaking techniques such as the casting method, which is more flexible than an automated float glass line and less energy demanding.

Deconstruction & Removal

The contamination of the cullet is the main technical challenge that must be overcome. Usually, the pollution of the cullet is occurred at the construction site owing to the carelessness of the working staff or visitors. Appropriately, the staff, which handles the deconstruction phase and removes the glass panels from the structure, should be fully trained and informed, in order the whole procedure to be held carefully from the building envelope. They will provide the necessary quality control required by checking and overcoming it at the source.

Collection & Separation

Accordingly, the staff that handles the cullet should also have sufficient training. Moreover, on the construction site, the proper number of bins must be present to cover all the diverse types of waste and source variants. These bins must be clearly labeled and distinguished by color, to avoid any misconception, and jeopardize the right collection of C&D cullet.

Storage & Transportation

Generally, the implication that contamination generates on the architectural glass cullet should be sufficiently comprehended. All skips and containers on the collection site must be recently cleaned and inspected in an effort to ensure that any foreign material or substances exist before the cullet is gathered. Additionally, the storage containers' surfaces must be covered to avoid any contamination, while their size should be enough to keep away the cullet from spillage and mixing of glass loads. Drainage on the skips and containers should also be arranged to let rainwater flow out of the storage area.

Logistic networks have to be in place for the diverse phases of the recycling process, in the case of closed-loop recycling. Adaptable supply chains are a key factor for cost optimization and reduction of environmental footprint due to gas emissions. Moreover, related to the contamination probability, nighttime transits are not ideal, in order for any contamination sources to be spotted. Inevitably, the cullet load needs continuous and thorough inspection, whilst the whole process must be overseen step by step.

Categorization

The float glass industry many times does not accept high-quality's glass cullets of unknown origin. It would be really beneficial if the glass source would be kept on track with recordings of the glass origin and characteristics. Products record would allow any possible contamination to be tracked and overpassed.

Processing

The range of glass procedures must be developed and adapted to meet all the recycling standards to avoid contamination (processes such as high-quality drilling and cutting, laminating, adhesives, and printing).

02.2 CONCLUSION

The current research concentrates on the investigation of the linear approach of the automated float glass industry. Simultaneously, the obstacles and limitations generated to move forward with a circular approach to the glass chain are tracked, in the absence of the economical practicability of this transition. These will be the guidelines for developing a supreme life-cycle of thin-walled glass upcycling method, whilst the possibilities and potentials will be explored at its end-of-life, constituting a keystone for further research for future float glass waste management.

The mapping of the promising closed-loop recycling approach is based on pre-existing recycling data, the float glass industry's testification, and investigations on the upcycling methods of glass sheets held by TU Delft's scientists and companies studies. The concept of the complete life-cycle of architectural glass enables the review, comparison, and analysis of the challenging glass waste management that exists at the moment, as well as an exploration of its potential and benefits. These will be the guides to choosing the best approach for the new recycling products of the ideal closed-loop, by taking into account their environmental impact of both theoretical and technical practicality. Then, the outcomes will be set side by side with the business-as-usual numbers, which is the standard circumstance in which the end of service life of sheet glass is either disposed of in a landfill or recovered.

01 | METHODOLOGY

01.1 CASTING PROCESS

In general, two methods of glass casting already exist, differentiated by the essential equipment and the practical steps that are followed during the process. On the one hand, there is the hot-forming technique where the material is firstly placed in a crucible, where it melts inside the oven, and then it is poured into the desired mold, which is preheated in a secondary oven. The working temperature in the main furnace varies from more than 1250°C in the melting phase to 500°C needed for the preheating, prior to the annealing procedure that operates with the aim of ambient temperature (Yu, 2019). On the other hand, kiln-casting demands the operation of a single oven in order to realize the whole melting and annealing phases, which are required for the manufacturing process. The cullet is placed in the proper mold before it is put into the furnace chamber.

The glass casting technique could be a favorable plan for overcoming the principal barriers of C&D cullet upcycling resulting in either glass impurities or different batch compositions. As opposed to the conventional float glass manufacture line, this experimental process is chosen to follow the kiln-casting method for the fabrication of the glass panel, entirely made of recycled cullet coming from the construction and demolition field. An interesting method with an abundance of prospects and novel solutions enables the fabrication of monolithic glass elements with higher thickness than conventional flat glass.

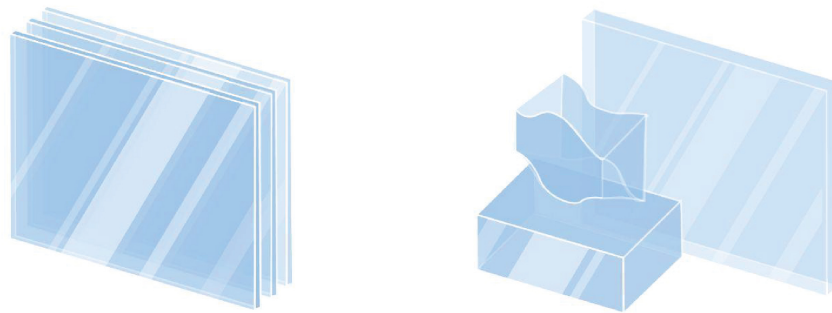


FIGURE 03.1 | Glass outputs of thin-walled glass by the float line (left) and thick-walled and 3-dimensional glass with casting method (right).

Casting is a versatile process, which is progressively utilized and explored for the re- and up-cycling of unacceptable to bring-back-to-the-loop glass. Attributable to the intrinsic flexibility of this glass formation method, and related to the non-automated and small-scale production, glass casting is capable of providing opportunities for experimentation in the firing schedule and glass formulas. A characteristic and tangible object lesson is that even a small shift in the batch of the glass recipe in the uninterrupted and automated float line ensues in the distortion, loss, and discharge of up to a weekly production of thin-walled glass (Oikonomopoulou, 2019). This is happening in order to ensure that the compounds that are used in the continuous ribbon have been effectively managed to alter. In contrast, casting is authorized to endure a simple alteration between various recipes and glass compositions without resulting in any risk in the production scheme. Besides the default batch recipe, the float line operates in a constant melting and annealing schedule. In contrast, casting is eligible to use a variety of glass compositions to be melted in the same furnace and be shaped by the usage of a variety of molds. Furthermore, casting takes advantage to modify the melting and annealing timetable easily, according to the design needs, in the absence of contaminating the kiln.

Owing to the monolithic nature and higher thickness, products (solid or thick-walled glass) made out of the casting method are allowed to tolerate a higher percentage of contamination and number of flaws in their mesostructure, compared to thin-walled glass (Bristogianni et al. 2018b). Moreover, casting products does not present the chance to alter the mechanical or aesthetic characteristics of the output (Oikonomopoulou, 2019). This success in casting objects compared to the float line production is ascribed to the greater volume and the correspondingly limited surface area of the latter, which issue in most of the critical faults (Bristogianni et al., 2020).

All the aforementioned contingents of the successful glass-to-glass approach by casting method have already been proved through the first practical testing and experiments in a wide generation of samples, composed of different types of glass waste. Students and researchers of TU Delft University and its Glass & Transparency Lab

have successfully proceeded in elaborate and extensive research on a broad variety of glass families and mixtures for the manufacture of recycled casting components, as it is already analyzed in a previous chapter. In this direction, these works have introduced that trivial blemishes, caused by pollutant particles, have a slight and controlled result to the final product's Young's Modulus and flexural strength, and in many cases where the strength-reducing contamination is localized off the maximum tensile stress sections, on that occasion the flexural strength of the object made out of glass waste is corresponding to that of a clean glass component (Bristogianni, 2020).

The recommended casting formation technique and the recycling-as-is strategy are remarkable shifts from the current accustomed open-loop recycling model of float glass to a closed-loop approach. Glass recycling is qualified to convert the manufacturing industry to its supreme productiveness with the smallest damage to the ecosystem through waste generation and concludes in significant environmental benefits.

01.2 EXPERIMENTAL VARIABLES

Prior to the experiment's start, an organized strategy and explicit definition had to be recorded for sufficient variable operationalization. A crucial phase in establishing and achieving reliability and consistency in the experimental outcome. Probably, there are numerous features that are able to be influenced and altered during the experimental exploration to evaluate the reactions and behaviors of the tested samples. These modifying quantities are referred to as the experiment's variables since they are factors, traits, qualities, or statues that may occur in alternative typologies and proportions.

Variables are a significant and undivided part of the experiment. They assist in the eye-tracking of the fact-findings, as an alterable that could change or be changed, controlled, or measured throughout the experiment's mode. Owing to the preparation of the new panel's experimental approach, a set of three main variables was defined, constituting the design criteria of the way to the final outcome.

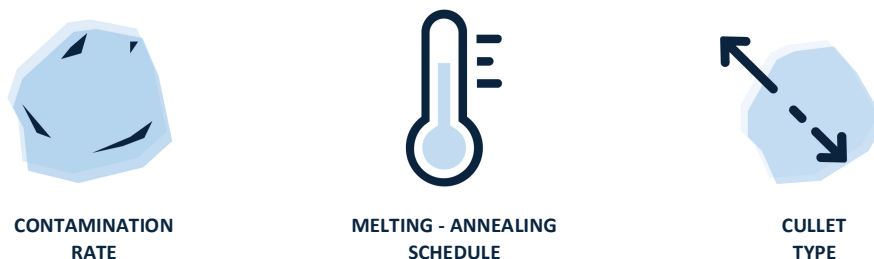


FIGURE 03.2 | Main experimental design variables.

Contamination Rate

This variable related to the contamination rate assisted the whole process of the experiment and the evaluation of the casting specimens. All three primary qualities of glass purity rate, defined by the industry, were examined. A primary focus was on Class B' of defined composition cullet, mainly coming from the external stage of pre-consumer glass products, and Class C' cullet, as the most challenging option, which refers mainly to mixed cullet of post-consumer use as an outcome of the recycling industry that the composition of it is completely undefined.

Glass could be considered a unique and sustainable material, due to its recyclability. However, not all diverse glass systems, which are removed from the built environment, meet the standards to be welcomed back to the melting furnaces of the float industry. The issue of contaminants attached to the recycled cullet is the main and substantial technical challenge that has to be controlled and overcome by the industry in an effort to enhance the availability of high-quality cullet for the remelting process. For the time being, the collection system obliges a thorough check of the contamination rate for any cullet to be accepted into the glassmaking loop of the float line.

The target of this thesis is to reintegrate the undesired cullet grades into the recycling loop, as a closed economy concept with the aim of casting method. Different grades of glass waste had been remelted and

testified into the furnace in order to first check their fluidity and secondly their homogeneity, according to the set firing schedule, and in another set of tests, the compatibility of different grades combined.

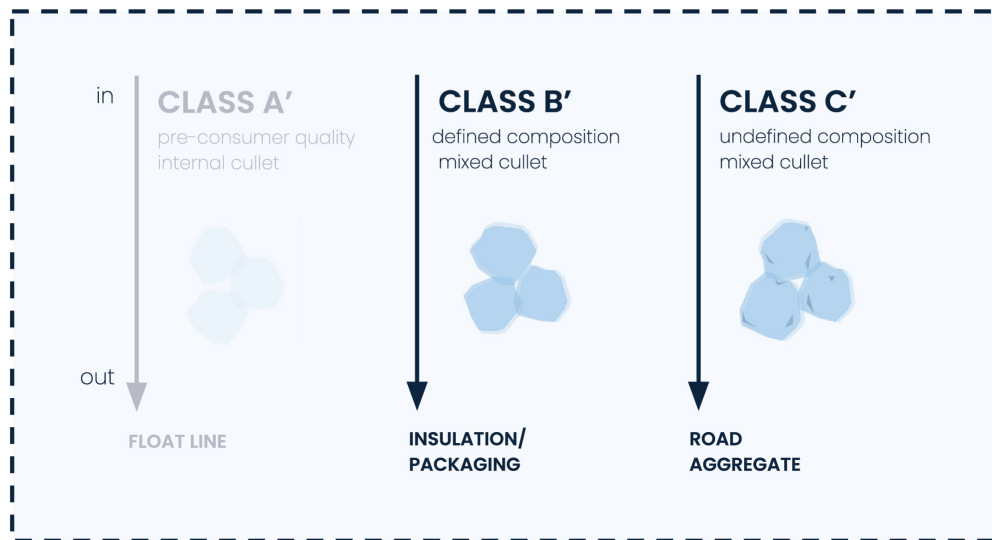


FIGURE 03.3 | Contamination rate variable set, to be considered in the experimental process.

Cullet Type

The next variable is the cullet type that defines the index of glass chips. The used types were mainly of irregular shape and they were categorized in three parts according to their size and the main outputs from the glass recycling industry. According to Bullseye, any selected size of cullet (shards, fines, powder, etc.) possesses a direct influence and impact on the quality of the final casting output of glass.

The biggest categorization is "shards", a common type used by the industry for its convenient size. This specific cullet size aims to mitigate bubbles formation after remelting, concluding in glass elements of greater purity and transparency (Bullseye Glass Co., 2009), while its size is suitable to localize any contamination during recycling and finally sorting of glass waste. The second size is reported as fine cullet, really small fragments of glass, whose dimensions vary between 1 mm and 4 mm. This type is accepted under specific proportions by the glass industry since it is really lucky to cause bubbles generation (Deng et al., 2018). Finally, it is a coarse powder that the particle sizes are under 1 mm, as the smallest cullet type variable to be considered in the experimentation. The powder is considered waste from the glassmaking manufacturing used mainly for reinforcement of synthetic resins and path lines (Deng et al., 2018), due to the fact that it presents a high amount of bubbles. Additionally, it is easily contaminated by small particles of ferrous and nonferrous metal, ceramics, and others that cannot be controlled in the cleaning and sorting process of glass recycling.

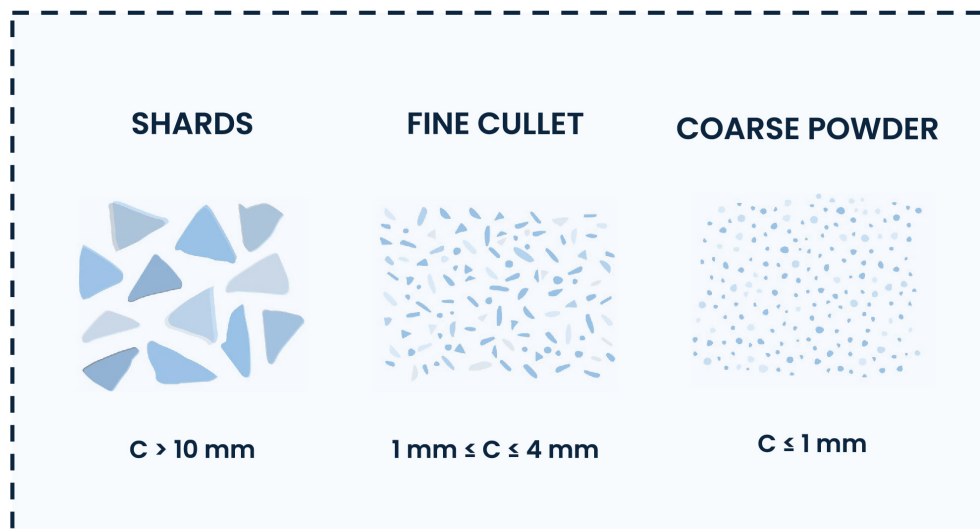


FIGURE 03.4 | Cullet type variable set, to be considered in the experimental process.

Melting – Annealing Schedule

Last but not least is the variable related to the melting and annealing schedule. A really crucial part of the experimental process, since the proper programming of the time frame organized for every stage of firing, displays a major role in the final output of the casting glass. The casting program indicates many conditions and variables on its own. Every combination, such as shape, thickness, and material, demands a unique firing that the sample is subjected to different temperatures, for their homogeneity and proper strength to be checked for the optimal results.

Through testing, the needed understanding of specimens' behavior allows for generating the proper firing series of steps that would correctly warm and chill the object inside the oven. The main target is to cause on the glass body the particular conditions that are able to be formed and then guide it to the ambient temperature in a fixed state without any risky internal stresses.

In a general sense, the glass acts as a liquid under high temperatures, but this depends on the viscosities of different types according to their primary composition. If the glass is warmed really quickly, it may trap bubbles within the cullet layers, while a lower rate may decrease their formation. The different temperatures are also able to affect the flatness or waviness of the specimen (Bullseye Glass Co., 2009). On the other hand, annealing has its role to relieve any stresses, by cooling the glass under a controlled process and equalizing the temperature throughout the specimen's body.

The experiments were remelted through three principally similar firing schedules, with small alterations occurring between them, on the forming temperature and its dwell time. In the beginning, a specific program was set where all the glass waste was tested individually for its fluidity and homogeneity. The reason that this happened was that the final product has to do with a composite between the different purity grades of the cullet. After this, the most successful materials were tested for their compatibility between them in two different schedules in order to distinguish the most optimal result and proceed with the final panel formation.

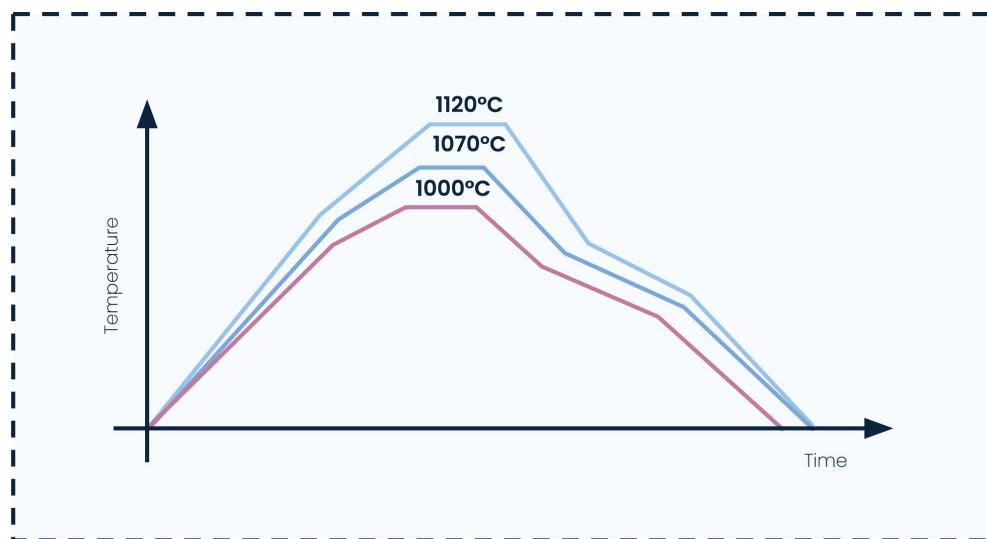


FIGURE 03.5 | Firing schedule variable illustration, to be considered in the experimental process.

01.3 MOLD PREPARATION

As stated in the previous section, a mold fabrication is in need of a casting technique, regardless of whether the hot-forming or kiln-casting is followed. Considering the various design purposes, such as the used material to generate the shape matrix or the geometry of the cast product, the concavity and convexity of the mold, the operation demands, related to the thermal expansion of the used material for the mold-making, since different materials bear different temperature ranges over time, and finally the casting techniques, there is a range of mold types that can be exploited. However, there are four prevailing typologies available in choice, depending on if the molds may be permanent or made with flexible material for many repetitions, or disposable, usually concerning a single or limited batch casting (Oikonomopoulou, 2019). The selection of mold type largely counts

on the components' fabrication volume and preferable level of precision of the glass output, and moreover the choice is related to the effect of cost and time.

TABLE 03.1 | Characteristics of prevailing mold types for glass casting. (Oikonomopoulou, 2019)

Characteristics	Mould Types						
Reusability	Disposable			Permanent			
Material	Silica plaster	Alumina-silica fiber	Steel/Stainless steel			Graphite	
Adjustability	-	-	Adjustable	Fixed	Pressed	Adjustable	Fixed
Production method	Investment casting/lost-wax technique	Milling	Milling/cutting and welding			Milling/grinding	
Manufacturing costs	Low	High	Moderate to high			High	
Top temperature	900-1.000°C	≈1.650°C	≈1.200°C / 1.260°C			n/a	n/a
Glass annealing method	Mould not removed for annealing		Mould usually removed for annealing but can also remain if high accuracy is required			Mould removed for annealing	
Release method	Immerse in water	Water pressure	Release coating necessary (ex. Boron Nitride)			Release coating necessary	
Level of precision	Low/moderate	High	Moderate/High	High	Very high	Moderate/High	High
Finishing surface	Translucent/ rough	Translucent/ rough	Glossy. Surface chills if the mould is not properly pre-heated			Glossy with surface chills	
Post-processing requirements	Grinding and polishing required to restore transparency and increase accuracy		Minimum or none post-processing required			Minimum to moderate post-processing required	
Applicability	Single component/low volume production		High volume production			High volume production	

Starting with, disposable molds are preferable as more efficient use for single component production or a limited number of specimens, since they are remarkably inexpensive compared to the permanent mold choice. As far as the rate of performed accuracy and the greatest temperature that is allowable to be reached, this type can diversify. For instance, there are available alternatives from silica-plaster molds suitable mainly for casting under 1.000°C even higher temperatures could also be adapted, proved by testing– to milled alumina-silica fiber ceramics for the highest temperature performance. These typologies are suitable and commonly used for kiln-casting. Despite that in either case, the surfaces of the molten glass that is in touch with the mold's walls will result in a translucent and coarse texture outer layers of the glass object, which need post-processing for a superior result.

For specific requirements and series production, the permanent mold is in favor of such cases. Especially, jointly with the quenching method, it is an approach more practical with time management in comparison with kiln-casting (Oikonomopoulou, 2019). However, molds made with stainless steel and graphite present higher accuracy and specifically in the choice of pressed mold, while the graphite option can obtain better detailing on the glass product's skin, placing it as a more costly solution. Aside from that, such mold can only be produced by specialized manufacturers under certain conditions, while before every use it is required a release agent, such as a nickel coating, boron nitride, or graphite, to be placed prior to the molten glass, in order the component to be effortlessly delivered from the mold (Oikonomopoulou et al., 2018). The permanent mold option can also become adjustable, to permit the shape's flexible adjustment. In contrast with the disposable molds, this option results in a transparent and at the same time smooth and shiny finish on the glass surface, and as regards the permissible tolerances, the least or no post-processing stands in need of a suitable preheated mold previous to casting phase (Oikonomopoulou, 2019). Insufficient preheating of the molds introduces the possibility of glass surface chilling, this risk is even higher mostly in the choice of graphite matrix.

The current thesis adapts the option of the refractory mold, due to the small production of needed specimens and the fact that it has to be produced in the laboratory. Even if this type is suitable for firings up to 1000°C, it was chosen for even higher temperatures, considering the previous experimental experience and existing testing. In general, the procedure of creating it involves a disposable mold around a positive object, when the latter is removed a cavity is generated in order for the glass cullet to be placed. The making process requires various step-by-step stages that were productively implemented in a well-organized space.

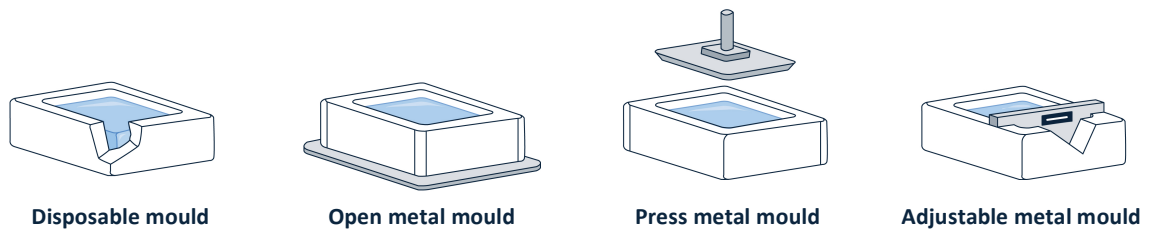


FIGURE 03.6 | Illustrations of the most common mold types, based on (Oikonomopoulou, 2019)

Mold Production

First and foremost, the desired shape of the original model was picked, an item usually made of metal or plastic, possibly a 3D printed object equipped with a substructure for easier removal from the mold. These items demand to have a fixed form and the appropriate solidity in order to withstand any pressure caused by the liquid state plaster that is poured on the top of it. In the current experimental setup two different shapes are exploited, a tile-shaped element with dimensions 10cm in length and height and 2cm in thickness, and a cubic box measured 5cm in length, height, and thickness, without taking into account the substrate that is supplied with. When the original shape has been chosen, it is positioned on a surface and fixed with a certain amount of clay on the attached edges. The selection of these forms is made in order to give the samples a considerable thickness of cast material, for the purpose of evaluating the glass waste melting and any occurred flaws in the bulk of the specimen. Additionally, retaining the cast glass mass under 1kg is suitable to limit the annealing time of the firing schedule.

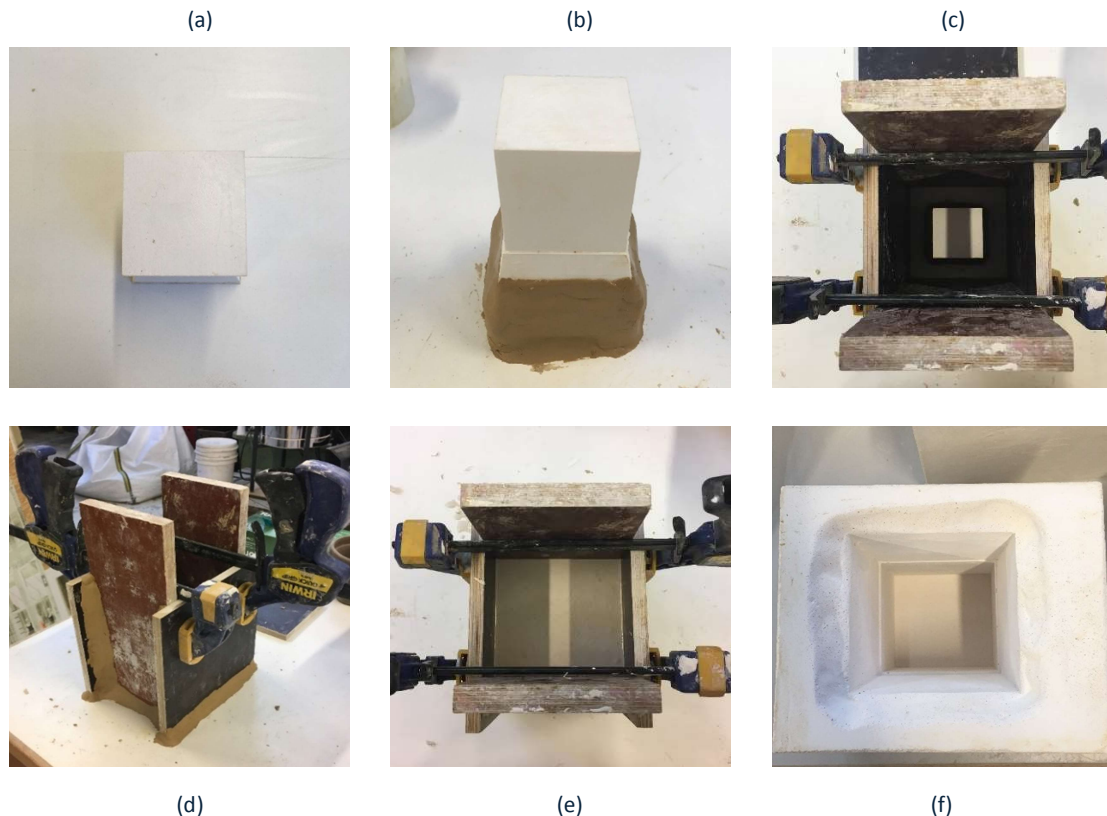


FIGURE 03.7 |

(a) 3D printed cube positive footage, (b) Cube fixed support by clay, (c) Wooden board positioning, (d) Boards clamping and sealing with clay, (e) Mold mixture casting, and (f) Final mold ready for the firing. (Anagni, 2018)

The next step is the building up of a border base for the mold. Approximately 2 centimeters around the positive footage model, wooden boards are placed to create a box with adequate and equal clearance around the edges and then they get fixed with the aim of clamping equipment, setting at that point the boundaries and the final form of the mold. Once the base is on, all the edges are sealed and fixed again with clay, in order to prevent any leakage of the flow outside the wooden dam, during the pouring of the liquid plaster. Prior to mixture pulling, the surface of the model should be spread with a thin layer of petroleum jelly, commonly vaseline, for an easier separating process.

Afterward, the final investment casting slurry is prepared with Crystal cast M248, a mixture in the form of powder consisting of Cristobalite, Quartz, Gypsum, and the addition of powder to water ratio equal to 2,8:1. This composition provides the mold with the proper structure and high refractive index, so as to withstand the high-temperature range. After the mixture has become saturated, any chunks must get dissolved by hand, so that the mixture possesses a creamy consistency. The liquid then is cast inside the dam and vibrated lightly in order to release out of the flow any trapped air bubbles. Following the curing time, where the mold has to dry properly in ambient conditions for approximately one hour, the crystalline silica mixture solidifies and the borders are removed, besides the positive object and the clay. The mold does not have to be wet, since this may result in rust damage to the furnace and contamination of the casting object (Weiler, 2014). Finally, the mold has to be thoroughly cleaned from any clay leftovers, dried before casting and the edges to be smoothed in order for the mold to be ready before firing.

When the entire firing process is over, the glass specimens are preferred to stay in the kiln at ambient temperature for a whole day. Then, directly fetched from the furnace, they are abstracted from the crystal-cast mol, cautiously. It can be seen that the mold body is significantly weaker than before and not structurally sound anymore, aiming for the easy removal of the material investment, with the aim of a small trowel tool, so that any damage of scratching is not to be provoked. Often, the samples would need to be fully immersed in water for a couple of minutes for cleaning. Finally, they may need some post-processing, in the case of any mold residues, and to work the glass object's surfaces and edges, by removing any excess material.

01.4 CULLET PREPARATION

Before proceeding into the sample firing, the various types of glass waste are cleaned with liquid isopropanol (C_3H_8O), to remove any surface contaminants. Moreover, any external materials such as plastics and corks are manually removed wherever it is feasible, and dried with air pressure in advance to be placed inside the moulds. Moreover, aiming to acquire the desired sizes, the cullet was either crushed with a manual hummer in order to have the shards or grinded mechanically for smaller particle generation. This action is held to achieve a more regular cullet form, equipped with smoother edges.



FIGURE 03.8 |

(a) Preparation of grinding cullet, (b) Fine cullet, (c) Coarse powder, and (d) Perforated plate sieves of 1 and 4mm holes. (Anagni, 2018)

The grinding procedure is held with the aim of a grinding machine. The use of such equipment demands a time range of 1 to 2 seconds for operation in the case of fine cullet pieces, and 6 to 8 seconds to produce coarse powder, in the manner of the initial dimensions of glass waste. Additionally, a sieving process is required, in order to separate the cullet outcome into the desired texture. Perforated plate sieves of 1 and 4 mm are used for a dry test, where the glass fragments are free-flowing in order to go through the stamping holes, by barely tapping or shaking movements. This process is really usual for various categories of laboratory sampling and particle dimension inspection.



FIGURE 03.9 |

(a) Grinding machine, (b) Cullet and powder sieving, and (c) Cullet particles separation according to sizes.
Image credits: Oikonomopoulou and Bristogianni.

In the end, the kiln-casting process permits directly the cullet position into the molds. The prepared material is firstly weighted and recorded accurately according to the glass waste category that it belongs to, and then the dam of the mold is loaded with the cullet on the basis of free-set deposition. Then, the sample set-up is ready for the firing process inside the oven, where the position of the specimens into it is captured.

01.5 SOURCE & MATERIAL SELECTION

Generally, glass panes are a widely used material for façade envelopes on the transparent surfaces of the built environment. These thin-walled glasses account for 30% of the whole production of the glass industry in European territory (Hestin et al., 2016), seeing the building field as its leading market. Nevertheless, the continuously increasing trend in the architectural and engineering field toward wider applications of transparent surfaces in the building facades has spread the need for float glass generation. Consequently, in several activities of the building sector, primarily the demolition and renovation operations, when they take place a considerably large amount of end-of-life post-consumer glass wastes are produced, with the intention of fulfilling the contemporary energy standards. Each year, this glass waste output of C&D glass mostly ends up downcycled in low-value applications, as the most common scenario, or they are sent into the landfill, aggravating the existing inextricable problem of glass upcycling. As is already mentioned, this issue emanates from the lack of an organized recycling scheme, the incompatibility of different glass recipes, the contamination rates of glass products, and the unknown origin of much post-consumer waste.

Among the down-recycled or landfilled glass waste, there is a large amount of high-value thin-walled glass, which is used for architectural projects, mainly coming from the Construction & Demolition resources. This current experimentation research exploits this glass category, which is rarely recycled into new glass products in its end-of-life, pointing out and providing evidence for the large potential in upgrading the float glass waste recycling process.

Generally speaking, the architectural flat glass is classified as soda-lime-silicate composition, which possesses in its primary chemical recipe roughly 73% of silicon dioxide and around 13% sodium oxide (Vieitez et al., 2011). However, sheet glass contains a wider variety of sources, compared with the hollow glass industry, that present chemical diversity in their structure, due to the fact of post-processing according to the customer's needs. As a consequence, not every diverse glass system that is removed from a building envelope fulfills the standards, in order to be accepted back to the production line of the float industry, turning away the recycling process from being more straightforward. Solely the cullet that follows the strict value limits of the float line is capable of proceeding in the up-cycling. According to this instruction, glass manufacturers have categorized three main qualities of glass fragments, corresponding to the degree of contamination, as it is extensively elaborated on in a previous chapter.

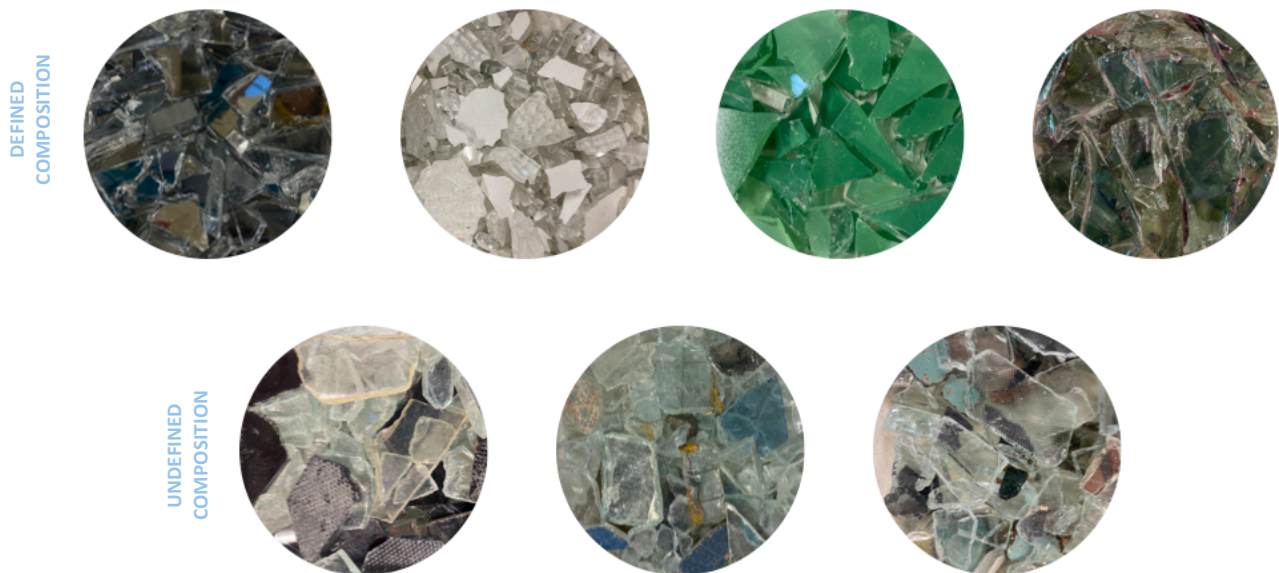


FIGURE 03.10 | Selected glass cullet categories used for the experimental research.

The current thesis with an eye on the remaining challenge of float glass coming from the C&D sector, recyclability topic, addresses a variation of multiple glass wastes that have undergone different secondary processing methods. As it is obvious, this cullet originates from every purity grade on the glass waste scale. The experiments include the following material groups:

TABLE 03.2 | Glass cullet used in the experimental research.

Defined Composition	Undefined Composition Combinations
Clean float glass (float line off-cuts)	HR combi float glass (heat resistant particles)
Coated glass (soft and hard coatings)	Mag combi float glass (ferous/non-ferrous metal particles)
Mirrored glass	CSP combi float glass, KSPV.KSP (CSP fractions)
Lacquered glass	
Fritted glass	

The above mentioned glass families were chosen, according to two factors. The first one has to do with their highest probability to be applied in the built environment and the second is characterized as the most challenging product output from the float glass recycling industry. The former, also referred to as defined composition glass waste, except the clean float glass, is related to commonly used types that are generally concluded as demanding along the flat glass recycling process. Moreover, even if most of them are accepted to be introduced back into the glass-to-glass loop, there are strict limits in the exploited amount in order not to risk the flat glass final derivation.

At the same time, undefined composition streams are not accepted at all to be used into the glass batch and therefore it is downcycled or disposed of. Maltha glass recycling company is the principal recycler of glass waste, and at the same moment a supplier of furnace-ready cullet. The gathered glass is cleaned and purified at its plants, utilizing advanced techniques and reprocessed into numerous sorts of cullet in an advanced manner, which rigorously work to correspond to the float glass industry needs. The used combinations provided by the company are not introduced to the waste-to-glass strategy, due to the undefined origin and high contamination rate that they carry. More detailed, "HR Combi Float Glass" contains heat resistant pollutants as the byproduct of rejection from the X-Ray sorter in the recycling line. Accordingly, "CPS Combi Float Glass" is a corresponding output of second recycling run, containing CSP fractions, whilst "Mag Combi Float glass" is the result of rejection

by the metal separator sorter, called MAG, which automatically takes out of the cullet stream any presence of ferrous and non-ferrous metal particles.

In accordance with the aforesaid material selection and categorization, characteristic samples from every float glass group were gathered in order a further analysis to be held with a Panalytical Axios Max WD-XRF spectrometer. This kind of test specifies the different chemical structures on various glasses with the aim of different energy release that arises through specific compounds in their composition. However only the coated side of the defined composition was taken into consideration. A bigger picture from the XRF test result held by Ruud Hendrikx and the research of Rong Yu, the chemical composition are quoted in the following table.

TABLE 03.3 | The original composition content of major glass categories, based on (Yu, 2018).

	Normal Float Glass	Soft Coating		Hard Coating	Printed Glass ^a (green)
		(light)	(dark)		
SiO ₂	74,432	64,96	64,665	49,967	50,25
Na ₂ O	12,524	4,765	4,736	0,577	9,587
SnO ₂		2,67	2,732	32,384	
CaO	8,23	8,969	9,253	14,241	0.452
MgO	3,884	3,778	2,273	1,153	1,287
Al ₂ O ₃	0,55	0,571	0,549	0,317	0,662
K ₂ O	0,145	0,139	0,16	0,453	0,232
SO ₃	0,113	0,125	0,171	0,237	
Fe ₂ O ₃	0,057	0,056	0,094	0,35	0,057
TiO ₂	0,029	0,025	0,364	0,154	4,154
SrO	0,009	0,01	0,024		
P ₂ O ₅	0,009		0,009	0,009	
ZrO ₂	0,009	0,012		0,055	
MnO	0,006	0,008	0,009		
ZnO	0,002		14,703	0,02	1,246
Ag ₂ O			0,04		
Au					
NiO			0,033		
Cr ₂ O ₃			0,021		1,852
PbO					28,433
Sb ₂ O ₃					0,931
Co ₃ O ₄					0,864
Rb ₂ O				0,013	
Cl				0,069	

^a The printed cullet surface analysis is not accurate due to the fact that the colored layer is too thin, as a result the XRF analysis scans part of the glass, related to the increased SiO₂ percentage.

01.6 FIRING SCHEDULE

Glass is a material with unique characteristics. An amorphous molecular pattern defines and makes it capable to react in various ways to heat, compared with any other material. For instance, metals possess the property of transforming from a solid-state to a liquid one under a certain melting point. On the contrary, the glass changes its behavior moderately, allowing it to be processed in numerous manners. This means that there does not exist a one-size-fits-all method in the working temperature, in order to be used during the firing procedure. Many variants influence this schedule of melting and annealing process, from the type of glass and the specimen's size to the kiln form and casting setup.

Generally speaking, float glass does not melt entirely at a temperature that is lower than 900°C. In this case, the glass cullet just fuses together and the fragments join one another. According to Telesilla Bristogianni, a

suggested temperature should exceed the aforementioned level. The working temperature for flat glass commonly starts between 927°C and 1000°C (Bullseye Glass Co). Within this range, many effective alternatives may be achieved by utilizing diverse firing schedules.

TABLE 03.4 | Firing schedule of different single tested glass materials and combination glass batches.

STEP	RAMP [°C/h]	TEMPERATURE [°C]	DWELL [h]	TOTAL WORKING TIME [h]
1	50	23	3.0	3.0
		160		
2	-	160	3.0	6.0
		160		
3	50	160	13.0	19.0
		820		
4	50	820	6.0	25.0
		1120		
5	-	1120	6.0	31.0
		1120		
6	- 186	1120	3.0	34.0
		560		
7	-	560	3.0	37.0
		560		
8	- 6	560	10.0	47.0
		500		
9	- 14	500	5.0	52.0
		430		
12	- 100	430	4.0	56.0
		23		

Likewise, different processes are picked up for the existing experiments and according to the glass type, where melting temperatures vary from 1000°C to 1120°C. This selection rests on previous experimentation held on float glass recycling specimens. Due to the fact of the undefined fluidity rate of every selected category of glass for remelting, a free-set arrangement is set up for the glass pieces into the molds. Then, they are placed in a ROHDE 1000S kiln, operating with electricity. This oven is intended for kiln-casting, designating that a single machine is employed for the overall casting procedure with all the appropriate stages of heating, forming, annealing, and finally cooling. Moreover, an automated programming schedule is followed in the total time consumption, without any manual process phases.

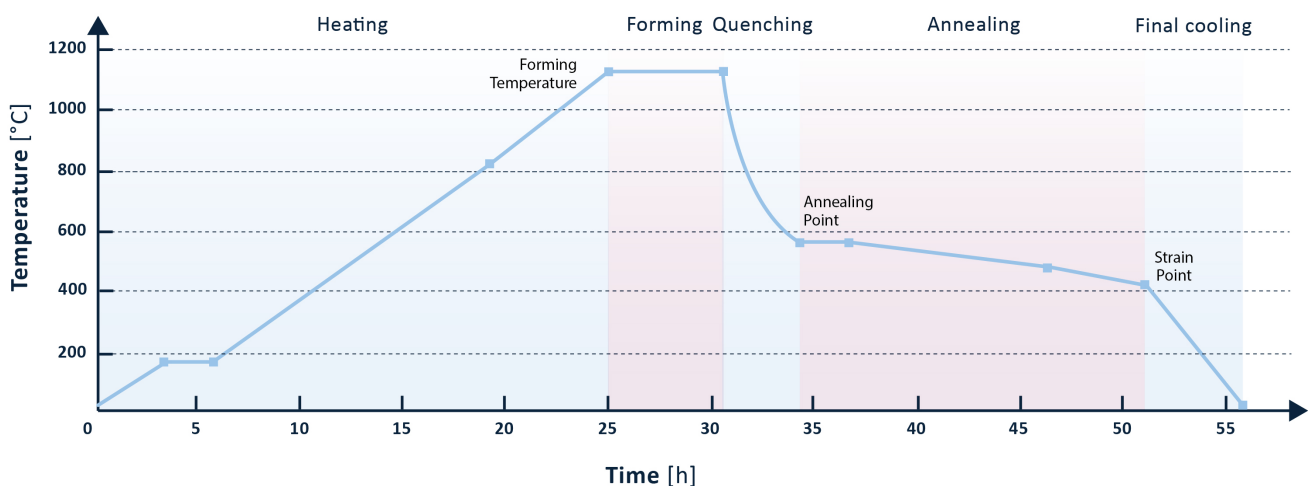


FIGURE 03.11 | The firing schedule and casting phases of single glass batch kiln-casting.

As shown in table 03.4 and the figure 03.10, a characteristic casting plan of five stages shown heating, forming, quenching, annealing, and final cooling, is described for the recycling of the single glass experiments, is analyzed. This production schedule sets the maximum heating rate at 50°C per hour and the highest melting temperature, which is permitted to be reached, at 1120°C. First and foremost, the temperature rise rate operates until it

attains firstly 160°C in 3 hours, where the temperature is maintained for another set of 3 hours, secondly at 820°C in the next 13 hours, until it will reach the forming temperature within the 19 hours of the kiln's operation. After 6 hours the temperature sharply decreases from 1120°C to 560°C. This stage is called quenching and presents a ramp of 186°C/h, carried in the next 3 hours, down to the annealing range. Once the inner temperature of the glass body has turned out uniformly, the specimen gradually heat-soaks until the strain point at 500°C, reached within 10 hours. Then the controllable cooling phase takes place until 430°C, which assists in stress-free glass outputs, whilst preventing the formation of crystallization zones. Finally, the ambient temperature is achieved in the last 2 hours as soon as possible, considering that the cooling rate is not so rapid as to provoke thermal shock.

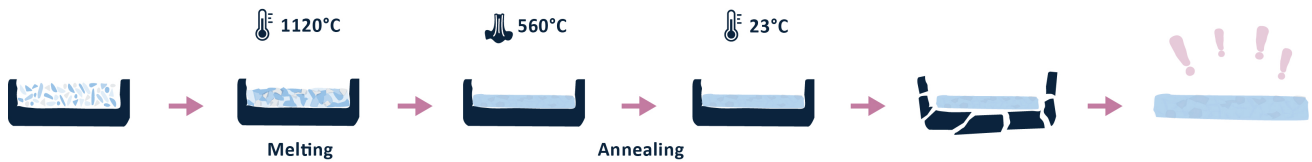


FIGURE 03.12 | Casting procedure step phases.

01.7 STRESS QUALITY CHECK

How an appropriate annealing processing of glass could be determined? In order to check the effectiveness of the annealing procedure that a glass product has gone through, and evaluation of strains should be held. Improper performance of this key step in glass production commonly occurs at high levels of residual stresses, as it is mentioned in a previous chapter. The presence of them makes the products vulnerable to fragility caused by impacts since, in essence, they diminish their strength and reliability.

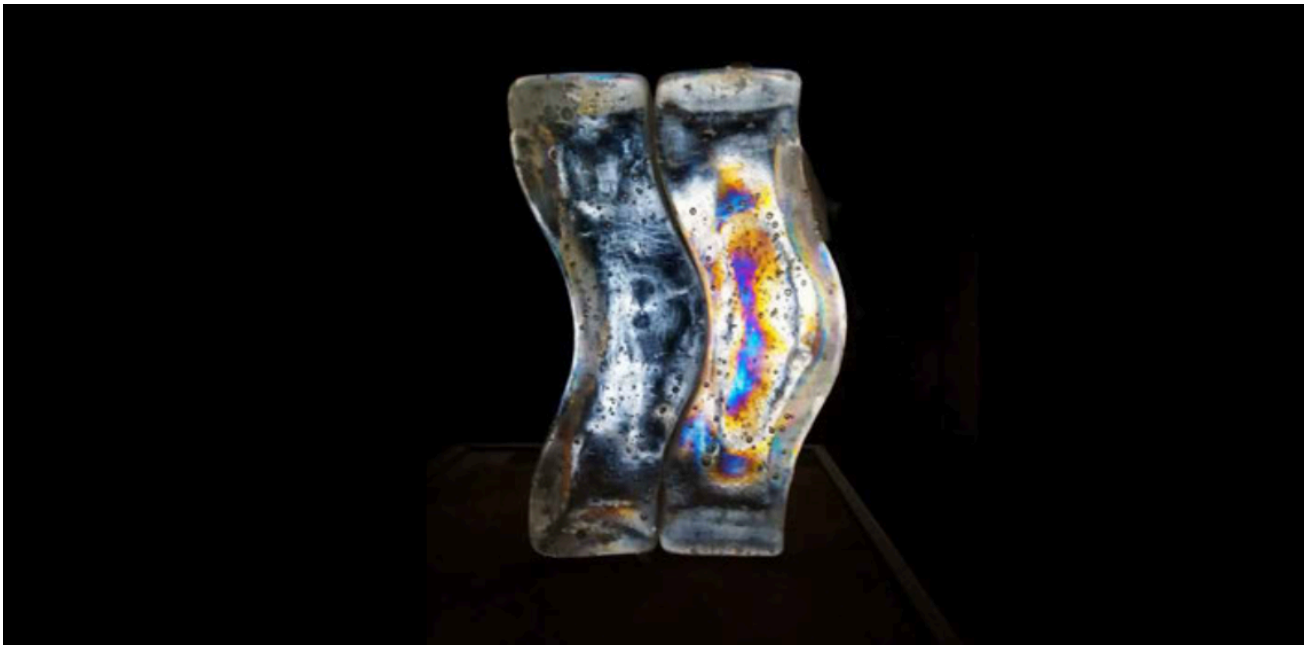


FIGURE 03.13 | Qualitative analysis of strain concentration by polarization test. Bricks such as the ones shown on the right have a clear indication of residual stresses. Elements with grey-scale spectral composition, such as the one on the left, have low residual stresses. (Oikonomopoulou, 2019)

Understanding the importance of inspecting glass residual stress, a special optical tool is required to expose any of them. The polariscope is a qualitative instrument for determining critical stress points in a material. It utilizes polarized light to unveil the existence and distribution of isochromatic fringes, essentially colored stress patterns or footprints, in transparent or translucent glass objects (McKenzie et al., 2011). To achieve this reveal, the polariscope uses a setup of two crossed polarized lenses and a light source, exploiting double refraction (birefringence). When the glow passes through stressed glass objects, which experience optical anisotropy, writes up the characteristic color chart, known as the photoelastic effect. Actually, that illustrates any alteration in the optical properties of the glazed component under mechanical deformity.

Photoelastic colors are able to point out the magnitude and direction of residual stresses. When any strain is not displayed inside a glass, the aubergine/black color can only be seen as an essence of darkness (Schott AG, 2004). If the brightness of the glass area amplifies, a presence of elementary retardance is illustrated through a white color in the range of 200nm (Shribak, 2015). A consecutive presence of only dark and white or gray-scale spectral composition eventually declares little residual stresses on a glass specimen. As the stresses rise, more colors of the range are visible, following the order of yellow, red, blue, and green (Oikonomopoulou, 2019). The coloration alters along in this sequence three more times until attaining 2200nm. From there on, the interpolation shade reaches white afresh and henceforward the retardance is not possible to be defined accurately by employing the region's spectral composition. This range of color spectrum revealed from the polariscope can only provide a measuring of the quality of stress-concentrated areas, meaning that the quantity of indicated stresses cannot be admeasured.

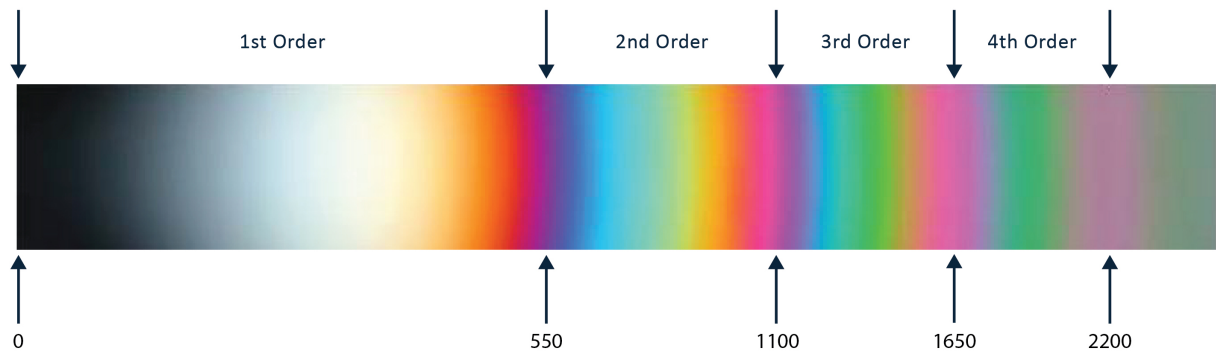


FIGURE 03.14 | Characteristic color range of spectral composition. Image credits: Derochette, J.M., 2006. The Gemology Project.

01.8 THERMAL SHOCK SET-UP

Typically, thermal fracturing could occur from either hot-cold or cold-hot thermal shock. During sunrise, while the glass surface is chilled, the direct daylight that the glass panel is exhibited is able to cause thermal fracturing, owing to the fact that the inner part of the panel warms up faster than the adjacent area and the glass edges, creating strains. The same could happen on a really warm and sunny day when the glass panels raise their temperature considerably, and there is sudden rainfall within the same day, where the colder water could lead to a thermal shock. Nevertheless, the latter is more probable to harm the glass element, since it produces tensile stresses on the quickly chilled surface.

Thus, to evaluate the glass panel's performance under utmost temperature fluctuations, two different types of thermal shock were considered. The first test involves the casting samples to be warmed up for 6 hours inside the oven, at a constant heat level of 80°C, so as to verify the thermal shock resistance. Subsequently, the specimens are immersed instantly into a water bath at a temperature of 20°C for roughly 15 minutes each, to cool them down ($\Delta T +60^\circ\text{C}$), in order to evaluate their behavior in uneven conditions. The second one is the reverse version of the former test under the same temperature difference ΔT . The difference, in this case, is that the samples in ambient temperature are firstly immersed in a bath of hot water at a constant temperature of 80°C, where they soak for 15 minutes. After the upshock situation, the samples are immediately transferred within a maximum of 15 seconds in a bath of colder water, roughly at 20°C for a period of 30 seconds, and then are removed from the bath (ASTM). This test is considered an instant evaluation, and accordingly, the first 1 to 5 seconds mark is deemed crucial in this new environment because the highest stresses are developed within this timeframe for a thermal shock examination.

The samples under consideration are divided into two groups. Firstly, unprocessed tiles of the composite samples in the three variants in thicknesses are tested and one sample of pure float glass is formed exactly with the same method as the rest. Accordingly, the second group contains specimens with the same material and dimensions as the aforementioned, but these tiles are treated further with surface and edge processing through grinding and polishing, while a UV coating is applied to every surface for further resistance.

Moreover, three alternative ways of heat shock set-up were tested, while two samples were employed for each test.

1. Splashed with water on the one surface (T_1)
2. Immersed only with the one side by 4mm into the water (T_2)
3. Half-immersed inside the water (T_3)

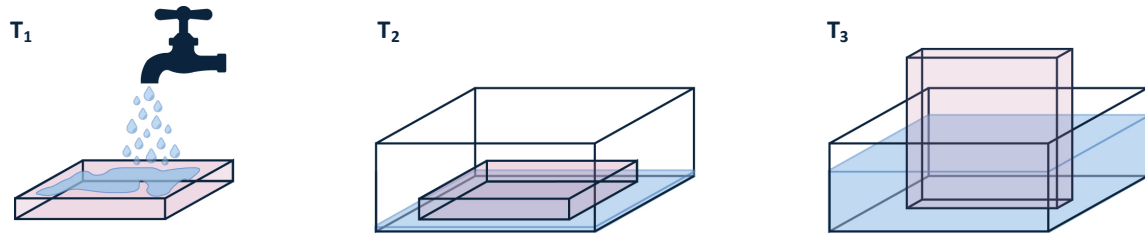


FIGURE 03.15 | The three different thermal shock test variables. Illustration by (Oikonomopoulou, 2019)

The fracturing intensity is associated with the temperature difference of the glass and the ambient, considering at the same time the thermal flow rate from the panel. Therefore, this intensity may be capable enough, in order to trigger any pre-existing minor defects or cracks, which can lead to breakage, if they are great enough. The risk of thermal shock is more likely to influence float glass, seeing that it is probable to succumb to heat shock up to 40 degrees of temperature variation. The magnitude of the occurred stresses rests on diverse parameters, such as:

- Temperature difference between the glass object and the environment
- Thermal expansion coefficient of the glass product
- Heat transfer coefficient between the two media
- Thickness of the glass element and the correlated heat storage capacity

(Paech et al., 2018)

02 | EXPERIMENTAL ANALYSIS

02.1 INTRODUCTION TO THE EXPERIMENTAL ANALYSIS

Over time, as an effort to protect the environment through a sustainable-organized society, most of the everyday products, instead of utilizing the non-renewable natural resources, will be produced from recycled stock. This strategy will aim at the mitigation of the ecosystem's threat from the boundless emission of greenhouse gasses and the production of disposed waste ending up in landfills.

An unsolved but important problem is the glass waste and especially the stream of float glass coming from the construction and demolition sector. At the present time, the existing upcycling mentions on such waste are lacking.

Notwithstanding, it is already stated above that tentative research has been contacted to acquire further experience and knowledge. This stresses the significance of evolving in the development of alternative glass-recycling methods that result in a more flexible state in order to accommodate all the obstacles to flat glass recycling. Accordingly, the current research thesis attempts to get into a more deep analysis with further experimentations on the glass recycling outputs. All in all, the proposed glass casting technique and the recycling-as-is plan of action are important transitions from the existing ordinary open-loop recycling process of sheet glass elements to the leverage of the closed-loop one for the creation of products that retain their value indefinitely.

During the exploration through the experimentation stage of this research, different steps have been taken, intending to discover if recycling flat glass is in fact feasible in practice. A variety of materials, combinations, and compositions were tested to introduce a thick-walled glass panel, which allows tolerating a higher degree of contaminants unaccompanied from any critical compromise to the object's properties.

To recycle float glass waste, knowledge should be gained on the fluidity, mixability, and compatibility of numerous types of them. Not all of the sheet glass products have exactly the same chemical composition, due to fluctuations in the recipe and have undergone post-processing, and on top of that the contamination that is carried. As a consequence, this could jeopardize the potentiality of successful glass melting and the generation of a homogenous thick-walled glass end-product.

02.2 EXPERIMENTAL OVERVIEW

The overall experimental research proceeded through numerous stages influenced by the set variables and restricted by the resources' outcome. This section explains all the observations that relied on the experimental methodology. Regarding that, the followed method is divided into identifying the most promising glass waste by contacting melting within the casting technique, and tools for the product's performance evaluation, such as qualitative defects evaluation, stress analysis, and thermal shock.

More specifically, the former is referred to as glass firings. In general, there are three main rounds of casting experiments until the completion of the final product with the most optimum recycled material selection out of characteristic variables. The first round evaluates the fluidity and homogeneity of glass cullets on individually tested recycled materials streams to observe their behavior under the same firing schedule. A variety of materials, purity grades and compositions are tested to introduce a thick-walled glass panel. After remelting completion, the most promising samples proceed to the next round of the composite firing, as a strategic combination of cullet arrangement between class B' and C' purity grade in such a manner to form an advantage tensile strength on the recycled panel, which is transferred on the surfaces and reinforces the object. The main priority of this stage is to observe the compatibility rate between the different glass waste groups to identify the most optimal result for the composite panel manufacture in the different compositions and the proper strength of the product, which allows for tolerating a higher degree of contaminants unaccompanied from any critical compromise to the object's properties. Finally, the third round tries to obtain further knowledge of the compatibility of the glass layers involved with the layers' thicknesses alterations on the outer skins of the panel while keeping the same amount of contamination in the inner layer. This is held as an optimization trial of the cast panel fabrication.

Identifying the existing research gaps, the focus of this thesis is contacting tools and methods that have not been utilized before on C&D glass waste, for further examination and evaluation of the remelted outputs. The experimental analysis of the new concept after the development of the composite panel concentrates on the qualitative defects evaluation, stress analysis, and thermal shock testing. Assessments that evaluate from every possible observation point the specimens for the most efficient result within the available time frame of the research as the most promising fit into the glass-to-glass circular strategy.

When the production of the numerous specimens is complete, the outputs demand a series of qualitative analyses. The first inspection is made for the detection of residual stresses and any faults' presence, occurring in the kiln-cast objects. This examination is in the first place to identify the location and the pattern of the critical faults, which need extra attention to be given, and then the documentation of them. Any defect observation in the glass source, followed either from contamination existence or casting process and post-processing, consequently may affect the samples' failure. Additionally, an inspection of located residual stresses is contacting with the aim of the visual method of photo-elasticity through crossed polarized lenses, for the generation of stress augmentation on critical points in the object's body. These observations can introduce and explain any causes for local or general failure in the specimens, especially in the case where the thermal expansion coefficient of different compositions acts with other kinds of stresses.

Last but not least is the evaluation of the glass panel performance through a thermal shock examination is significantly uneven temperatures. A test that is held for the first time in such a glass waste target. The thermal failure of a glass element, either hot-cold or cold-hot, is a tool that actually responds as an outcome to temperature alterations across different zones of the cast glass object since, for instance under the effect the different weather conditions favorable circumstances are created for the generation of tensile stresses causing damage or failure to glass components, such as cracking or breakage.

In the contents of my experimental research that refers to a product introduced for the building envelope, the implementation of all the aforementioned methods of performance evaluation is deemed necessary. These verifications on the recycled cast glass panel assist to imitate any probable weaknesses and failures caused by numerous factors.

02.3 SPECIMENS EVALUATION

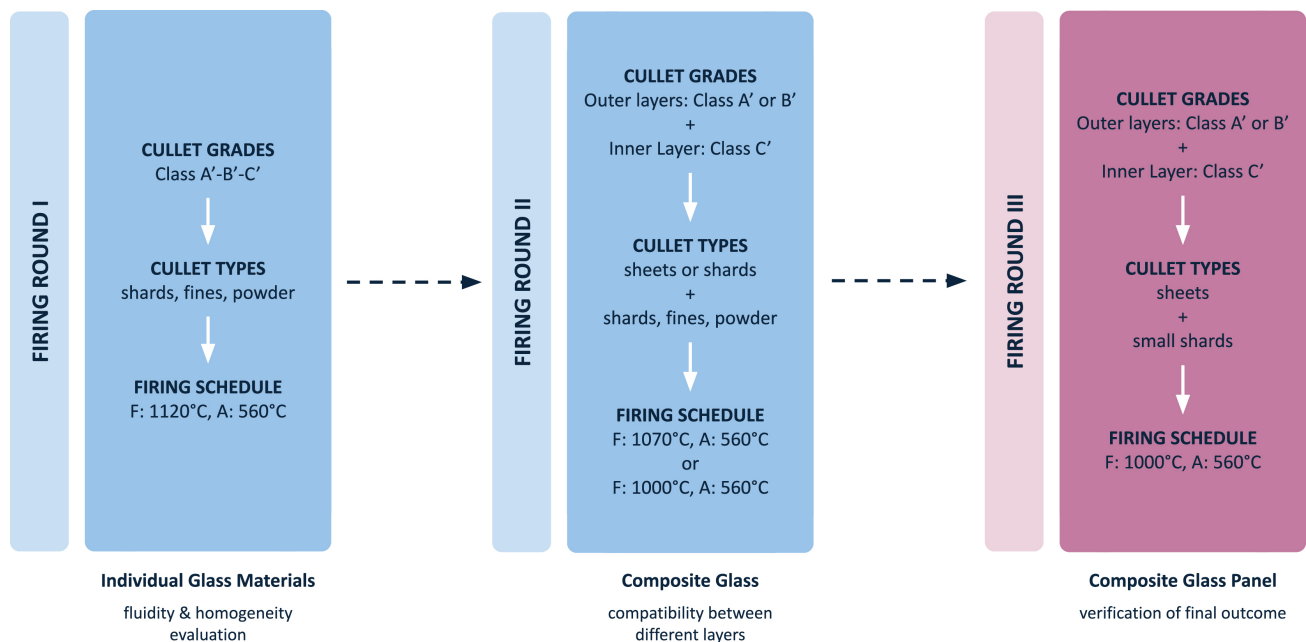


FIGURE 03.16 | Progress diagram according to the firing rounds process.

The overall experimental research proceeded through numerous stages influenced by the set variables and restricted by the resources' outcome. More specifically, there are three main rounds of casting experiments until

the completion of the final product with the most optimum recycled material selection. Every sample is labeled according to the three variable characteristics that it possesses (figure 04.2).

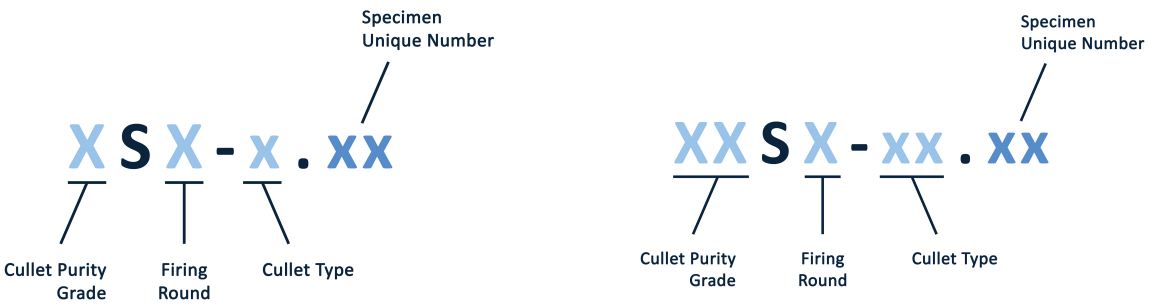
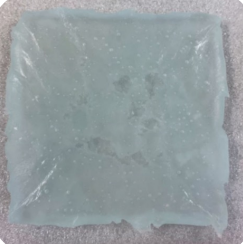


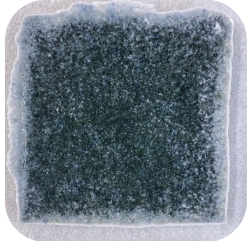
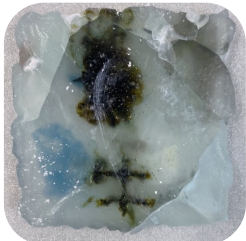
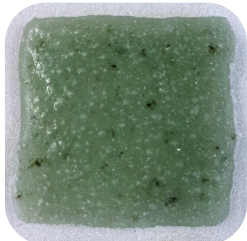
FIGURE 03.17 | Labeling specimens according to their unique characteristics as individual materials (left) or composite outputs (right).

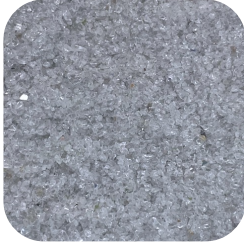
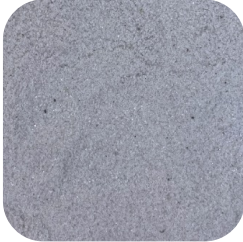
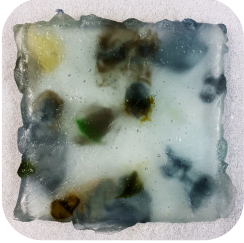
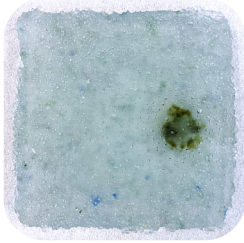
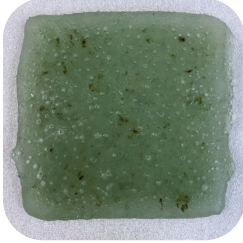
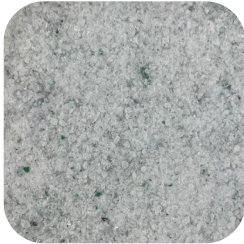
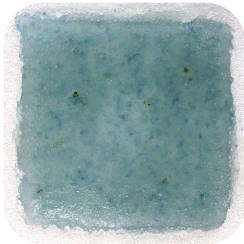
Firing Round I

The first one evaluates the fluidity and homogeneity of glass cullets with different contamination rates and fragments size. Actually, it refers to individually tested recycled materials coming from all the purity grades of the cullet in order to observe their behavior under the same firing schedule. The maximum forming temperature is set at 1120°C with an increased rate of 50°C/h, whilst the annealing phase starts at 560°C. After remelting completion, all the samples are evaluated to keep or eliminate glass batches that are capable to proceed to the next round of the composite firing.

TABLE 03.5 | Detailed overview of the kiln-cast specimens produced by the first round of firings under the same firing schedule.

SAMPLE CODE		BSI-s.02	BSI-s.03	BSI-s.04
Input	PRODUCT	Lacobel LT White (AGC)	SNX 60/28 (Guardian)	HD Silver Grey (Guardian)
	CULLET GRADE	Class B'	Class B'	Class B'
	CONTAMINATION	Ceramic frits	Soft Coating	Soft Coating
	CULLET TYPE	Shards	Shards	Shards
	FORMIN TEMPERATURE	1120°C	1120°C	1120°C
				
	HOMOGENEITY	High	High	High
	TRANSPARENCY	Transparent	Transparent	Transparent
	MOULD REACTION	Low	Absent	Absent
	CRACKS PRESENSE	Absent	Absent	Absent
	BREAKAGE	Absent	Absent	Absent
	BUBBLES LEVEL	Absent	Absent	Absent
				

SAMPLE CODE	CSI-s.01	CSI-f.06	CSI-p.05
PRODUCT	Combi HR Float (Maltha)	Combi HR Float (Maltha)	Combi HR Float (Maltha)
CULLET GRADE	Class C'	Class C'	Class C'
CONTAMINATION	Heat Resistant Glass no ceramics	Heat Resistant Glass	Heat Resistant Glass
CULLET TYPE	Shards	Fine Cullet	Coarse Powder
FORMIN TEMPERATURE	1120°C	1120°C	1120°C
			
HOMOGENEITY	High / Low specific area	Low	High
TRANSPARENCY	Transparent	Opaque	Opaque
MOULD REACTION	Absent	High	High
CRACKS PRESENCE	Medium specific area	Absent	Low
BREAKAGE	Absent	Probable	Absent
BUBBLES LEVEL	Absent	-	High
			
SAMPLE CODE	CSI-s.08	CSI-f.07	CSI-p.10
PRODUCT	Combi Mag Float (Maltha)	Combi HR Float (Maltha)	Combi HR Float (Maltha)
CULLET GRADE	Class C'	Class C'	Class C'
CONTAMINATION	Mettalic Elements	Mettalic Elements	Mettalic Elements
CULLET TYPE	Shards	Fine Cullet	Coarse Powder
FORMIN TEMPERATURE	1120°C	1120°C	1120°C
			
HOMOGENEITY	Medium	Medium	High
TRANSPARENCY	Transparent	Translucent	Translucent
MOULD REACTION	Absent	Absent	Absent
CRACKS PRESENCE	High	High	Absent
BREAKAGE	Failure	Failure	Absent
BUBBLES LEVEL	Absent	Low	High
			

SAMPLE CODE	CSI-s.13	CSI-f.12	CSI-p.11
PRODUCT	Combi CSP Float (Maltha)	Combi CSP Float (Maltha)	Combi CSP Float (Maltha)
CULLET GRADE	Class C'	Class C'	Class C'
CONTAMINATION	CSP Pollutants	CSP Pollutants	CSP Pollutants
CULLET TYPE	Shards	Fine Cullet	Coarse Powder
FORMIN TEMPERATURE	1120°C	1120°C	1120°C
			
HOMOGENEITY	High	High	High
TRANSPARENCY	Transparent	Transparent	Translucent
MOULD REACTION	Absent	Absent	Absent
CRACKS PRESENCE	Absent	Absent	Absent
BREAKAGE	Absent	Absent	Absent
BUBBLES LEVEL	Absent	High	High
			
SAMPLE CODE	CSI-s.15	CSI-f.16	CSI-p.14
PRODUCT	Printed Float Green	Printed Float Green + Black	Printed Float Green
CULLET GRADE	Class C'	Class C'	Class C'
CONTAMINATION	Ceramic frits	Ceramic frits	Ceramic frits
CULLET TYPE	Shards	Fine Cullet	Coarse Powder
FORMIN TEMPERATURE	1120°C	1120°C	1120°C
			
HOMOGENEITY	High	High	High
TRANSPARENCY	Transparent	Translucent	Translucent
MOULD REACTION	Absent	Absent	Absent
CRACKS PRESENCE	Absent	Absent	Absent
BREAKAGE	Absent	Absent	Absent
BUBBLES LEVEL	Absent	Medium	High
			

As a first consideration, the given outputs of the tested specimens are distinctly influenced by specific factors. These are related by their composition and contamination conditions, along with the given cullet type related to the particle's size, and together with the undivided effects resulting in the introduced firing settings. Mold limitations are observed as an interaction incidence with some powder samples that may arouse glass contamination, which is really luckily to have altered the remelted material's properties. Consequently, the selection of a suitable steel mold would assist to steer clear of probable interactions with the powdered cullet. Given the aforementioned general considerations, the following remarks can be expressed.

The coated glass samples of defined composition and contamination rate present a quite similar output. Even if coatings are referred to as contamination; they were not able to affect the properties of the remelted specimens. The high formation temperature at 1120°C on the set firing schedule was enough to burn and vanish them without leaving any trace. However, a hue alteration is observed in the final products that may issue from either the glass or the compounds of the different coatings. This expresses the inevitable obstacle of flat glass recycling which is no other than color contamination. Finally, surface crystallization can be seen that arises either from mold reaction or the exposure to the air inside the kiln.

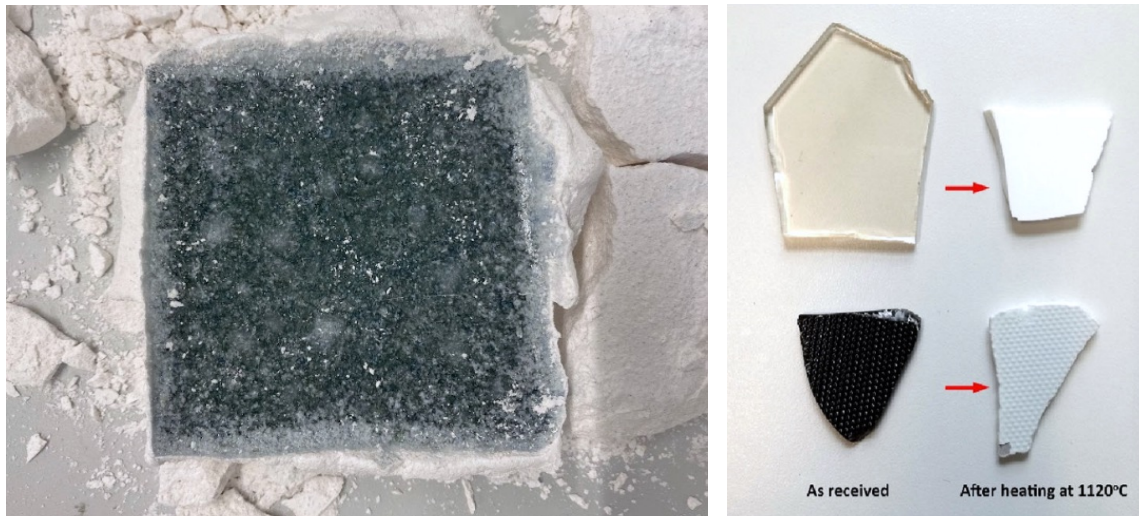


FIGURE 03.18 |

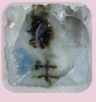
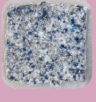
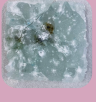
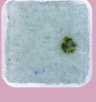
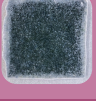
Powdered glass specimen's interaction with mold (left).
Glass ceramics transition from transparent condition to opaque under heat treatment (right), (Bristogianni et al, 2020)

As far as glass cullet with ceramic frits is concerned, a similar pattern can be also observed. In the case of sample BSI-s.02 with the Lacoble LT White cullet, the whole white frits were burned except for some residues of the coating in the bottom of the sample, which interacted with the mold. On the other hand, the green ceramic fritted cullet preserved color strikes owing to the partially molten localized frits of the shards. Additionally, the green frits turned out in blue traces, a piece of evidence that is verified by the XRF analysis that was held in the specific cullet sample. The source of this outcome is the fact that the primary frits of the glass waste contained in their composition are low amounts of chromium oxides that are responsible for the green coloration and a high amount of lead that assists in the tint alteration after melting.

Following a general observation of the kiln-cast specimens, all the powder consisted bodies concluded to similar outcomes. The decrease of the initial dimension of the cullet waste stretches the existence of contamination amount, along with the level, size, and density of entrapped bubble formation in the glass body. Moreover, the aforementioned reasoning contrasts the homogeneity of the resulting samples. These events can be seen also in the samples utilized with fine cullet types, but at a lower level.

In the experimental approach, three batches of combined cullet mix, coming from the recycling industry, are included. These are the sorting of glass, containing heat resistant pollutants, as the byproduct of rejection from the X-Ray sorter in the recycling line, cullet with metallic elements resulting from the deposition of the metal separator sorter, and finally glass with CSP fractions. These combinations provided by Maltha Company are not introduced to the waste-to-glass strategy, due to the undefined origin and high contamination rate that they carry.

TABLE 03.6 | Firing round I overview table.

SAMPLE INFORMATION					Homogeneity	Transparency	Cracks Absence	Breakage Absence	Bubbles Level Absence
BSI-s.02		Ceramic frits	Class B'	Shards	+++	+++	+++	+++	+++
BSI-s.03		Soft Coating	Class B'	Shards	+++	+++	+++	+++	+++
BSI-s.04		Soft Coating	Class B'	Shards	+++	+++	+++	+++	+++
CSI-s.01		Heat Resistant Glass (no ceramics)	Class C'	Shards	++	+++	+	+++	+++
CSI-s.08		Metallic Elements	Class C'	Shards	++	+++	-	-	+++
CSI-s.13		CSP Elements	Class C'	Shards	+++	+++	+++	+++	+++
CSI-s.15		Ceramic Frits	Class C'	Shards	+++	+++	+++	+++	+++
CSI-f.06		Heat Resistant Glass	Class C'	Fine Cullet	+	+	+	+	
CSI-f.07		Metallic Elements	Class C'	Fine Cullet	++	++	-	-	++
CSI-f.12		CSP Elements	Class C'	Fine Cullet	+++	+++	+++	+++	+
CSI-f.16		Ceramic Frits	Class C'	Fine Cullet	+++	++	+++	+++	++
CSI-p.05		Heat Resistant Glass	Class C'	Coarse Powder	+++	+	+	+++	+
CSI-p.10		Metallic Elements	Class C'	Coarse Powder	+++	++	+++	+++	+
CSI-p.11		CSP Elements	Class C'	Coarse Powder	+++	+++	+++	+++	+
CSI-p.14		Ceramic Frits	Class C'	Coarse Powder	+++	++	+++	+++	+

The combo of HR Float was tested in the three different cullet types, in order to check if homogenization of smaller particles could be carried out. In the case of powder, a degree of homogeneity was accomplished, accompanied by a surface cracking, noticed along with the whole tile form. Fine cullet specimen of the same batch concluded on a non-homogenized material. As it was unavoidable, the forming temperature was not enough to melt the fragments, and in the end resulted in a fused glazed batch form, which is then fractured due to the dissimilar density between the different pieces included in the combo, leading to the phase separation. Additionally, the heat resistant fragments transformed from the as-received transparent state to the later one that scatters the light and concludes in an opaque translation after the heat-treatment inside the kiln. The Mag Combi flat glass mix, due to the high contamination from ferrous and nonferrous elements, presents a high level of inclusions. This is observed in the shards and fine cullet version, which directly end up in the samples fracture. These verify also the forbiddance of such contamination from the glass industry. Speaking of which, the CSP glass cullet is likewise undesirable from the glassmaking manufacturing lines, due to the undefined composition and rate of critical elements, concluded in an unpredicted result. The specimen of the shard is homogenized with different colored traces, coming from coating and frits, along with various color streaks in the glass matrix.

All in all, with the execution of the first round of firings the most promising results are identified. For the evaluation, the samples are divided according to the first variable of the purity grade of the used cullet, and then these are distributed into three sub-categories according to the second variable, which is the size of the fragments. Before proceeding with the sample selection, the first step is the elimination of those that present breakage or a considerable rate of cracks. Specimens like CSI-s.08 and CSI-f.07, are characterized as inadequate, due to different compositions or thermal expansion between the various cullet. Subsequently, from its subcategory at least one of the most promising and interesting specimens is chosen for the next round, covering in this way all the probable grades and textures that the recycling glass stream can generate.

However, the most promising results aren't identified only with the best possible solution, but also the most challenging one. The main focus of this research is intended to reintroduce into the flat glass production the discarded cullet coming from every grade and texture. By selecting the most demanding one, but also favorable, the aforementioned target is achieved. Correspondingly, the sample BSI-s.02 with the ceramic frits is selected from the cullet grade B', owing to the extra challenge that the coating traits cause, compared to the rest. On the other hand, the selections of the specimens with cullet grade C' are the CSI-s.13 with material that came out of the second recycling run as mixed cullet containing CSP fragments, the CSI-f.06 with heat resistant flat glass, since it is a sample that differentiates from the rest of this category, which outcome is quite close to the ones of the coarse powder category where three samples were selected to gain further knowledge according to their different compositions of heat resistant (CSI-p.05), metal (CSI-p.10) and CSP (CSI-p.11) compounds.

Firing Round II

After the individual casting of the recycled glass specimens to identify their behavior under specific working temperatures, the abovementioned selection was made with the most suitable outcomes. These samples were used to test further the compatibility between different waste groups for the manufacture of the final combination on the panel.

Throughout the experimental research of this second round, the strategic approach to the fabrication of the thick-walled composite panel is attempted. After remelting completion, the selected samples, coming from the two purity grades of glass and diverse cullet types related to their size, are utilized for the formation of the resulted translucent component. On the one hand, the cullet of defined composition of pre-consumer use that contamination rate is known, is positioned on the outer skin surfaces, while on the other hand the undefined composition's glass with the uncountable contamination ratio of post-consumer use is placed inside. This deliberate coexistence of cullet arrangement between class B' and C' purity grade exploits an arrangement with advantage tensile strength on the recycled panel, which is transferred on the surfaces and reinforces the low-quality cullet in the bulk of the element and in extent it supports the whole composite panel.

The main priority of this stage is to observe the compatibility rate between the different glass waste groups to identify the most optimal result for the composite panel manufacture in the different compositions and the proper strength of the product, which allows for tolerating a higher degree of contaminants unaccompanied from any critical compromise to the object's properties.

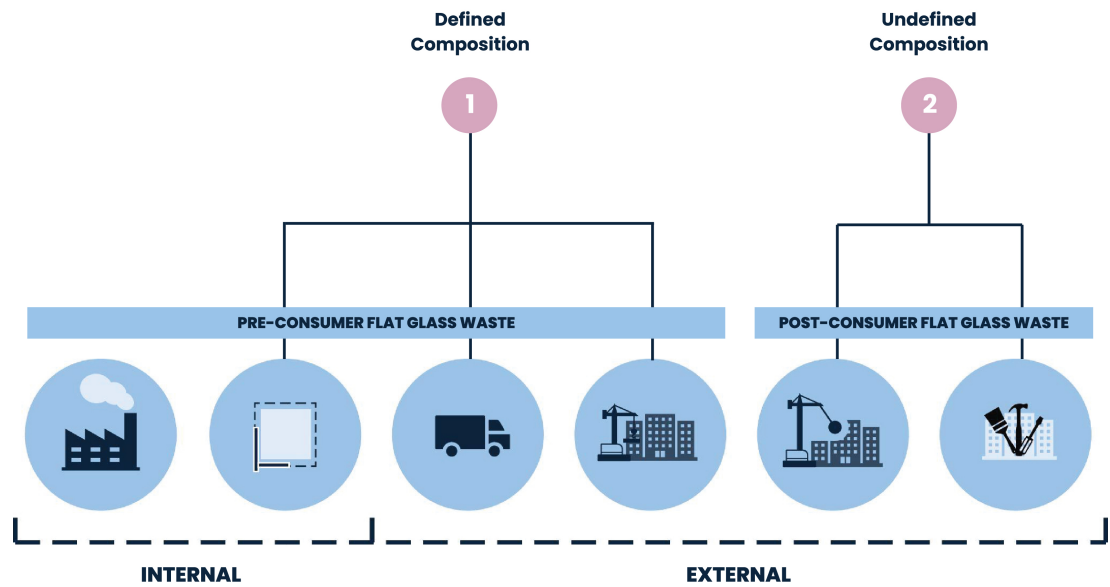


FIGURE 03.19 | Cullet's origin diagram according to its end-of-life phase within the life cycle.

This second round of firing tests has two different assumptions according to the position typology of glass layers inside the molds. The one covers the case that every layer is from glass cullets and the second refers to when two glass panes are positioned in the outer layers and the glass cullet in the inner one. The following illustration presents the layers set up before the firing process.



FIGURE 03.20 | Composite panel's layering set-up variations.

Lastly, the experimental process requires two different melting and annealing schedules. These tested the reactions of the composite specimens under different heat treatments, as a final evaluation before selecting the materials for the final panel's fabrication, while it also serves on the experiment efficiency related to the kiln's energy consumption. The first kiln setup is slightly different from the firing schedule utilized in the previous round since they are sharing the whole process profile, but only the maximum temperature is decreased to 1070°C. Similarly, the second schedule is just altered in the forming temperature, which is even lower at 1000°C and the dwell time is set at 4 hours.

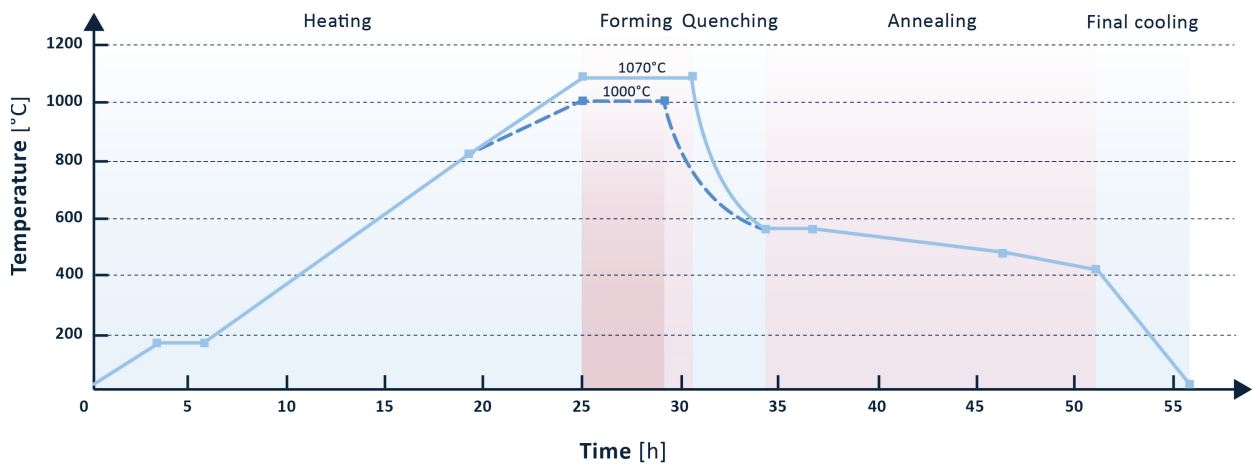
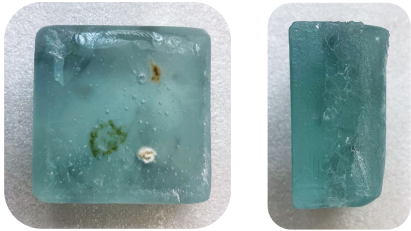
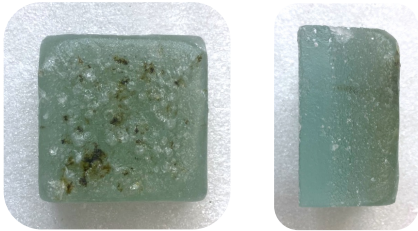
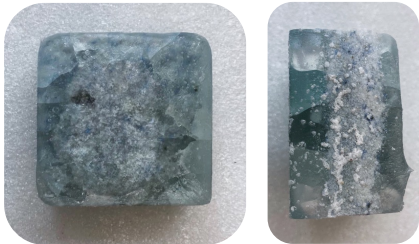
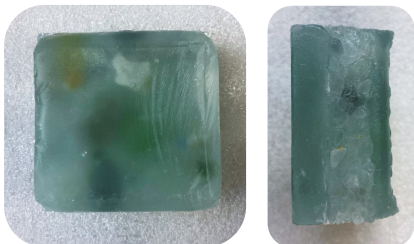
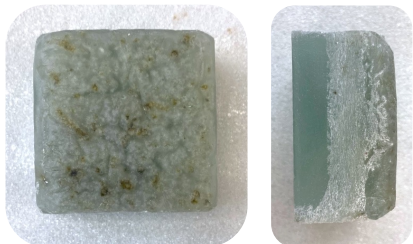
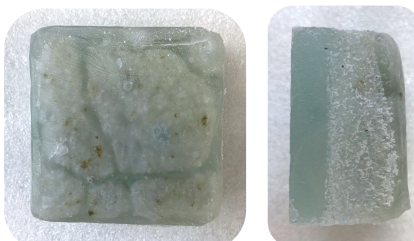


FIGURE 03.21 | The firing schedules and casting phases utilized for the testing of composite samples.

TABLE 03.7 | Detailed overview of the kiln-cast composite specimens produced by the second round of firings under the two similar firing schedules.

SAMPLE CODE	ACSI-ps.20	ACSI-pp.21
PRODUCT CULLET GRADE CONTAMINATION CULLET TYPE FORMIN TEMPERATURE	Float Glass + Combi CSP Float (Maltha) Class B' + C' Float Glass + CSP Pollutants Sheet + Small shards 1070°C	Float Glass + Combi Mag Float (Maltha) Class B' + C' Float Glass + Metallic Elements Sheet + Coarse Powder 1070°C
		
COMPATIBILITY TRANSPARENCY MOULD REACTION CRACKS PRESENCE BREAKAGE BUBBLES LEVEL	High Translucent Absent Absent Absent Medium	Medium Opaque Absent Absent Absent High
		
SAMPLE CODE	ACSI-pp.22	ACSI-pf.23
PRODUCT CULLET GRADE CONTAMINATION CULLET TYPE FORMIN TEMPERATURE	Combi CSP Float (Maltha) + Combi HR Float (Maltha) Class B' + C' Float Glass + Heat Resistand Glass Sheets + Coarse powder 1070°C	Printed Float Green Class B' + C' Float Glass + Heat Resistand Glass Sheets + Fine Cullet 1070°C
		
COMPATIBILITY TRANSPARENCY MOULD REACTION CRACKS PRESENCE BREAKAGE BUBBLES LEVEL	Absent Opaque Absent High Probable High	Absent Opaque Absent High Probable Low
		

SAMPLE CODE		ACSI-ps.24		ACSI-pp.25	
	PRODUCT	Float Glass + Combi CSP Float (Maltha)		Float Glass + Combi Mag Float (Maltha)	
	CULLET GRADE	Class B' + C'		Class B' + C'	
	CONTAMINATION	Float Glass + CSP Pollutants		Float Glass + Metallic Elements	
	CULLET TYPE	Sheet + Small shards		Sheet + Coarse Powder	
	FORMIN TEMPERATURE	1000°C		1000°C	
					
	COMPATIBILITY	High		Low	
	TRANSPARENCY	Translucent		Opaque	
	MOULD REACTION	Absent		Absent	
	CRACKS PRESENCE	Absent		Absent	
	BREAKAGE	Absent		Absent	
	BUBBLES LEVEL	Low		Low	
					
SAMPLE CODE		ACSI-pp.26			
	PRODUCT	Combi CSP Float (Maltha) + Combi HR Float (Maltha)			
	CULLET GRADE	Class B' + C'			
	CONTAMINATION	Float Glass + CSP Elements			
	CULLET TYPE	Sheets + Coarse powder			
	FORMIN TEMPERATURE	1000°C			
					
	COMPATIBILITY	Low			
	TRANSPARENCY	Opaque			
	MOULD REACTION	Absent			
	CRACKS PRESENCE	Absent			
	BREAKAGE	Absent			
	BUBBLES LEVEL	Low			
					

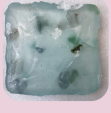
SAMPLE CODE		BCSC-sp.17	BCSI-ss.18	ACSI-ps.19
INPUT	PRODUCT	Lacobel LT White (AGC) Combi HR Float (Maltha)	Lacobel LT White (AGC) Combi CSP Float (Maltha)	Float Glass Combi CSP Float (Maltha)
	CULLET GRADE	Class B' + C'	Class B' + C'	Class B' + C'
	CONTAMINATION	Lacquire Coating + Heat Resistant	Lacquire Coating + CSP Pollutants	Float Glass + CSP Pollutants
	CULLET TYPE	Shards + Powder	Shards	Sheet + Shards
	FORMIN TEMPERATURE	1070°C	1070°C	1070°C
				
	COMPATIBILITY	Low	High	High
	TRANSPARENCY	Opaque	Translucent	Translucent
	MOULD REACTION	Absent	Absent	Absent
	CRACKS PRESENSE	High	Absent	Low
	BREAKAGE	Probable	Absent	Failure
	BUBBLES LEVEL	High	Absent	Absent
				

As a general observation, the resulting outputs of the composite specimens were distingly influenced accordingly by the samples of the first round of firings. These are associated once again by their composition and contamination rates and type, the given particle's size, whilst evident differences are presented between the samples that underwent both firing schedules. Given those general considerations, the following considerations can be reported.

Generally, the outer layers behaved in the same way as the aforementioned assumptions, no matter the size of the waste glass positioned on the bottom and top surfaces, being a pane or just shards, or the kind of contamination. The most important influence factors were the composition of the inner layer and the size of the cullet. Apart from the firing settings, powder in every sample has a general direction to penetrate inside the top layer trying to escape from the objects' forms. This is probably associated with gravity, where the heavier matter is moving downwards. Consequently, the powder is not the most suitable example for the application of such a composite object. At least when it is formed with this specific method.

With regards to the heat-resistant glass combination, the result was predictable according to the first tests on the different wastes that were melted individually. Due to the high-temperature difference in the thermal expansion coefficient of the three layers, the composite failed, concluding in multiple cracks on the top surface of the object. Additionally, the variation in the density of the cullet contributes greatly to the phase separation of the glass layers.

TABLE 03.8 | Firing round II overview table.

SAMPLE INFORMATION						Compatibility	Transparency	Cracks Absence	Breakage Absence	Emersion Absence
BCSI-ss.18		Lacquire Coating + CSP Pollutants	Class B' + Class C'	Shards + Shards	1070°C	+++	++	+++	+++	++
ACSI-ps.19		Flat Glass + CSP Pollutants	Class B' + Class C'	Sheets + Shards	1070°C	+++	++	+++	-	+++
ACSI-ps.20		Flat Glass + CSP Pollutants	Class B' + Class C'	Sheets + Small Shards	1070°C	+++	++	+++	+++	++
ACSI-ps.24		Flat Glass + CSP Pollutants	Class B' + Class C'	Sheets + Small Shards	1000°C	+++	++	+++	+++	+++
ACSI-pf.23		Flat Glass + Heat Resistant	Class B' + Class C'	Sheets + Fine Cullet	1070°C	-	+	-	+	++
BCSC-sp.17		Lacquire Coating + Heat Resistant	Class B' + Class C'	Shards + Coarse Powder	1070°C	+	+	+	+	+
ACSI-pp.21		Flat Glass + Mettalic Elements	Class B' + Class C'	Sheets + Coarse Powder	1070°C	++	+	+++	+++	+
ACSI-pp.22		Flat Glass + Heat Resistant	Class B' + Class C'	Sheets + Coarse Powder	1070°C	-	+	-	+	-
ACSI-pp.25		Flat Glass + Mettalic Elements	Class B' + Class C'	Sheets + Coarse Powder	1000°C	+	+	+++	+++	+
ACSI-pp.26		Flat Glass + CSP Elements	Class B' + Class C'	Sheets + Coarse Powder	1000°C	+	+	+++	+++	+

All in all the most successful effort is coming from the CSP float glass. The samples were firstly tested in the most promising firing schedule. However, it was evidenced that the composite can be remelted at a more efficient and relatively low temperature for less time, set up at 1000°C. The outcome pictured a better result as far as bubble generation is concerned but also in a more translucent state.

Firing Round III

After the whole experimental research, the optimum glass waste along with the lower forming temperature was identified. The information, as it is explained previously, came from the series of tests held in the different composite schemes with the selected glass size. Main the purpose is the generation of the intended composite glass panel, coming from recycled glass waste of the C&D cullet.

Subsequently, float glass of purity grade B' and CSP Glass combination of class C' are picked for the outer layers and the inner ones respectively. As a consequence of the undefined composition and contamination rate of CSP glass, different compounds are probable to result in different outcomes in the color of the glass sample after the cullet's remelting.

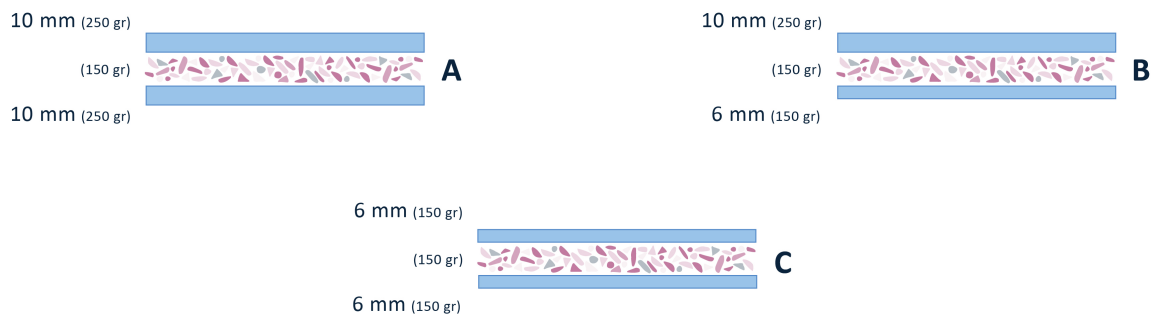


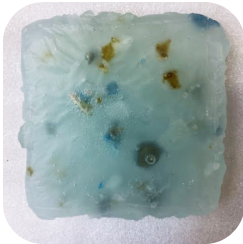
FIGURE 03.22 | Specimens variations on the thickness of the outer panes.

To obtain further knowledge of the compatibility of the glass layers a next firing set-up was recommended. This time the specimens were made in the size of a tile, dimensioned 10 mm by 10 mm, for further exploration and optimization of the panel fabrication. The firing schedule was maintained at 1000°C as the higher temperature for 4h and annealing stayed at 560°C.

In the current firing schedule, an effort was made to gain knowledge about the form of the recycled panel. Each tile has been formed out of three alternative assumptions. Through testing, the needed understanding of specimens' thickness and the most efficient product setup is obtained. This is related to utilizing thickness alterations of the outer layers of a glass pane, while on the inside of the composite the same cullet proportion is positioned to distinguish, which assumptions can contain the corresponding contamination rate of the recycled batch cullet. The specimen setup is illustrated in the following picture.

Through testing, the needed understanding of sample behavior allows for generating the proper firing series of steps that would correctly warm and chill the object inside the oven. The main target is to cause on the glass body the particular conditions that are able to be formed and then guide it to the ambient temperature in a fixed state without any risky internal stresses.

TABLE 03.9 | Detailed overview of the kiln-cast composite specimens of float glass and CSP cullet of different thicknesses.

INPUT	SAMPLE CODE	ACSI-ps.27	ACSI-ps.28	ACSI-ps.29
	PRODUCT	Float Glass + Combi CSP Float (Maltha)	Float Glass + Combi CSP Float (Maltha)	Float Glass + Combi CSP Float (Maltha)
	CULLET GRADE	Class B' + C'	Class B' + C'	Class B' + C'
	CONTAMINATION	CSP Pollutants	CSP Pollutants	CSP Pollutants
	CULLET TYPE	Sheet + Small shards	Sheet + Small shards	Sheet + Small shards
	FORMIN TEMPERATURE	1000°C	1000°C	1000°C
				
	Outer Layer Thicknesses	10 mm – 10 mm	10 mm – 6 mm	6 mm – 6mm
	Total Weight	650 gr	550 gr	450 gr

The experiments were remelted through three principally similar firing schedules, with small alterations occurring between them, on the forming temperature and its dwell time. In the beginning, a specific program was set where all the glass waste was tested individually for its fluidity and homogeneity. The reason that this happened was that the final product has to do with a composite between the different purity grades of the cullet. After this, the most successful materials were tested for their compatibility between them in two different schedules in order to distinguish the most optimal result and proceed in the final panel's formation.

The specimens quoted in the table are the outcome of this recycling scientific exploration. According to the findings, all of the thicknesses can be used according to the consumer's needs. However, in favor of the most flattering result, the second set-up would be ideal, wherein the bottom a layer of 6 mm thick pane can be used, since it can be preserved untouched, maintaining its initial thickness while at the top layer a pane with a thickness of 10 mm seems to be appropriate, in order not to let any contamination to emerge on the top surface.



FIGURE 03.23 | The translucent composite tile from recycled glass waste in front of a light source.

All in all, the final tested outputs are examined and tested further. A qualitative examination of the defects and a stress analysis are held along with thermal shock testings to evaluate from every possible observation point the specimen for the most efficient result within the available time frame of the research. The verification of the final product takes us a step further to fit into the glass-to-glass circular strategy.

02.4 DEFECT EVALUATION

When the fabrication of the various specimens is complete, the outputs demand a qualitative analysis. This inspection is made for the detection of residual stresses and any defects' presence, occurring in the kiln-cast objects. The scope of the current examination is in the first place to identify the location and the pattern of the critical faults, which need extra attention to be given, and then the documentation of them.

The flaws findings are capable to assist in the correlation of them, observed in the glass source and followed casting process and post-processing, which consequently affect the samples' failure stresses (Bristogianni et al., 2020). In essence, numerous blemishes could be encountered in casted glass products. On the one hand, the casting flaw outputs are caused by the set casting schedule across the surfaces and the bulk of the glazed products. On the other hand, the phase of post-processing, just like cutting, drilling, edge processing, and polishing, and together with handling with combination to the predisposition of each glazed object are probable to result in their damage and probably their failure.

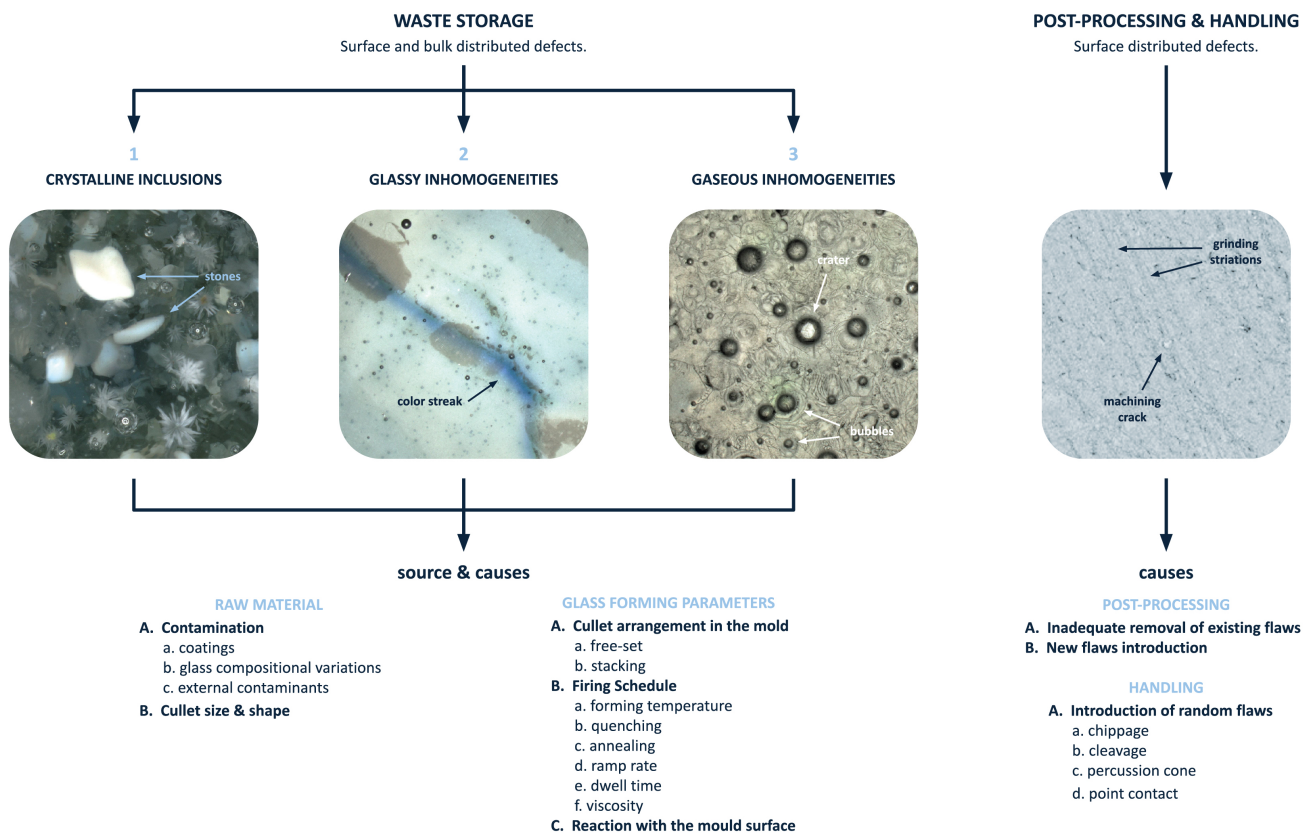


FIGURE 03.24 | Categorization and causes of the defects encountered in the kiln-cast glass specimens, based on (Bristogianni et al, 2020)

A device of VHX-700 Digital Microscope was used, accommodated by the visual review of the specimens' surface, intending to perceive flaws and any breakage mechanisms that may lead to failure. Firstly the related faults are presented and then they are evaluated as claimed by the caused influence on the kiln-cast samples. The effects are divided as follows, based on Aldinger and de Haan (2019):

- **Stress increasing:** the flaws, which generate stresses in the glass adding to stress linked to adjusted loads. Defects like this one are either located either on the surface or the bulk of the glass.
- **Strength reducing:** such flaws dop the glazed products' strength, whilst they are primary regarding glass outer skin layer.

Moreover, the flaws linked with the casting method are classified into three groups, according to T. Bristogianni(2020):

- **Crystalline Inclusions**
- **Glassy inhomogeneities** (such as cords/ream and stones)
- **Gaseous inhomogeneities** (bubbles and craters)

Additionally the post-processing and handling defects on the samples surfaces are evaluated.

An overview of the different defect typologies is provided in figure 04.9, which were found on the casting samples during firing or machining and handling.

Crystalline Inclusions

As it is explained in the previous chapter, the cast glass outcomes are made from either purity grade B' glass which was remelted individually as a single batch or cullet class C' that was collected from the rejection of the recycled industry of float glass. In the former case, the contamination occurs owing to the used variables for the experiment, referred to thermal history, utilized mold and glass type related to the particles sizes. Simultaneously, the latter stream of post-consumer used recycled glass gives emphasis on the contaminants' influence on the flaws generated during firing. This cullet is accompanied by numerous undesired pollutants for glassmaking, such as float glass variations originating from different manufacturers or compositions, coatings, ceramic frits, lamination layers, metallic elements, and finally ceramic-stone-porcelain fragments.

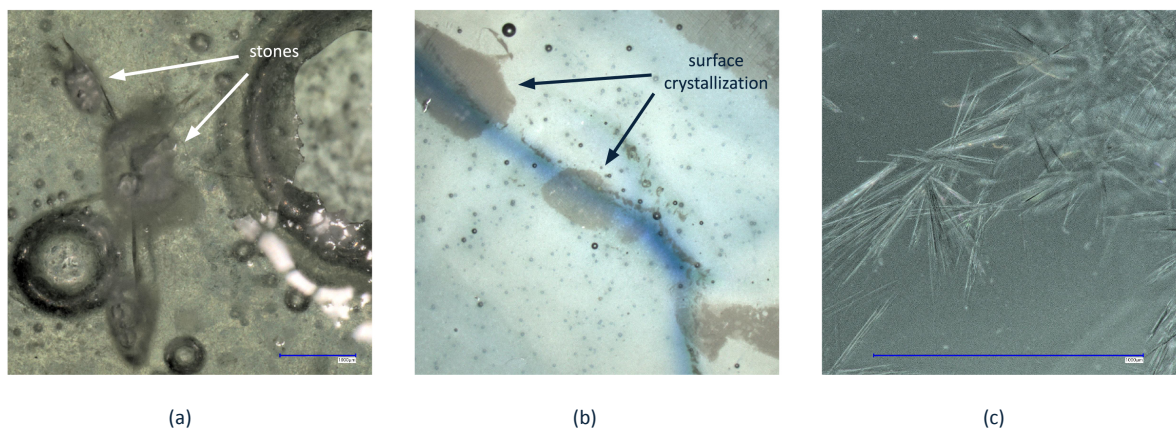


FIGURE 03.25 |

(a) Stones due to contamination, (b) Crystalline fusion interface pattern along with the burned coatings remnants, and (c) Devitrite crystal formation in the middle of the glass bulk.

Stones can be met both on the surface of a glass object as it can be seen in figure 04.10a or its inner body of it. These types are linked with the existence of contamination. Surface crystallizations are incurred as well in the two aforementioned zones of the glass. Crystalline fusion interface patterns (b) refer to surface generation exposed to the air inside the kiln and reacted usually with the presence of a contaminant (Ceramic fritted float glass in green color, "BSI-s.15", with forming temperature 1170°C). Simultaneously, this type (c) can be formed also in the bulk zone of the specimen (composite sample "BCSI-ss.18", formed at 1000°C). The category of crystalline inclusions on the surface or the bulk of the glass body could also be formed in variations, as it is presented in figure 04.11 where two possible patterns are collocated. These reactions are influenced by the variation in each case condition that every specimen batch contains.

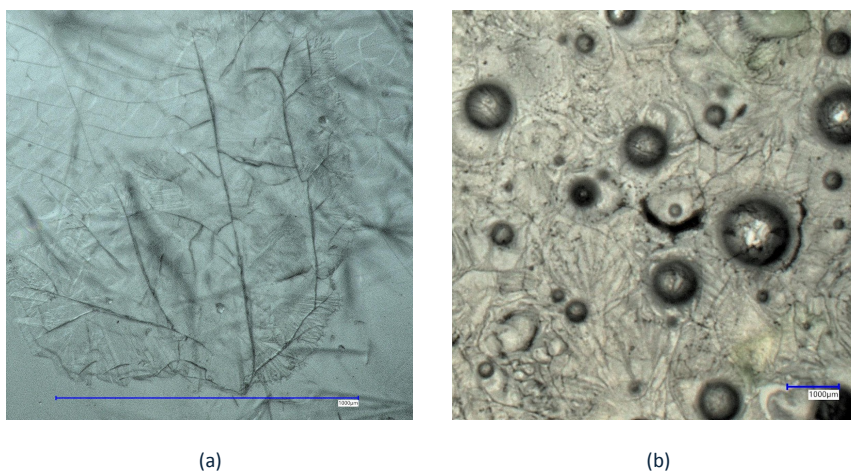


FIGURE 03.26 |

Surface crystallization variants: (a) Crystalline interface of typical formation, and (b) Voronoi-like patterns of the crystalline interface.

Glassy Inhomogeneities

As far as glassy inclusions are concerned, they arise with the existence of many contamination typologies. Such pieces of evidence were traced in the casting products that were formed along with the selected high casting viscosities. These are referred to either on color variations between the glass fragments, minor compositional alternatives throughout the recycled cullet from different glass applications or manufacturers, and the various combinations between them while the glass melts or due to external pollutants such as coatings and the presence of metallic particles. Even if characteristics of the cullet, like the size, shape, and origin, affect the homogenization of the glass material, the shape, and the optical quality of the located glass inclusion, non of the produced specimens display any weakness or fracture owing to their display of such blemishes. The latter case is even the same in the subtle inhomogeneities caused by coatings in the form of the colored trace as it can be seen in figure 04.12c or metal and iron chemical reaction generating color sacks in the bulk of the glass sample in the case on the figure 04.12b.

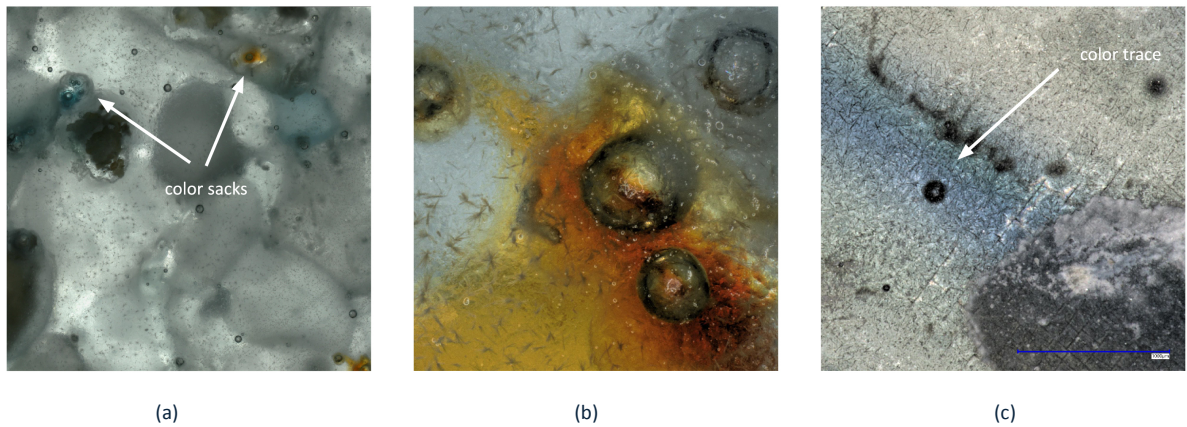


FIGURE 03.27 |

- (a) Different color streaks presented in the glass body due to different tints on the cullet in the CSP batch,
 (b) Color sack caused by the presence of metallic element in the glass mix, and
 (c) Color cord of ceramic fritted cullet, originally of green color before remelting.

Gaseous Inhomogeneities

During the current experimentation, every specimen produced through kiln-casting displayed minuscule bubble formation, in some cases to a lesser and others to a greater extent. This is caused due to several observed causes. The listed origins of bubble generation are the entrapment of gaseous air into the batch of cullet pieces or powder granules, chemical reactions in response to the cullet bonding and vaporization of volatile pieces contained in the melted batch, and reactions and incomplete melting of ceramics, stones, porcelain and metallic inclusions (Bristogianni et al., 2021). An overall observation of the former bubble origin is that the finer the cullet size, the greater the formation rate of enclosing air and gas bubbles (fig. 04.13). Whilst any clustering formation of gas-pockets in the glass matrix can be observed owing to the free-set placement of the cullet.

Moreover, the firing schedule operated for the remelting of the various specimens possesses a crucial role in the prevention of bubbles generation according to the selected formation temperature that influences the viscosity of the glass and also the annealing point. These could be characterized as insufficient due to low forming temperature and small dwell periods that create extended zones that enable gases to be trapped and undesired fusion to be formed along with the specimens' interfaces. In general, the bubble formation could be proceeded as critical for the glass element, since it affects the final output's strength, but it is also possible to impair it when they are located at the surface of the object (Bristogianni et al., 2021). However, in contrast to the negative result on the strength of the glass object, this event can also be proved as advantageous within the molten material, because bubbles formation and their motion upwards assist in the convention and glass mixture homogenization between the cullets (Nemec, 2008).

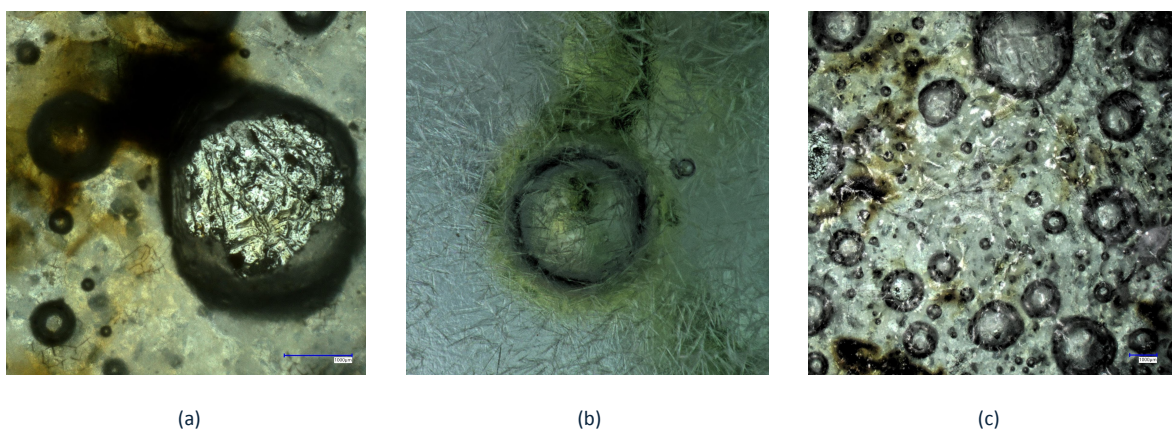


FIGURE 03.28 |

- (a) Crater generated on the surface of the kiln-cast sample by a broken bubble,
 (b) Colorized bubble in the middle of the glass body, and (c) Bubble generation in specimen made by the combi Mag powder.

Post Processing

Along with the factors that influence the glass elements' damage and failure stresses is the flaws generation on the objects due to post-processing. This is divided firstly into the inadequate removal of the existing defects and the introduction of new blemishes caused by the processing.

The former is referred to as the unsuccessful attempt at surface flaws removal since not all of them can be sufficiently and fully ground. For instance, the glass surface in touch with the mold's material often creates a localized thin crystallization layer, which can be effortlessly removed, while in contrast some mold reaction imperfections are extending far deeper on the bulk of the glass sample and maintain upon the surface grinding, owing to occasional incorporation in the melt or complete fusion between the glass pieces. Moreover, localized or network infolds can be formed with the exposure of the entrapped bubbles in the glass body after grinding, adding increased risks to the strength reduction.

Meanwhile, the post-processing also introduces faults that may cause damage or even worse the glass object's breakage. This is observed in glass areas with lower hardness compared to neighbor melted cullet into the same sample. None of the present blemishes unveiled after grinding and polishing on the processed samples introduce any critical stresses of high-energy that could be proved critical for failure. Nevertheless, an interesting observation is made in low-energy stress generation during grinding that creates minor cracks on the composite specimens. These are limited only to one of the panel's layers and there is no crack propagation to the rest, indicating that the sample does not react as one entity from the moment that is not fully fused. In the case of low loads could mean that the produced cast glass component behaves as laminated glass, something that could also be considered a safety characteristic of the product.

Handling

During the handling of glass components, various blemish types (chipping, cleavage, percussion cone, point contact) can be introduced. At the moment there is no extended investigation on the cast glass specimens handling compared to the industrially made float glass. Notwithstanding, additional observation and research should be given to the products that contain contamination, just like in the composite panel case, since accidental flaws on such a component's surface that are greater than 2mm, increase the consequences of an impact that may result in failure (Bristogianni et al., 2020).

02.5 QUALITATIVE STRESS ANALYSIS

Just after the trace of the various defects and their generation source, an inspection was made with the aim of the visual method of photo-elasticity, introduced by crossed polarized lenses and the inherent transparent and birefringence characteristics of glass. This examination of the glass specimens presents any residual stresses located in critical points in the object's matrix, revealing optical anisotropy through colored stress patterns.

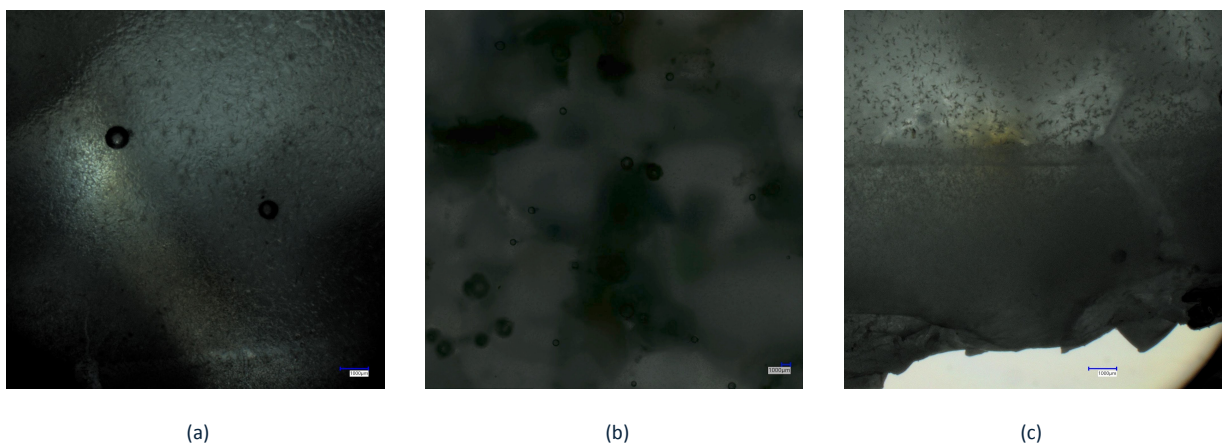


FIGURE 03.29 |

(a) Minor residual stress located in specimen ACSI-ps.27,

(b) No stresses are observed along the whole body of ACSI-ps. 28, and

(c) Minor residual stress was noticed, in sample ACSI-ps.29 close to the edge of the tile with a volume smaller than 1000 μ m.

The tested samples have a variety of flaws related to casting and post-processing that do not generate stress augmentation. As far as the final specimens of round III are concerned three flaw types appear to sporadically

induce stresses, related to first cords between two dissimilar glass recipes fragments, secondly with external bodies such as small particles of ceramic-stone-porcelain contamination, and lastly crystalline interfaces in fused cullet. Nevertheless, these stresses are not introduced as ample to cause and lead to local or general failure in the specimens, especially in the cases where the thermal expansion coefficient of different compositions acts with other kinds of stresses. Even in the spectrum of metal particles inclusions, coating residues, bubbles, and craters, no stress is observed in the glass tiles' bodies.

However, a more in-depth inspection would be in need in order to evaluate the influence of the defects. A bending test setup would assist to comprehend further their result in the cast glass products and recognize the tolerable from the critical blemishes. Finally, that could point out methods to keep away from the failure incidence.

02.6 THERMAL SHOCK RESULTS

The thermal failure of a glass element responds as an outcome to significantly uneven temperature alterations across different zones of the object. Under the effect of sun radiation, favorable conditions are created for the generation of tensile stresses causing failure to glass, such as cracking or breakage, under certain exceptional values.

In the contents of my experimental research, the application of thermal loads is deemed as a requisite verification of the recycled panel in order to imitate any failure caused by a thermal shock in practice. Even in most safety codes, no assumption has been made on standards to foresee heat fracture (Anastasiou, 2016). The context of this paragraph indicates the results from the thermal test, while an overview can be found in the following table.

Every simulation under consideration in the current experimentation can be assumed as the closest to the real case scenarios with an extreme temperature difference (ΔT) at 60°C. At the beginning of the experiments the first method of thermal shock that the specimens should be pre-warmed, was used with the series of the unprocessed tiles from the C&D cullet and the pure glass to simulate the needed conditions. However, due to the fact that the second group of tiles treated with UV coating was not allowed to be placed and pre-heated into the oven, since they contained chemicals. Consequently, the alternative of the reversed thermal shock method of upshock was utilized, repeating from the very start of the experimentation.



FIGURE 03.30 |
The composite sample unprocessed (left), and the composite sample after the post-processing of surface and edge treatments with grinding, polishing, and the addition of UV coating for extra strength (right).

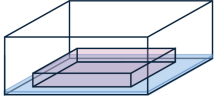
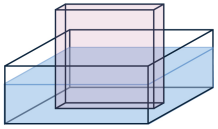
Set-up T_1 and T_2 of the tests reproduce the warm facade's element resistance to rainfall during a hot summer day. Along with the former test with the spraying on the one surface of the samples, none of the tiles of the unprocessed and processed group presented any weaknesses. During the T_2 evaluation with the one-side immersion, the outcome looked to be intact again for all of the tiles, at least in the beginning. However, a day

later, minor cracks can be observed in the outer layers that were immersed in the water of the composite tiles with the C&D cullet of the unprocessed group, starting from a central point at their edges.

In general, the pattern of the breakage can reveal information about the magnitude of the stresses, their source, or either the type of implemented glass. Based on that, the crack can be characterized as low energy release breaking, starting from the edge of the tile and positioned perpendicular to it. Such damage is usually related to edge imperfections or the absence of any treatment, carrying lower resistance to thermal breakage compared to clean-cut edges, and consequently greater risk for failure (Mognato et al. 2013). To an extent, micro-cracks are really probable to grow their dimensions up to a critical flaw and fail, due to their insufficient rate of tensile strength (Anastasiou, 2016). Nevertheless, the fact that the unprocessed pure cullet sample didn't present any flaw, increases the probability that the generation of the cracks on the composite tiles arises from the material weakness of the recycled glass.

As far as specimens T_3 is concerned, this set-up was designed to simulate unique conditions against thermal failure. This could be related to a window panel in contact with snow and heating operation on the inner side of the building or in the case of shading attached to the panel. In any case, the exposed areas soak up solar radiation, and immediately an uneven temperature alteration is created across the uncovered area and the rest of the pane which is cooled either by the contact with the snow or the shade.

TABLE 03.10 | Results of thermal shock set-up tests with temperature difference (ΔT) at 60°C, based on (Oikonomopoulou, 2019)

Temperature Difference ($\Delta T = 60^\circ\text{C}$)		T_1	T_2	T_3
				
Unprocessed Samples	Pure Glass	No cracks generation.	No cracks generation.	Perpendicular to the edge low-energy cracking on the immersed side, in one layer.
	Recycled Glass Composite	No cracks generation.	Perpendicular to the edge low-energy cracking on the immersed side, in one layer.	Perpendicular to the edge low-energy cracking on the immersed side, in one layer.
Processed Samples	Pure Glass	No cracks generation.	No cracks generation.	No cracks generation.
	Recycled Glass Composite	No cracks generation.	No cracks generation.	Minor cracking of low-energy in one point on the tile and limited within a layer.

According to this test where the sample is positioned perpendicular half immersed in the hot water, some interesting observations were made. All the unprocessed specimens presented cracking limited between one layer. More specifically, the pure glass cullet showed some micro-cracks in the first minutes of the evaluation, while the most considerable cracking took place in those samples of the composite set-up, observed only in the division that was immersed inside the boiled water. In the latter, the cracks continued to partly grow perpendicular to the edges just after they were shifted to the colder water. Only in one specimen, the crack propagates in the middle layer of the composite where a stone was located. On the contrary, the processed tiles with the coating addition in first look didn't generate any cracking, remaining untouched, after the testing concluding that the surface and edge treatment along with the coating acted positively on the thermal resistance of the tiles. Just a day later, two tiles of the C&D composite unveiled a micro-crack in only one point which was located vertically on the edge.

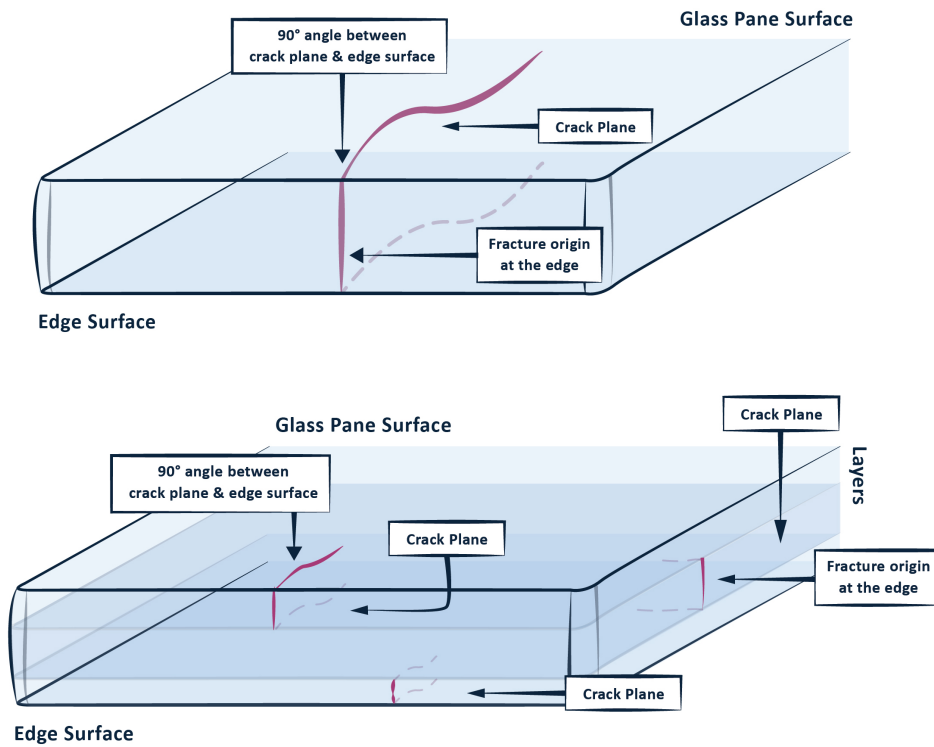


FIGURE 03.31 |

Low energy release thermal breakage patterns in one layer glass tile (top), and in a composite tile of multiple layers, based on (Mognato et al., 2013).

All in all, the developed tensile stresses generated on the sample layering are mostly linked with the critical points where defects exist, especially stones and glass recipe alterations. However, in most of the cases that the samples experienced low-energy impact did not present adequate stresses to activate the micro-cracks and finally lead to breakage failure. Moreover, thermal shock tests present a similar observation on the cracking behavior on the tested composite panels. The minor cracks are restricted in one layer again and they are not propagating in the neighboring layers. Due to the fact that the glasses are not fully fused between them, they function in a way as a layered composite after remelting. Proving and verifying the observation of the cracking pattern during the post-processing of the samples that was mentioned in the previous chapter about flaws evaluation. Lastly, the extra edge and surface working and especially the additive coating significantly assist in the prevention of stress generation to a rapid temperature change, indicating benefits to the safety characteristics of the panels.

03 | EXPERIMENTAL FINDINGS CONCLUSION

The main objectives of the current experimental research are first to point out the different combinations that can create a composite panel fully made by C&D glass waste, as a cast glass element for building applications, and secondly utilizing tools and methods to evaluate and verify the product's performance. An overall approach, which intends to highlight the promising latent qualities of rejected flat glass waste in new the same product. A material that is proved through the experiments valuable but is still considered as waste and almost consistently is kept out of the recycling loop of glassmaking.

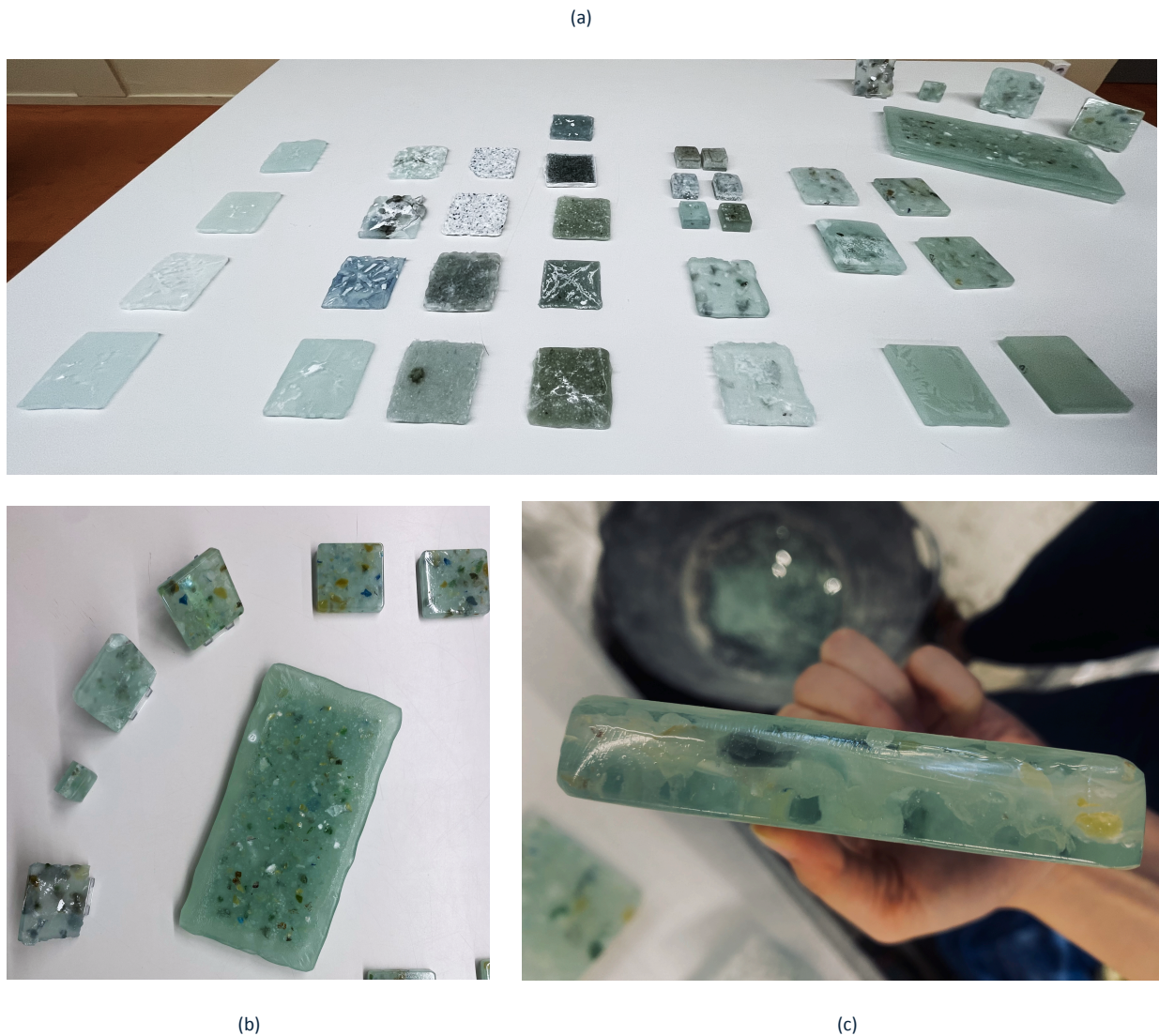


FIGURE 03.32 |

Produced samples during the experimental research.

(a) Samples collection, (b) process evolution findings for the production of the composite tile with CSP mixed cullet, and (c) Side view on the a post-processed composite panel.

Various attempts have been implemented to point out the potentialities of float glass waste, establishing a direction for future research and experimentation. The approach was achieved through numerous **firing test results** in relatively low temperatures compared to the float glass industry, varying from 1000 to 1120°C as a more sustainable and efficient strategy. The outputs were evaluated, firstly, according to their viscosity, and fluidity of the individual streams with cullet of all the different purity grades, coming from the recycling facilities of glass, and then on their compatibility of the combination of cullet classes on the composite samples. The obtained experimental results are influenced in particular by specific factors related to the recycled cullet composition and contamination conditions, the given particle's size of the used cullet, and the undivided effects resulting from the established firing settings, while limitations are observed from the utilized molds as an interaction incidence with some powder samples that may arouse glass contamination. All and each of the

aforementioned conditions deemed luckily to implement alterations on the properties and characteristics of the remelted specimens results.

Considering the abovementioned prevailing considerations, some main observations on the individual streams and general remarks on the tested samples can be voiced.

- The defined composition and contamination cullet of class B' covered with diverse coatings present a quite similar output with a homogenized and transparent result.
- Even if coatings are referred to as contamination; they are not able to affect the properties of the remelted specimens, since they are burned and vanished in the forming temperature at 1120°C. Only an alteration in the color tint is observed on the fired samples that may issue from either the glass or the compounds of the different coatings, expressing the concerns of the industry to accept them under specific rates since they may be referred to as color contamination.
- As far as glass cullet with ceramic frits is concerned, a similar pattern can be also observed. In these cases, most of the frits are burned to leave behind traces of either color contaminations, related to the compounds used on the particular cullet, or coating residues that interacted with the utilized mold.
- On the contrary, cullet mix coming from the recycling streams that the composition is undefined together with uncountable contamination rate, present diverse results in viscosity, homogenization, and transparency of the end result.
- Following a general observation of the kiln-cast specimens, all the powder consisted bodies concluded to similar outcomes. Even is coarse powder samples presented to be the most suitable one in terms of homogenization, the decrease of the initial dimension of the cullet particles stretches the existence of contamination amount.
- Similarly, the cullet size is linked with the level, size, and density of entrapped bubble formation in the glass body. The smaller the particles, the higher the generation of air pockets.
- The combo containing heat-resistant glass fragments, under the form of fine cullet, alters its amorphous phase transforming to a crystallized outcome under the temperature of 1120°C, that scatters the light and concludes in an opaque translation after the heat-treatment inside the kiln. This forming temperature is not enough to melt the cullet, and in the end, resulted in a non-homogenized but fused glazed form.
- Mixed cullet with ferrous and non-ferrous elements, present a relatively high amount of inclusions related to the biggest size of cullet.
- The CSP cullet mix, even in the form of cullet shards, presents a homogenized result with different colored traces, coming from coating and frits, along with various color streaks in the glass matrix. However, this type is based on a matter of luck since if cullet of different thermal expansion is placed into the batch, it is possible to jeopardize the remelted output.
- Surface crystallization can be seen in most of the specimens that arise either from mold reaction or exposure to the air inside the kiln.

Throughout the experimental research of the first round, and the focus on bringing into the glassmaking loop of flat glass the most challenging cullet grade C', the idea of the composite panel attempt, as a strategic approach to the fabrication of the thick-walled composite panel, arose. Starting as an exploration with interesting results at the end of the experimental process. This deliberate coexistence of cullet arrangement between class B' and C' purity grade exploits an arrangement with advantage tensile strength on the recycled panel, which is transferred on the surfaces and reinforces the low-quality cullet in the bulk of the element and in extent it supports the whole composite panel. Accordingly, the following promising achievements are presented.

- The resulted outputs of the composite specimens are distingly affected by utilized cullet characteristics related once again with their composition and contamination rates and type, and the given particle's size, whilst evident differences are presented between the samples that underwent both firing schedules.
- The most important influence factors are the characteristics of the inner layer with the undefined composition cullet.
- Coarse powder placed in the middle layer has a general direction to penetrate inside the top layer trying to escape from the objects' forms. This is probably associated with gravity, where the heavier matter is moving downwards.
- The heat-resistant glass mix, regardless of the particle size if it is a shard, fine cullet, or coarse powder, due to the different thermal coefficients of the outer layers of glass results in multiple cracks on the top surface of the object.
- The tested formation temperature on the firing schedules affects considerably the composite panel. On the one hand, the lower temperature prevents the generation of a higher rate of bubble formation, while on

the other hand, it doesn't let the cullet completely melt and homogenized the cullet, giving them a fused state. The latter plays a considerable role in the finding of the composite panel related to the test held for the product's performance evaluation.

All in all, **the final output of the composite panel** with the most potential and challenging, but also successful effort is coming from the CSP float glass. This mixed cullet is categorized in the purity grade C', which was the focus to get it back to the production loop. Even if it carries a considerable amount of contamination, it is feasible to be remelted, achieving homogenization. Moreover, the form of shard prevents the formation of bubbles in the format of the composite tile, while it achieves compatibility with the cullet B' of the defined composition. It evidences that the composite can be remelted at a more efficient and relatively low temperature for less time, set up at 1000°C, and generating a more translucent result. To obtain further knowledge of the compatibility of the glass layers a next firing set-up is recommended, as an effort for further exploration and optimization of the panel fabrication.

Nevertheless, as it was inevitable the performed experiments denoted an unambiguous correlation between contamination of cullet, compositional variations, annealing schedule, and cullet type and the generation of various defects on the tested samples. In point of fact, coatings, ceramic frits, and traces or small pieces of external pollutants create **flaws generation** on the panel but they are endured by its thick-walled matrix. On the other hand, especially different recipes of glass when they are in proper size can lead to failure of the cast component during either cooling inside the kiln or the usage.

Along with the factors that influence the glass elements' damage and failure stresses are the defects formed on the objects due to post-processing. These are divided firstly into the inadequate removal of the existing imperfections and the introduction of new blemishes caused by the post-processing. After the surface and edge treatment of the specimens, low-energy stresses were generated on some of them, forming minor cracks. However, an interesting observation is made. The cracks are limited only to one of the panel's layers and there is no propagation to the rest, indicating that the sample does not react as one entity from the moment that is not fully fused, operating as a safety mechanism.

Just after the defect evaluation, the specimens proceed for a **qualitative residual stresses observation** with the method of photo-elasticity. Even if the samples possess a variety of flaws related to casting and post-processing, they do not generate notable stress augmentation. Consequently, negligible stresses are not introduced as ample to cause and lead to local or general failure in the specimens.

Last but not least is the evaluation of the glass panel performance through a **thermal shock examination** in significantly uneven temperatures. A test that is held for the first time in such a glass waste target. The thermal failure of the glass elements, applied also in external building envelopes, suggests such an evaluation on response to temperature alterations across different zones of the cast glass objects for the generation of tensile stresses causing damage or failure. The developed tensile stresses of low-energy, generated on the tested sample layering, are mostly linked with the critical points where defects exist, especially stones and glass recipe alterations. Nevertheless, the thermal shock tests present a similar observation on the cracking behavior on the tested composite panels. The minor cracks are restricted in one layer again and they are not propagating in the neighboring layers owing to the half-fused state of the cullet. Finally, the edge and surface treatment and especially the additive coating considerably prevent the generation of stresses in uneven temperature changes, providing a safety mechanism on the panels.

In the contents of my experimental research that refers to a product introduced for the building envelope, the implementation of all the aforementioned methods of performance evaluation is deemed necessary. These verifications on the recycled cast glass panel assist to imitate any probable weaknesses and failures caused by numerous factors.

04 | SUSTAINABILITY ASSESSMENT

01 | METHODOLOGY

01.1 INTRODUCTION TO SUSTAINABILITY ANALYSIS

In view of the continuous growth of the worldwide population, the economic expansion and goods production have been disengaged from the efficient exploitation of natural resources. At the moment being, climate change threatens a negative impact on humanity and the natural ecosystem, since it still remains an unsolved problem. Significant efforts are made by scientists and researchers to alter the current situation by either pursuing solutions or actions for the reduction of these unfavorable results.

Even if many greenhouse emissions occur physically, human activities seriously raise these atmospheric concentrations. The major responsibility is owned by four end-use sectors that are industrial, residential, transportation, and lastly commercial. However, the former is in charge of the higher emissions due to inattentive energy consumption and natural resources exploitation. According to the U.S. Energy Information Administration (2016), more than 50% of the global delivered energy is exploited by the branches of the industry.

Accordingly, the built environment makes up one of the industrial sub-sectors with the highest utilization of energy demand, exploitation of natural resources, and waste generation, causing environmental pressure generated by the construction and demolition sector. This consideration places it, as a substantial field, where sustainable approaches such as reuse and recycling have to take ambitious and pioneering actions. Construction and demolition materials constitute a significant waste stream and regardless of their contingents to be recycled, their mass quantities are either landfilled or diverted to a “next use” market, for instance, aggregate, soil amendment, and fuels. Sizable quantities of various materials and products in the C&D sector and extended construction areas represent the ideal and inviting circumstances, where recycled materials could be exploited in a circular economy.

Looking at the world of construction, glass panes are all the time used material for façade applications in transparent surfaces, such as curtain wall components, windows, glazed doors, or sometimes roofs and floors, produced by the float line. However, the continuously increasing trend in the architectural and engineering field towards wider applications of glass surfaces and demand for transparency in the building facades has spread the need for float glass generation. Several activities of the building sector, primarily the demolition and renovation operations, when taking place post-consumer glass wastes are generated. Consequently, the aforementioned activity implies that a big amount of end-of-life sheet glass is concentrated. For the time being, several directions and operations have been planned aiming to handle the current situation of waste, including glass coming from the C&D sector. It's about time to move towards a circular economy and a more sustainable way of living, with the main objective of the extension of products and materials service-life that are currently landfilled, in order to assist in waste depletion.

Into the spectrum of this research is to create potentialities in the conventional glass chain to shift to a circular version, without considering the economical practicability, with the fabrication of a thick-walled glass panel made out of glass waste coming from the Construction and Demolition field. The focus is to examine the environmental consequences of the production of recycled flat glass panels as a potential to develop the management of such waste hereafter.

The progressive awareness about the impact of the product on the environment has activated the need to create practices and tools assisting in the understanding of such negative outcomes. One of those tools is the Life Cycle Assessment (LCA), which defines the impact on the ecosystem by analyzing the whole or part of the circle of life of a product or process, considering every phase.

01.2 ANALYSIS DEFINITION & SCOPE

In the analysis that is held for the new cast glass product, an idealized life-cycle is taken into account exploring its potentialities and environmental impact as an upcycling approach within theoretical and practical strategies. Cast glass method within the applications in the built environment, even the promising prospective, has not been discovered to a great extent yet. However, questions are raised on the subject of the effects on the environment and the total life chain. Moreover, the exploitation of waste glass in the place of natural stock material draws conclusions about its efficiency, in regard to the lower temperatures operation for the glass

remelting, the consideration of C&D waste, and the need to mitigate the carbon emissions by replacing the raw materials. This chapter indicates a preliminary Life Cycle Assessment, in terms of quantity and environmental impact through embodied energy calculations.

TABLE 04.1 | BS EN 15978. Product and building life-cycle stages indicated for a LCA assessment. (Gibbons, & Orr, 2020)

LIFE CYCLE INFORMATION																Beyond LIFE CYCLE
PRODUCT STAGE			CONSTRUCTION PROCESS STAGE		USE STAGE							END-OF-LIFE STAGE				BENEFITS
A1	A2	A3	A4	A5	B1	B2	B3	B4	B5	B6	B7	C1	C2	C3	C4	D
Raw Material Supply	Transport	Manufacturing	Transport	Construction - Installation Process	Use	Maintenance	Repair	Replacement	Refurbishment	Operational energy use	Operational water use	De-construction & demolition	Transport	Waste processing	Disposal	Reuse / Recovery Recycling Potential
50%			4%	1%	20%					23%			2%			Approximate distribution of LCA emissions
A1-A3			A4	A5	B1-B5					B6-B7			C1-4			

The scope is to highlight the important issues that arise from the introduced recycled material within the spectrum of the sustainable movement. To achieve this, the employed embodied energy calculation is performed within default limits to give us the final estimated impact. The setup of the assessment commences with the inventory analysis step by step, with the gathered data from every stage of the life-cycle for the completion of the product.

In general, the life-cycle of float glass has six primary stages to be considered in every analysis. The start is the extraction of the raw material from the Earth's crust to be transported to the industrial facilities. There the manufacturing process begins as an intense energy process for sheet glass production. When the components are ready, the glass panes are moved to the post-processing phase, which includes numerous applications from glass lamination and coating to ceramic printing and heat strengthening. When the desired panels are complete according to the customers' demands, they are proceeded to the assembly of the Insulated glass Units (IGU) to be sent for application in the building envelopes to perform their service life for a certain timespan. Eventually, when the product's life cycle is complete the glass waste is generated.

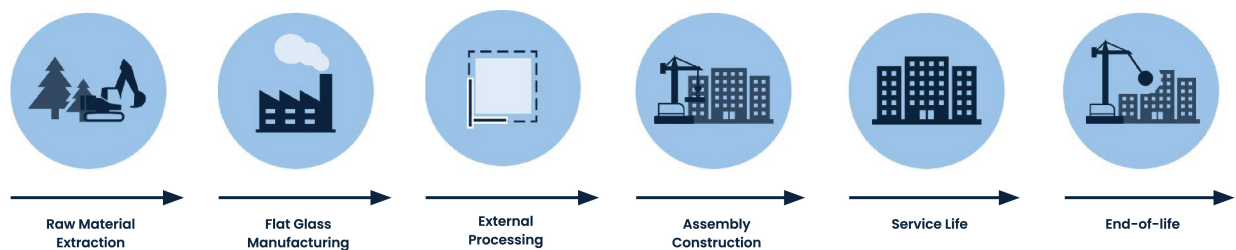


FIGURE 04.1 | Primary stages in LCA assessment of float glass production.

The typical life-cycle of flat glass is illustrated in a linear approach. However, efforts are made as the glass to be circulated inside the life-cycle loop, for a circular approach to be generated for more efficient outcomes that are less detrimental to the ecosystem. To significantly drop the environmental impact, the conventional life-cycle of the flat glass must evolve into a circular model that requires a higher degree of waste to be upcycled back to the flat glass-making loop. Small efforts have been made such as the use of a small proportion of high-quality cullet in the glass sheets produced by the industry (Glass for Europe, 2020). This is happening due to the fact that there are limited recycling systems for float glass to be gathered and recycled in a traceable manner, along with

the relatively strict rules that the float glass industry has set on cullet acceptance in order not to jeopardize the quality of its products. Consequently, the technical, infrastructural, and financial barriers confine the increase of recycled glass exploitation at a higher rate (VDMA, 2020).

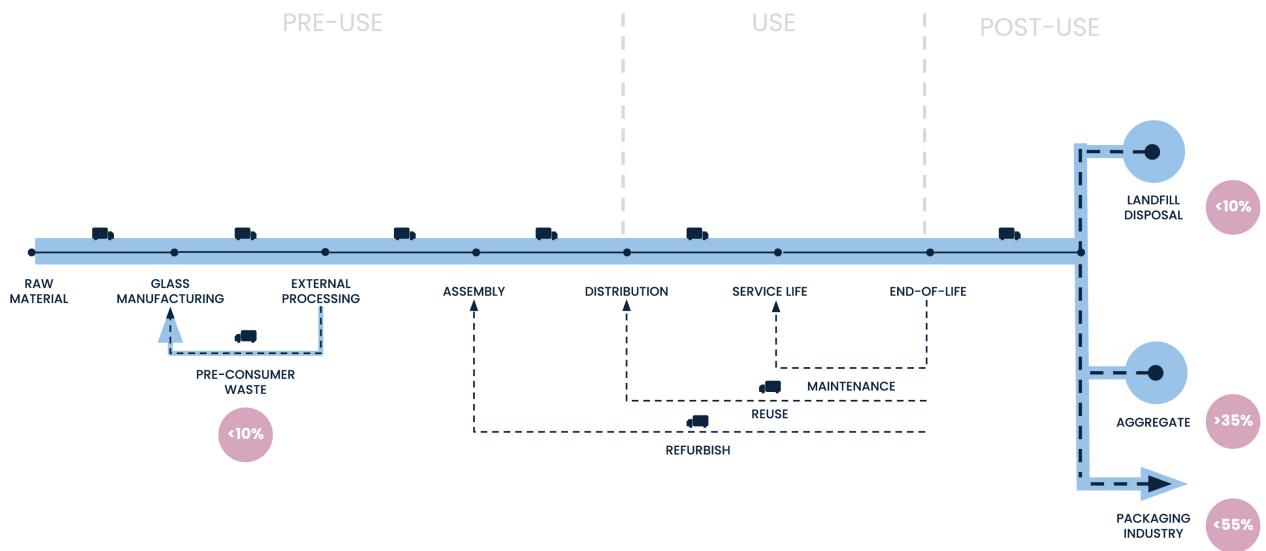


FIGURE 04.2 | Scheme of the current situation of float glass life cycle.

This thesis concentrates on the development of a life-cycle scenario for the production of the cast glass panel made by C&D cullet, corresponding to a closed-loop recycling concept and assessing the main stages of the system. Based on the available glass collection, recycling, and production scheme data, the potential carbon emissions required for the new proposed process for the fabrication of the element through C&D glass waste use into the thick-walled glass production will be calculated.

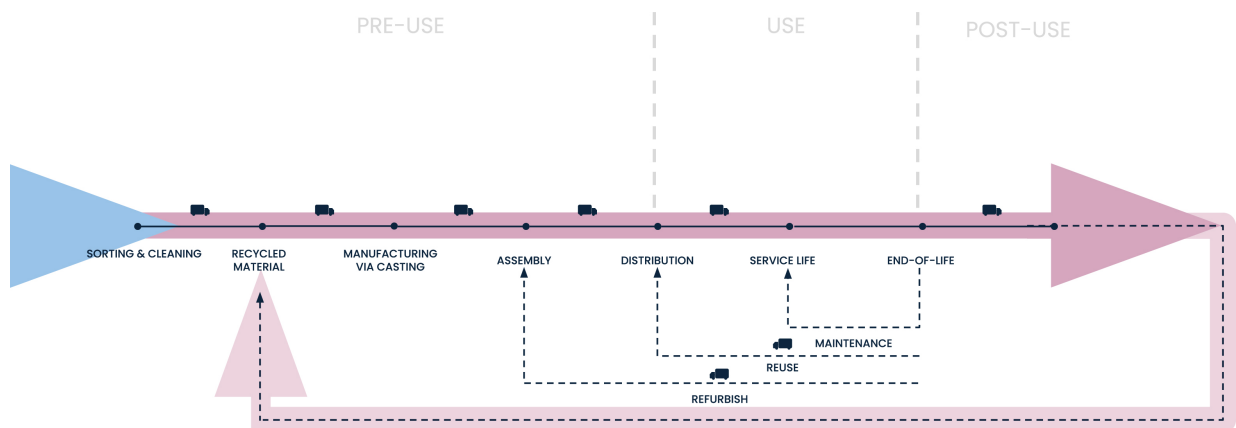


FIGURE 04.3 | Scheme of the circular model of cast glass life cycle.

Nevertheless, the whole service life is not considered on the LCA, as a highly variable, focusing only on the production phases in a cradle-to-gate evaluation. Apart from the conventional float line production, an explanation is given in the energy use, indicating the potential forward steps for the application of the recycled panel. This intends to determine not only the impact of the casting method in the fabrication of the panel but also creates the most effective utilization of both energy and natural resources within the exploitation of the recycled cullet from the waste stream.

The savings along the various steps of the glass recycling process are related to three stages. Firstly, the extra step of sorting and cleaning the C&D cullet is considered, whose embodied energy is negligible, in order to take the recycled cullet, which is already decarbonized and requires lower temperature and therefore less energy to be melted. Then, the casting method, which is a less energy-intensive method with a small production scale compared to float line and additionally, assumptions are made to limit the transportations' potential CO₂

emissions, assuming that the transportation from the collection site to the recycling facility to be 100km and the transportation of cullet to glass manufacturer to be 500km one way.

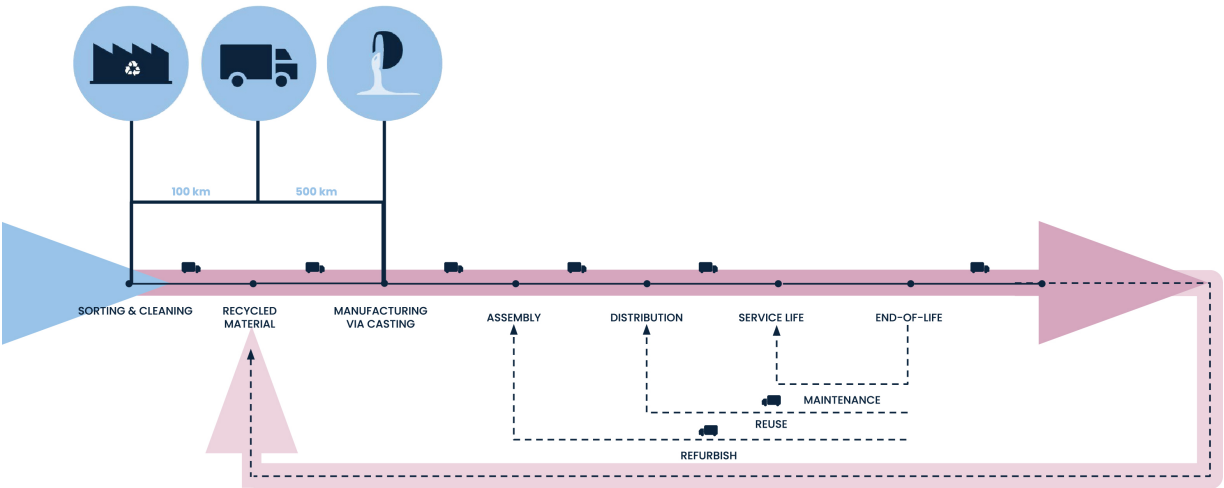


FIGURE 04.4 | Life cycle path of the casting panel with the major steps of the embodied energy generation for the LCA.

02 | LIFE CYCLE ASSESSMENT

02.1 STRATEGY

The current analysis considers three stages along the LCA path of float glass from the conventional float line to the new production method for the recycled cullet. This start with the manufacture of flat glass, then it proceeds to the collection and recycling of C&D waste glass, in order to be used for the fabrication of the new glass component through the method of casting.

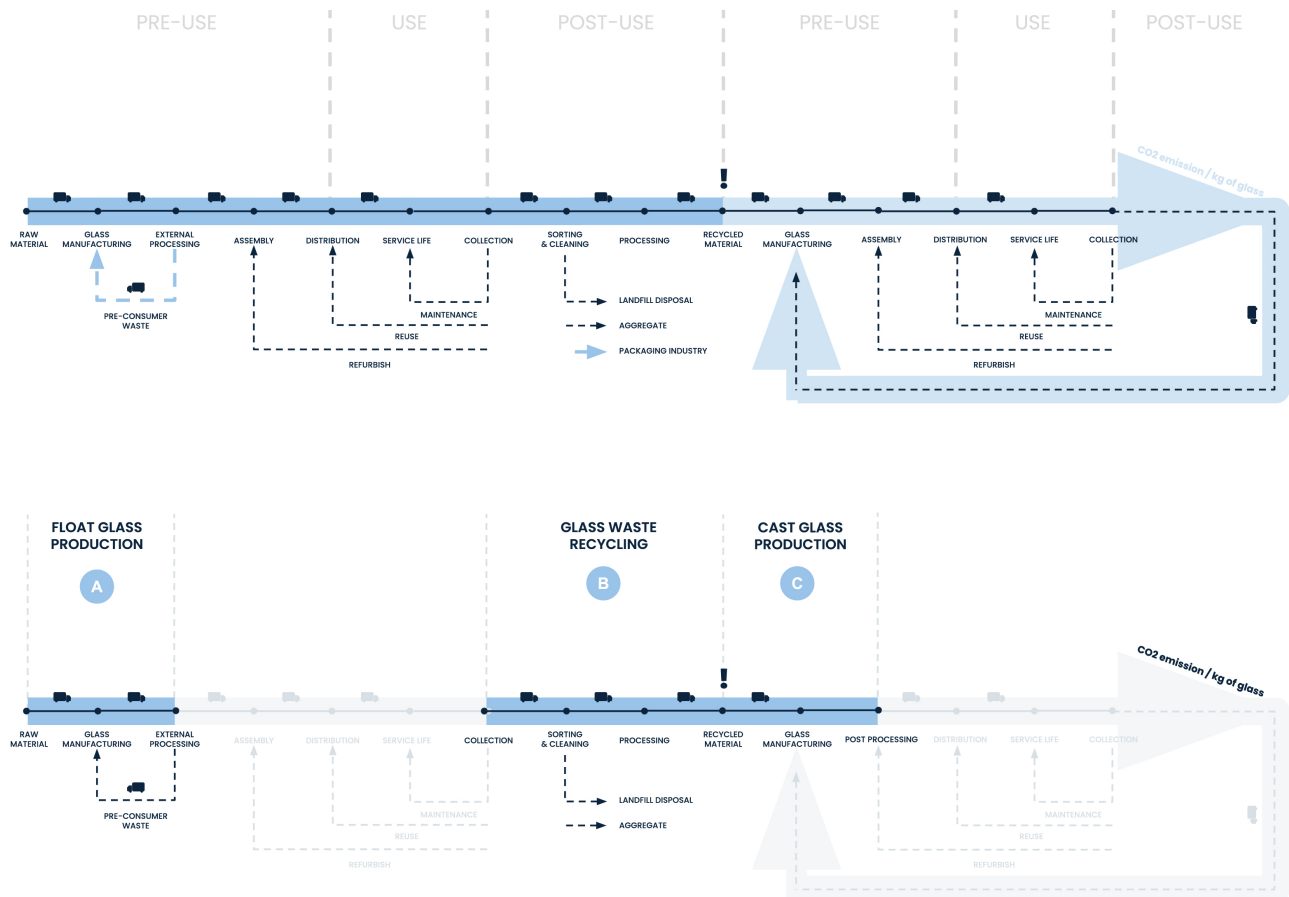


FIGURE 04.5 | Overall life cycle path of float glass and benefits beyond the conventional through cullet recycling and the introduction of casting method for the fabrication of the recycled composite component (top). The considered phases for the LCA path calculations (bottom).

Nevertheless, the whole service life is not considered in the LCA calculation, as a highly variable, focusing only on the production phases through float line and cast technology methods for sheet glass production. Robinson-Gayle research (2003) explicitly explains that the service-life and end-of-life of a product like a float glass is really complicated to accurately trace, owing to the circumstance that is a material with a broad variety in countless project implementations. As a consequence, there is a missing part of the life-cycle assessment on the cradle-to-grave environmental consequences of both the processes of float line and casting technique cycles, and the assessment is restricted and calculated by a cradle-to-gate evaluation.

Finally, an explanation is given of the energy use, indicating the potential forward steps for the application of the recycled panel. This intends to determine not only the impact of the casting method in the fabrication of the panel but also create the most effective utilization of both energy and natural resources within the exploitation of the recycled cullet from the waste stream. It is important to state on this point that due to difficulties or inability to find accurate data, the embodied energy calculations are heavily based on assumptions for the completion of the presented evaluation, mostly used in the cast glass production phase and the kiln operational energy. The intention of the current chapter of the research is not to hand over precise numerical data, even so, to compose an overall view of the ecological impact of understanding both the conventional float line and the

proposed casting method operating with recycled C&D cullet flows, while finding the “weak” spots that could induce improvements for a more efficient outcome.

LCA PATH



FIGURE 04.6 |

Life cycle path of float glass until the fabrication of the casting panel, together with the stages to be considered for the embodied energy calculation, namely A. Float glass manufacture, B. Glass waste recycling process, and C. Thick-walled cast glass production.

02.2 INVENTORY ANALYSIS

Float Glass Production

The conventional float glass production requires the conversion of organic raw matter into a finished glass, which accomplishes determinate claims. This is achieved utilizing various phases. Several procedures demand energy to generate controlled transformations of the configuration characteristics from the ingredient materials to the glass output. Accordingly, industrial emissions for the float glass formation are inextricably connected with those step-activities that are involved in the manufacturing. In the energy assessment for the consumption, the implemented melting method, utilized infrastructure, fuel type exploitation, and investigated glass element's features should be considered and evaluated.

As an overall picture, the entailed process stages for the thin-walled glass formation indicated for the embodied energy calculations are numerous and diverse. It includes the mining phase, glass manufacture that is made up of the batch preparation, melting & refining, float bath, annealing, inspection, and cutting to order, while the transformation and processing step referred to as post-processing is not considered since different processes possess diverse energy demand that may considerably vary, and transport phase which intervenes between most of the steps.

The first phase in the life-cycle of sheet glass is the claiming process of the natural resources, extracted by the earth's crust for the exploitation of the main ingredients are silica sand, soda, and lime. The formation of one tonne of thin-walled glass corresponds to a 1.17 tonnes batch with the former mixture (Dubois et al., 2013). Unfortunately, there is no precise data on the energy consumption of this stage and its impact is quite complicated to be defined, due to the lack of forthwith accessible studies.

Secondly, manufacturing is the most energy-intensive phase of all. Most of the energy consumption is linked to the melting process of the heterogeneous batch mix, which inasmuch is deemed accountable approximately to 85% of the overall power requirements of the float line plant (AGC, 2021). The indicated losses of 170 kilograms during the transformation process in melting are interpreted as instant gaseous emissions in the form of probable carbon dioxide. Considering that, float facilities form on average 650 tonnes of glass from 760 tonnes of raw material daily (Glass for Europe), which is equal to 110 tons of direct losses. Contemplating the European production through 50 float plants (Glass Alliance Europe), which have a mass-scale production operating 24 hours per day, 365 days yearly to mitigate the costs and the ecological footprint (Glass for Europe), this concludes in the gigantic number of more than 2 million tonnes of annual direct emissions. Additional is the energy consumed for the formation of one tonne of glass, accounting for around 9 Giga Joule, according to Dubois (2013).

Lastly, the transport phase is required in almost every stage, for instance, the transfer of the raw resources to the industrial facilities. A number that always differentiates between the destinations, along with the corresponding impact on the environment.

In the present research, a total indication is assumed on the LCA calculation, which stated that in general industrial terms float glass carries an embodied carbon of 1,44 kgCO₂ for every kilogram of product according to ICE database. A number that may vary between the different phase and efficiency systems that industries use.

TABLE 04.2 | Float glass production emissions per generated kg, indicating A1-A3 modules of life cycle.

Life Cycle Module	Information	Embodied Carbon
Raw Material Extraction	n/a	1,44 kgCO ₂ /kg
Transport	n/a	
Float Glass Production	Melting carries 85% of the overall power requirements	

Glass Recycling

Just like the conventional float glass production, which demands raw material for the fabrication of glass panels, simultaneously the composite panel necessitates material to be utilized for its fabrication. As the whole research is stated the final glass output is completely made out of the recycled glass of the class B' and C' purity grades. But what is the energy demand for all the phases included in the C&D glass recycling? This part of the life cycle analysis concerns the collection scheme of the flat glass at its end-of-life, the followed procedure to obtain the cullet that is attributed is sorting, cleaning, and processing of glass waste into valued cullet, and certainly the transport between the stages.

In construction and demolition sites, glass elements are either removed and ideally placed into containers or smashed out of the window frames, since IGUs are hardly ever disassembled (Geboes, 2020). Unfortunately, no data were gained about the current phase. However, the number could be considered zero or negligible compared to other processes included in the present life cycle assessment, since it regards a manual removal process without the operation of any mechanical equipment (DeBrincat & Babic).

Just after demolition, the collection of the containers filled with cullet and the transportation to the recycler facilities is following. This stage can generate a considerable amount of embodied carbon that affects the total life cycle assessment. Several studies have been made for the evaluation of transport's impact on the environment. Research held by Deloitte, analyzing the waste routes in the C&D glass, states that the average emissions of carbon dioxide equivalent for a truck filled with more than 30 tonnes, which covered 43 kilometers, is approximately 0.085 kg (Hestin et al., 2016).

The current thesis reproduces a realistic and optimized scenario for the current module of the circle. An assumption has been made for the covered distance concluded in an assessment based on a round trip of 200 km, which is deemed empty outwards and roughly 80% full on the way to the recycling facilities. According to UK regulation (Structural Engineers, 2020), which is taken into account for the calculations, this distance is considered as national transport with embodied carbon to be calculated at 0,0213 kgCO₂ for every kilogram of glass waste.

TABLE 04.3 | Default embodied carbon values for transport module per kg of glass, for the UK.

Transport	Distance by road	Distance by sea	Embodied Carbon ^a
Local	50 km	-	0,005 kgCO ₂ /kg
National	300 km	-	0,032 kgCO ₂ /kg
European	1500 km	-	0,160 kgCO ₂ /kg
Global	2000 km	10000 km	0,183 kgCO ₂ /kg

^a The number calculation arises by the following equation $TD_{mode} \times TEF_{mode}$ (50 km $\times$ 0.10650 gCO₂e/kg/km / 1000).

Then, the containers with mixed cullet arrive in the recycler plants where the glass materials are cleaned and sorted out to be processed back for use or discarded as waste. Unfortunately, at the moment there are no inadequate data on the traceable material flow of thin-walled glass. In consequence, the discovery of information on the recycling line operation was also deemed challenging.

Some information provided by the Maltha Recycling industry indicates that from a float glass recycling stream 94% is sheet glass, 2% is waste suitable for recycling, mostly referred to aluminum strips of insulated units, and finally, the rest 4% is linked to discarded waste (TNO, 2019). Thereafter, the sorted float glass is distributed by 15% back to the closed-loop of the float line, 72% is utilized from the glass packaging industry, whilst the remaining proportion is downcycled for the fabrication of glass fibers (TNO, 2019). For the aforementioned cleaning, sorting, and processing steps, the electricity used is 9.65 kWh for the motor operation of the machines and an additional amount of 0.81 liters of diesel are utilized only in the separation scheme. The embodied carbon released for this whole process is 0,006 kgCO₂ per kg of recycled cullet.

TABLE 04.4 | C&D glass recycling scheme emissions per generated kg.

Life Cycle Module	Information	Embodied Carbon
Glass waste collection	Manual operation.	Negligible
Transport	National transport with 200 km round trip.	0,0213 kgCO ₂ /kg
Sorting, Cleaning & Processing	9,65 kWh of electricity and 0,81 liters of diesel are utilized.	0,006 kgCO ₂ /kg
TOTAL :		0,0273 kgCO₂/kg

Cast Thick-walled Glass Manufacture

Just after the preparation of the valuable cullet of grades B' and C' that is used for the fabrication of the panel, the separated material should be transferred to the cast glass facilities. Again the material is transferred by a lorry based on the assumption, which goes through a distance of 1000 km round trip to cover a wide area around the fabrication studio as a realistic scenario. This covered range, as stated in table 05.3 based on the UK regulatory framework, emits 0.1065 kgCO₂ of carbon for every kilo of material transferred.

Before proceeding to the casting technique demands, the basic characteristics of the panel product should be defined. The final output, from the moment that could be directly utilized in the Built Environment as a part of a building, either in the facade envelope or the interiors (IGU, partition walls, cladding, flooring, etc.), is deemed necessary to have a maximum format at 3500 x 1500 mm to be utilized according to the requirements of every possible project. The panel characteristics are formed according to the following tables:

TABLE 04.5 | Approximate calculations of 1m² cast glass panel with recycled cullet.

	Calculations	
Length	100 cm	1 m
Width	100 cm	1 m
Height	3 cm	0,3 m
Area	10000 cm	1 m ²
Volume	30000 cm ³	0,3 m ³
Density	2,46 g/cm ³	2460 kg/m ³
Weight	73800 g	73,8 kg

TABLE 04.6 | Panel characteristics.

	Information
Length	3,50 m
Width	1,50 m
Height	0,3 m
Area	5,25 m ²
Volume	1,575 m ³
Density	2460 kg/m ³
Weight	387,45 kg

The current module of the casting process is heavily based on assumptions, owing to many missing data on the kiln operation and energy consumption trends. Even the efforts made to gain information by contacting people and companies to draw a conclusion, in the end, the calculations held as specified by the following presumptions, and are used as the basis in a practical framework. Accordingly, the assumptions used for the thermodynamic calculation are followed in the table below. These are formed in a manner to be utilized for an industrial environment as a more correlated approach to reality.

TABLE 04.7 | Assumptions made for the cast glass manufacture scheme.

Assumptions	Information
Furnace	The selected kiln for the manufacture of the panel with maximum dimensions of 3500 x 1500 mm is the fusing furnace FE 5200/10. A hood kiln with maximum temperature at 1000°C, electric power demand at 110kW, and dimensions 6000 x 2650 x 330 mm (Rohde).
Furnace Efficiency ^a	80%
Heat Losses ^a	20%
Furnace Walls U-value	0,06
Air Mass in the kiln	1,27 kg/m ³
Panel characteristics	The panel into consideration possesses maximum dimensions of 3500 x 1500 mm, with a volume of 1,575 m ³ , and a total weight of 387,45 kg.
Glass Heat Capacity	840 J/kg K
Melting Glass Energy	0 kWh/kg
Air capacity	700 J/kg K

^a It is assumed at a percentage of 80% efficiency and 20% of heat losses due to the fact that is a hood kiln that is lifted vertically and just covers the panel.

In general, greenhouse gases emissions associated with the manufacture of float glass stem not just from the consumption of energy or fuels burning for the purpose of achieving the needed forming temperature of the batch inputs, but also from the emission of carbon dioxide coming from the effort to conduct the procedure of the raw material decarbonization and their transformation to glass products. A major focus of the whole industrial sector is the achievement of a sustainable system and strategy to compensate for the carbon released into the atmosphere from the natural resources throughout the recycling process and the recycled cullet utilized back in glassmaking. To achieve significant energy savings is the use of recycled cullet in the glass melt, as another step toward sustainability.

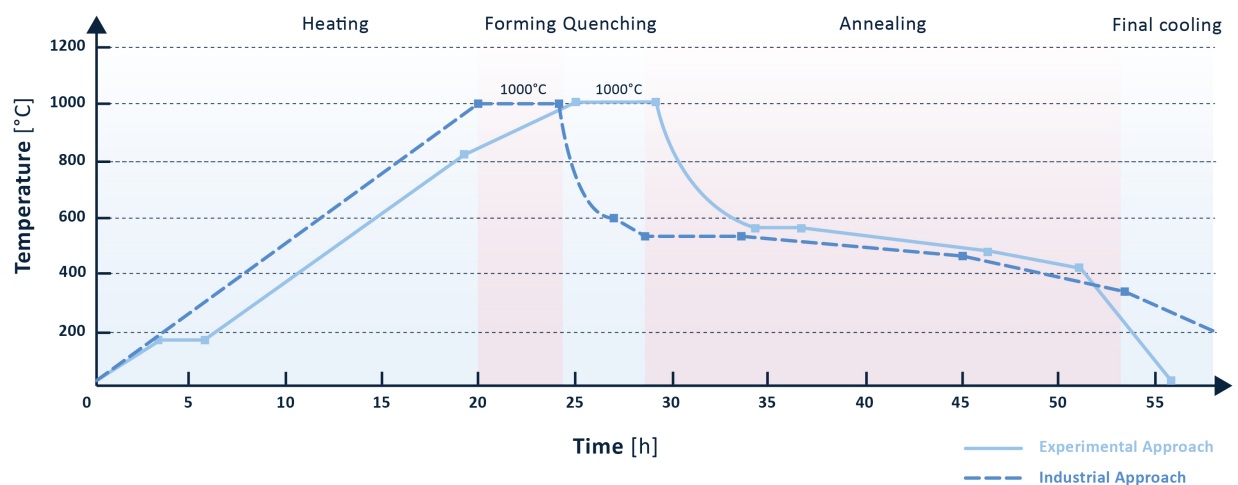


FIGURE 04.7 | The firing schedules and casting phases considered in the LCA for the panel's kiln-casting.

As the fraction cullet in the batch of glassmaking grows, the positive impact on the outcome grows accordingly. The composite panel indicated for the life cycle assessment is made out of 100% recycled glass material. In this case, there are no chemical reactions on the cullet melting since it is already glass that directly warms up,

becomes soft, and then in a more liquid state. Apparently, no phase change occurs and no latent melting energy is utilized for the panel forming (Hoyle et al., 2021). Consequently, even if the conversion of natural matter constituting the batch for glass making commence with the decomposition and then the forming of the carbonates that conclude into the hazardous emissions, something that is not the case in the current analysis and the melting energy of the panel is assumed to zero.

Last but not least factor indicated for the calculation is the chosen firing schedule of the sample. This selection rests on the previous experimentation held on composite panel generation. The cullet is placed into the ceramic mold whilst the bottom is covered with a high-quality refractory cloth made out of fibers. Then, the bed is placed in the ROHDE FE 5200/10 hood-kiln, operating with electricity. This oven is intended for kiln-casting, while it was a customized furnace for MAGNA Glaskeramic company. The overall casting procedure with all the appropriate stages of firing employs a single machine.

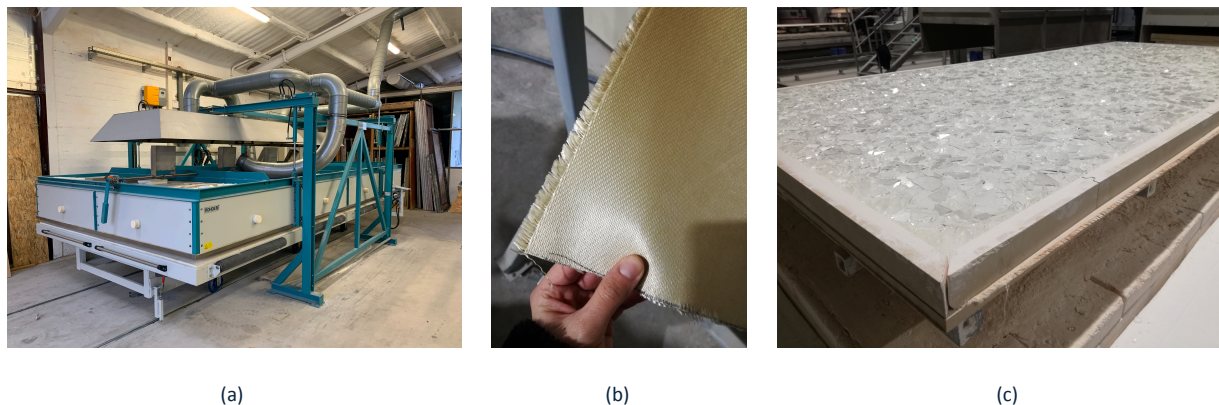


FIGURE 04.8 |

(a) Rohde FE 5200/10 hood kiln operated with electricity, (b) Refractory fiber-cloth, (c) Ceramic mold loaded with recycled cullet.
Image credits: Faidra Oikonomopoulou

The characteristic casting plan is constituted by five stages shown heating, forming, quenching, annealing, and final cooling. This firing schedule sets the maximum heating rate at 50°C per hour and the highest melting temperature, which is permitted to be reached, at 1000°C, while the whole firing schedule operates for 54 hours. This set program along with the assumptions made before concluded in 0,0654 kgCO₂ for the fabrication of one kilogram of the composite panel.

TABLE 04.8 | Firing schedule I, utilized for the fabrication of the composite panel.

STEP	RAMP [°C/h]	TEMPERATURE [°C]	DWELL [h]	TOTAL WORKING TIME [h]
1	50	23	3,0	3.0
		160		
2	-	160	3,0	6.0
		160		
3	50	160	13,0	19.0
		820		
4	45	820	6,0	25.0
		1000		
5	-	1000	4,0	29.0
		1000		
6	- 186	1000	3,0	32.0
		560		
7	-	560	3,0	35.0
		560		
8	- 6	560	10,0	45.0
		500		
9	- 14	500	5,0	50.0
		430		
12	- 100	430	4,0	54.0
		23		

However, an alternative firing schedule could be proposed based more on a timeframe and temperatures closer to the industrial process. A process that is adapted in terms of minimizing the cost and time, as a rather fast program that the last step could be skipped by shutting down the oven and letting the piece cool down naturally inside until reaching the ambient temperature considering that the cooling rate is not so rapid as to provoke thermal shock. According to the adaptations made the followed firing schedule produces a slightly decreased performance rate at 0,0620 kgCO₂ per kilogram.

TABLE 04.9 | Firing schedule II, utilized for the fabrication of the composite panel and adapted to the industrial process.

STEP	RAMP [°C/h]	TEMPERATURE [°C]	DWELL [h]	TOTAL WORKING TIME [h]
1	50	23	20,0	3.0
		1000		
2	-	1000	4,0	6.0
		1000		
3	50	1000	2,5	19.0
		600		
4	45	600	1,5	25.0
		560		
5	-	560	6,0	29.0
		560		
6	- 186	560	11,0	32.0
		490		
7	-	490	8,0	35.0
		370		
8	- 6	370	12.0	45.0
		25		

As far as post-processing is concerned, the material would be suitable to surface and edge processing to gain the final outcome. For the former, a CNC machine is utilized for the grinding finishing, to mill the surfaces of the panel and abstract the natural convex, while polishing obtains a smooth touch on the flat surface. These can be accomplished with the use of any machine with a water supply utilized also for marble or granite materials (MAGNA). The edge processing is made manually with small tools named "Alpha Ceramica EX" polishing pads and "Alpha AIR-680" polisher. The stone used for the pads must have a grit size from 200 to 3000 grinding for the edge polishing and turning speed set at roughly 2000 rpm. Even if data are provided for the steps and machinery needed for post-processing, no data are provided for operational time, the energy consumption and the embodied carbon of the process. Nevertheless, these procedures seem insignificant compared to other modules of the whole panel manufacturing stage.

TABLE 04.10 | Casting production emissions of thick-walled glass panel per kg.

Life Cycle Module	Information	Embodied Carbon	
Transport	European transport with 1000 km round trip.	0,1065 kgCO ₂ /kg	
Casting method operation	Based on assumptions.	0,0654 kgCO ₂ /kg	0,0620 kgCO ₂ /kg
Polishing	Not always applied.	Negligible	
TOTAL :		0,1719 kgCO₂/kg	0,1685 kgCO₂/kg

02.3 RESULTS

Based on the evaluation made on the easily measurable part of life cycle of the conventional float line products and the casting technique according to the composite panel needs, considerable data are reported. The presented analysis is taking into account specific parts of the overall life of the products, since post-processing and service life are eliminated from the research as high variables. The focus is mainly on the utilized material for the fabrication of the product, the transportation between the phases and the overall manufacture procedure. As a consequence, the assessment in both methods is restricted and calculated by a cradle-to-gate life span.

On the one hand, conventional float glass production requires the conversion of organic raw matter into a finished glass, which accomplishes determinate claims. The entailed process stages for the thin-walled glass formation indicated the mining phase, glass manufacture, and transport phase which intervenes between the aforementioned steps. The final number indicated in this research is 1,44 kgCO₂ for every kilogram of float glass product according to the ICE database. However, this number may vary between the different phases, efficiency systems, and sustainable strategic lines that different industries use.

On the other hand, the fabrication of the composite panel consisted entirely of recycled C&D cullet including firstly the collection of waste glass, transport to the recycler, and sorting and cleaning of cullet to get the valued material to proceed then to the transit on the production space, the casting of the panel and the primary post-processing to get the final product. The former part concludes with the embodied carbon of 0,0273 kgCO₂ per kilogram, while the latter about the fabrication of the element examines two scenarios, which differentiate in the firing schedule and are based on the decarbonized cullet. The first indicates a program based on the experimental approach reaching a rate of 0,1719 kgCO₂/kg, while the second based on the industrial approach that the main intention is to minimize cost and time possesses a lower value at 0,1685 kgCO₂/kg, improving the carbon emissions impact.

TABLE 04.11 | Overview of embodied carbon calculations.

Life Cycle Module	Information	Embodied Carbon	
FLOAT GLASS PRODUCTION	Raw Material Extraction, Transport, Float line	1,44 kgCO ₂ /kg	
RECYCLED CAST GLASS PRODUCTION	Collection, Transport, Glass Waste Recycling Transport, Casting Method	Scenario I	Scenario II
		0,0273 kgCO ₂ /kg	0,0273 kgCO ₂ /kg
		+ 0,1719 kgCO ₂ /kg	+ 0,1685 kgCO ₂ /kg
		0,1992 kgCO ₂ /kg	0,1958 kgCO ₂ /kg

With the intention to highlight the difference between the utilization of decarbonized cullet and the raw material within the same industrial processing a third scenario is presented. In this case, the cullet is replaced by the raw material that needs to proceed through chemical reactions to form glass, where latent melting energy is considered at 0,6044 kWh/kg (Galitsky et al., 2008). The amount of the embodied energy of the product made out of raw material considerably increases, reaching 0,2216 kgCO₂/kg, more than three-time higher compared to the decarbonized version. With the addition of the transport to reach the casting facilities, the final embodied carbon is formed at 0,3609 kgCO₂/kg. This number doesn't include the input material in the sum of the final number since there are no specific data on the extraction of raw material, which may also increase significantly the scenario III. However, in comparison to the other two cases, this number is more than doubled. This translation specifies the need to switch to more sustainable methods of glassmaking in order to prevent carbon emissions and negative environmental impacts.

TABLE 04.12 | Overview of scenarios on cast glassmaking utilized either decarbonized cullet or raw material.

Life Cycle Module	Information	Embodied Carbon [kgCO ₂ /kg]		
CAST GLASS PRODUCTION	Transport, Casting Method	Scenario I	Scenario II	Scenario III
		0,1719	0,1685	0,3609

According to all the aforementioned findings, the total embodied carbon of the final composite panel made out completely from glass waste coming from the C&D sector is presented. In a realistic scenario and taking into account the industrial level production, the component with a format of 3,5 by 1,5 meters and weight of 387,45 kg includes an embodied carbon of 65,29 kg, while a corresponding panel produced by the float industry possesses a rate of 557,93 kg.

03 | SUSTAINABLE APPROACH CONCLUSION

In the spectrum of this research, the major focus is the shifting into a more sustainable approach of float glassmaking involving the utilization of recycled glass, tools, and methods that create potentialities into the scope of a circular strategy. To comprehend this alternation approach, the environmental consequences of the production of recycled flat glass panels were examined through the casting method, as a potential to develop the management of C&D waste hereafter. The progressive awareness about the impact of the products on the environment, and specifically glass, has activated the need to create practices and tools assisting in the understanding of the negative outcomes through the calculation of embodied carbon that sheet glass carries. One of those tools is the Life Cycle Assessment (LCA), which defines the impact on the ecosystem by analyzing in the present case the part of the life cycle that refers to the utilized materials, production schemes, and the transportation in between these modules. A Life Cycle Assessment has been performed on the conventional float line and the new method of the composite glass panel made out of completely recycled cullet with the aim of casting technique to provide a preliminary resolution on the operation of both the different formation methods of flat glass and the input materials employed for the process.

Although the assessment executed for the life cycle of both float glass and the cast glass panel does not take into account well-grounded information, the results could be considered valuable. Due to a lack of information on specific case studies that contain precise facts and figures, the research comprises only scenarios about transport, production and processing methods, waste treatment, and machinery consumption as contributions based highly on logical assumptions. Nonetheless, it is still capable to present some interesting and practical indications on what are the measurable factors related to the whole evaluated processing phases that influence further the overall impact on the ecosystem. Furthermore, the present study is also able to be used as the base for revealing relevant facts on the adopted course of procedure phases in future assessments.

These rough estimations with missing data have been executed for the LCA calculations, which may be misleading. So any use of the is confessed with a high margin of error and the part based highly on assumptions should be managed with thoughtful consideration. Especially in the energy consumption calculations of the furnace, attention must be paid not only due to the lack of data but also based on the scenario that different projects may need a different manipulation, for instance, furnace operation and firing schedule accordingly.

The final outcome of the whole assessment indicates that the cast glass process with the utilization of recycled C&D cullet is a considerable sustainable process, looking also at the conventional energy-intense float line. This preliminary analysis through the scenarios indication on the cast glass part, also reveals that cullet use is a beneficial parameter for the overall sustainability of the process. The kiln operation, where melting, forming, and fining of the glass object happen, figures to possess the major part of the energy expenditure and carbon emissions, while transportation places a significant role. Moreover, the collection and recycling process of the waste cullet seems to be a less energy-demand process, compared to the raw material which also damages the biodiversity of the extraction area. The exploitation of such a process unveils additional benefits on both financial savings for the glass manufacturers coming from the energy mitigation expenditures and the need for raw material.

Moreover, to further improve the mitigation of the final energy consumption and the embodied carbon accordingly, several actions could take place. To identify where these actions could be considered, attention must be paid, about what are the efficient parts of the process and what is not, in order to propose solutions for further development in the whole procedure. These could be applied either to the assumptions made for the transportation routes with more local market dealings or using vehicles that consume renewable energy. Another case for improvement is the oven employed for glass generation, which could exploit low-carbon innovations, utilizing more efficient energy sources, with waste heat exploitation through heat exchangers.

In conclusion, the scope of this assessment is to set the guidelines to identify the areas where energy consumption can be reduced rather than providing absolute numbers while establishing the foundation for further questioning and research in this field.

05 | DESIGN APPLICATION

01 | INTRODUCTION

Based on the whole experimental research and examinations of the product's performance, the recycled glass panel made out of ultimately glass waste coming from the construction and demolition sector has been evidenced to be feasible with the aim of casting method. A panel is constituted by a material that can be fully utilized at its end-of-life for the manufacture of a new product. The successful narrative of this circular economy material attaches a meaningful dimension to the protection of the natural ecosystem with the careful exploitation of its resources, and the amelioration of the viable balance in the design and construction of glazed projects. This pioneering recycled component by float glass waste holds a role of great significance for the sustainably generated materials, indicating the transition efforts for a low-carbon environment and sustainable builds.

The next step is the applicability of the product outcome for architectural purposes in order to fulfill the main goal of this whole journey on the closed-loop approach. The illustration of practical application aims to provide a better point of view about the potential of this recycled glass panel.

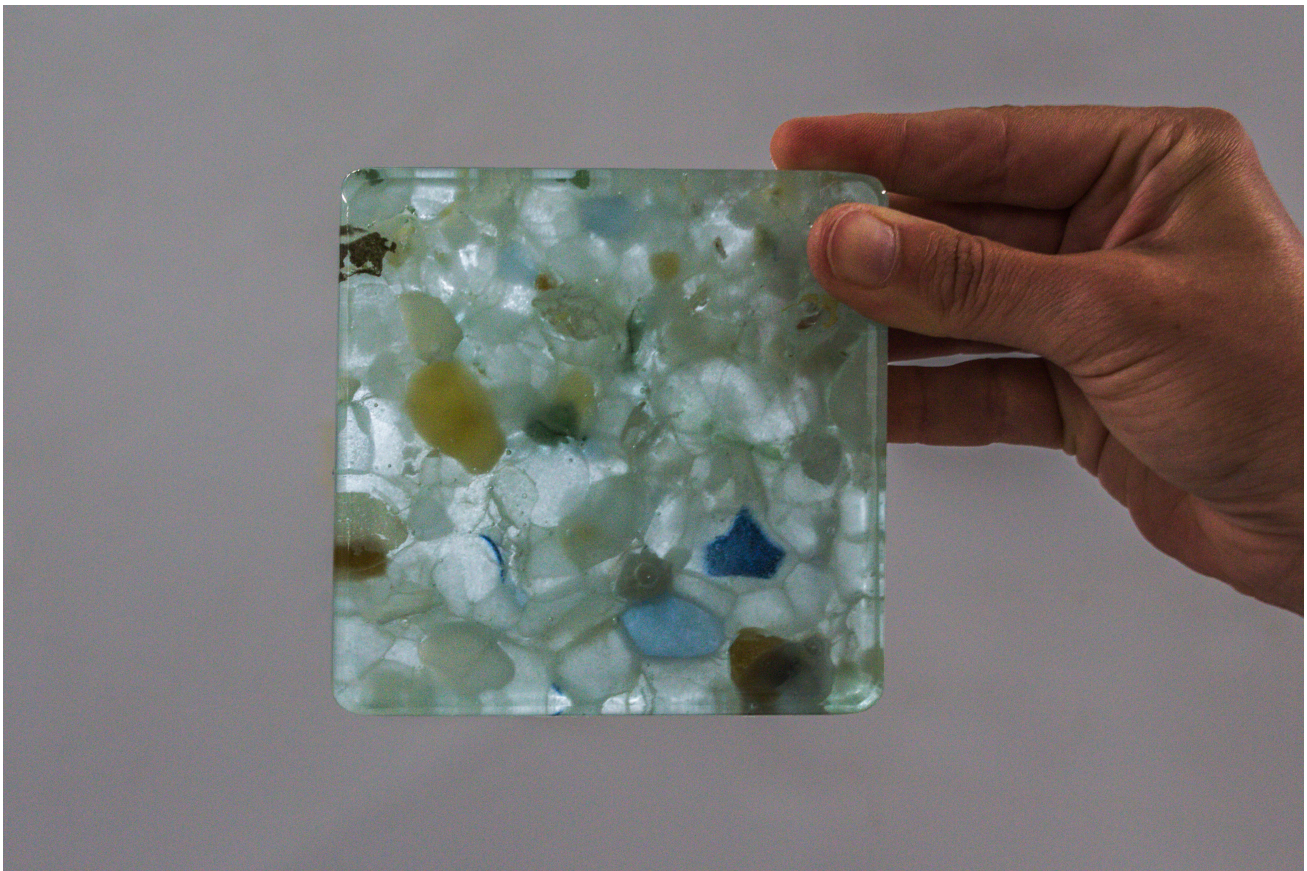


FIGURE 05.1 |

The translucent composite tile from recycled glass waste after edge and surface treatment, application of UV coating, in front of a light source.

02 | APPLICATIONS

This unique glass panel arises a lot of interesting potential for applications. However, to fulfill the diverse needs of the potential implementations on projects the final result could have many alternatives. These are referred to as variations on the size format of the panel, which is typically at a maximum of 300 by 150 cm, according to the taken assumptions during the environmental assessment and the manufacturing setup, the achievable thickness that was evaluated on the firings and finally the material finishes linked to the surfaces post-processing.

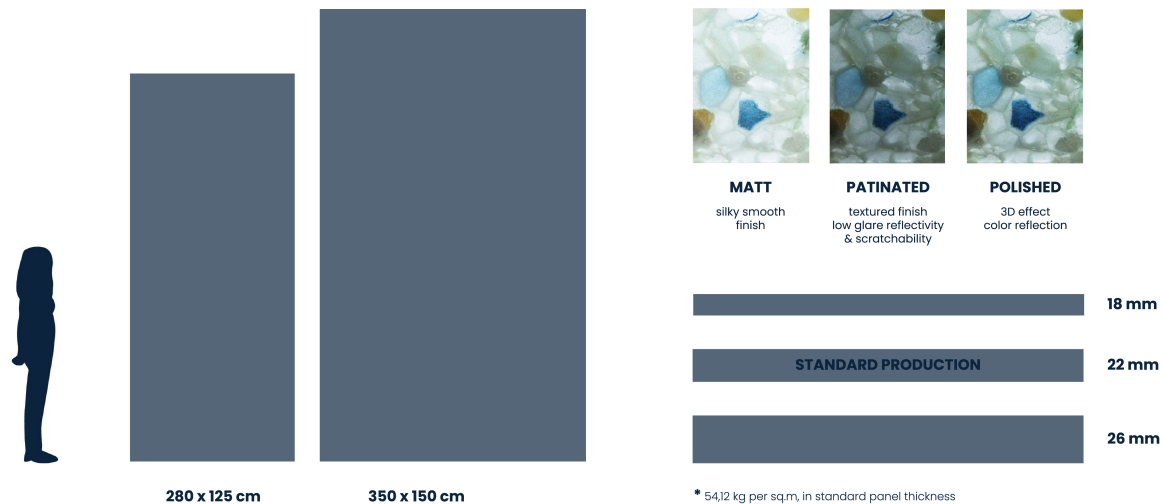


FIGURE 05.2 | Production specifications of the composite panel.

From the beginning of this research, the recycled component was intended to be developed for buildings' facade applications. It presents the same potential just like conventional float glass, but in a more translucent and recyclable solution for a wide variety of outdoor applications. Due to its unique nature relying mainly upon the undefined composition cullet that is placed in the middle layer of the composite and it is really diverse, none of the produced panels would be the same. The outcome from the mixed cullet possesses special characteristics in the color, shades, depth, and air-pocket distribution. The irregular cullet deposition and fragment size also apply a dramatic depth and let the light go through it, generating an exciting aesthetic result.



FIGURE 05.3 |

The "Kunsthau Bregenz" in Austria with the composite recycled glass panel applied on the facade cladding.



FIGURE 05.4 |

The foundation of “Stavros Niarchos” in Athens, Greece, with the composite recycled glass panel applied to the façade system.

Moreover, the developed panel could also replace materials that they intend to let the light partially diffused between the spaces. Such an example is the translucent marble which is widely used for façade applications due to the luminous result along with the daylight or during night-time. With the same approach, the recycled composite glass panel can replace this material, since the inner layer of the cullet which is half-fused and partially crystallized can achieve the same effect.



FIGURE 05.5 |

The Apple Store in Macau in the before version of translucent stone and glass composite façade application and the after, with the implementation of the composite recycled glass panel.

The primary advantage is that even if the recycled panel is a newly introduced material component, a wide number of implementations could be achieved based on findings of the product's performance during the evaluation experiments and proven capabilities. The glazed composite output is not only geared toward the exterior project but also the panel's implementation could be expanded indoors. There, it can be utilized for a broad spectrum of application possibilities such as flooring, wall cladding, room partitions, and other architectural elements.

(a)



(b)



(c)



(d)

FIGURE 05.6 |

Architectural outdoor and indoor applications of the composite recycled glass panel. (a) Internal partition walls, (b) exterior balustrades, (c) flooring, and (d) wall covering.

01 | DISCUSSION

04.1 INTRODUCTION

The present thesis aims to explore the feasibility of manufacturing a thick-walled panel, entirely made out of glass waste coming from the Construction & Demolition sector, and formed through the casting technique. Moreover, the focus is extending to the proper mapping of the current situation of thin-walled glass recycling, and the identification of the most promising C&D glass waste, by contacting melting through experimental research. This assists to adopt a strategic approach of a translucent composite component, which is made out of specific glass waste layering, between different purity grades of cullet, arranged in such a manner to form an advantage tensile strength, which is transferred on the surfaces and reinforces the object. The product's performance evaluation is achieved with tools that have not been utilized before, referred to as thermal shock under uneven temperature differences, and LCA analysis that assesses its life cycle impact on the environment. Simultaneously, this thesis contributes to creating awareness of the unsolved problem of float glass exploitation after its end-of-life, by introducing closed-loop alternatives that extend the panel's service life, which is designed for use in the building envelope.

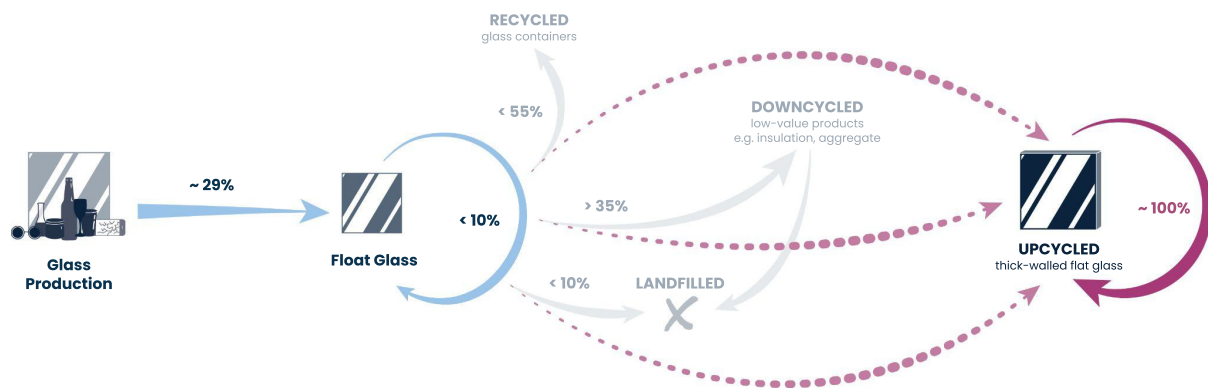


FIGURE 06.1 |

The research goal on float glass recycling utilization for the fabrication of thick-walled flat glass components for the built environment.

This chapter summarizes the findings of the experimental exploration in answering the main research question, formed at the beginning of the graduation thesis. Furthermore, it discusses any constraints connected with the whole evolution of the casted composite panel, while it ends with suggestions for future exploration and development of the current project.

04.2 RESEARCH QUESTION

R.Q. In what ways can we develop a glazed facade panel made by recycled glass, coming from Construction & Demolition cullets, through an upcycling approach and taking into account its life-cycle assessment?

In accordance with the main research question, the answer can be formed as follows.

The scope of this research is to develop and experimentally verify with the aim of casting the fabrication of a recycled glass panel utilized in building envelopes. A component completely constituting not just from any post-consumer glass waste, but cullet that is an output of flat glass waste coming from the construction and demolition sector. Prior to this attempt, limited investigation has been held on such glass waste. By contacting melting and other tools such as thermal shock to evaluate the panel's performance through explorative experimentation, this production is deemed feasible. While further exploration has been introduced through the closed-loop alternatives that extend the panel's service life, which is designed for use in the building envelope. These alternatives are then evaluated according to the embodied carbon carried by the recycled product fabrication, as an evaluation of the efficiency of the product.

The research commences with the exploration of the current situation of float glass waste recycling. An investigation of the folds of the whole life cycle of this product to identify and evaluate every obstacle rest on the shifting to a more circular model and the exploitation of such waste at the highest possible level, by providing solutions for its achievement. While taking into account all the advantages of using recycled cullet in the glassmaking process.

Right after, the whole comprehension of the recycling process, the most suitable and simultaneously challenging flat glass waste is identified to constitute the panel. Different waste streams containing several contamination rates and diverse particle sizes are melted under specific firing schedules to be evaluated in terms of fluidity as a single stream and then proceeding in compatibility firings between different purity grades of the cullet. With the findings of this exploration, the most promising result of the composite specimen is examined further to gain extra knowledge and serve as an optimization trial on the panel's format to be available in different kinds of projects, while providing the feasibility of this intention.

Identifying the existing research gaps, the exploration continues by contacting tools and methods that have not been utilized before on C&D glass waste, for further examination and evaluation of the remelted outputs. The experimental analysis of the new concept after the development of the composite panel concentrates on the qualitative defects evaluation and stress analysis, for the detection and explanation of residual stresses and any faults' presence, occurring in the kiln-cast objects. In point of fact, the viewings reveal that in the specific samples any coatings, ceramic frits, and traces or small pieces of external pollutants even if they generate some flaws generation on the panel, they are endured by its thick-walled matrix without causing any critical points. As the component is destined also for outdoor facade applications, thermal shock testing is assumed necessary for the glass panel performance on thermal failure, as a response to temperature alterations due to weather conditions that may lead to damage or failure of the component. The developed tensile stresses of low-energy on the tested samples are linked with the critical points where defects exist, especially stones and glass recipe alterations. Moreover, important observations are noted on the micro-cracks, which are restricted in one layer of the composite panel and they are not propagating in the neighboring layers owing to the half-fused state of the cullet and providing a safety mechanism to the product.

Into the spectrum of this research is the major focus on the movement into a more sustainable approach of float glassmaking involving the utilization of recycled glass, tools, and methods that create potentialities into the scope of a circular strategy. To comprehend this alternation approach, the environmental consequences of the production of recycled flat glass panels are examined through the casting method, as a potential to develop the management of C&D waste hereafter. This method is then investigated through the Life Cycle Assessment (LCA), which defines the impact on the ecosystem by analyzing in the present case the part of the life cycle that refers to the utilized materials, production schemes, and the transportation in between these modules. Under rough estimations, the outcome of the whole assessment indicates that the cast glass process with the utilization of recycled C&D cullet is a considerable sustainable process, looking also at the conventional energy-intense float line. While it reveals that cullet use is a beneficial parameter for the overall sustainability of the process. In conclusion, the scope of this assessment is to set the guidelines to identify the areas where energy consumption can be reduced rather than providing absolute numbers.

The thesis exploration does not conclude in a single design proposal, but rather with material ready to be cut and chapped and applied to existing projects and new ones. The exploration of different materials and combinations results in a broad understanding of the parameters that influence the development of this product. Whilst, the performance assessment scenarios form an impression of tested samples to gain the most efficient result within the available time frame of the research as the most promising fit into the glass-to-glass circular strategy that the research focuses on. Furthermore, these verifications on the recycled cast glass panel assist to imitate any probable weaknesses and failures caused by numerous factors.

01.3 RECOMMENDATIONS FOR FURTHER RESEARCH

Based on the main findings and conclusions of the present thesis and the whole experimental exploration, this paragraph discusses some recommendations and thoughts for the further exploration of float glass waste exploitation with the aim of the casting method, into the scope of the circular approach.

The fabrication of architectural thick-walled glass components with the casting procedure, to tolerate the high contamination rate of the undefined composition recycled cullet that is constituted, is still at an early stage of investigation and development, since it has been little examined. This research presents the first steps on the feasibility of such a recycled panel under a specific combination, which is proved through a particular investigation process. Even if their recycling and the design of the composite panel is a quite promising approach, further investigation is necessary. Consequently, several recommendations become apparent.

- 01** During this research, a sufficient amount of specimens for the evaluation of the different flat glass waste were produced. However, the main suggestion would be to explore even further the alternative combinations between waste selection, and cullet types in terms of size, cullet arrangement, mold technology, and firing schedules. There are uncountable combinations that will lead to unexplored paths to gaining knowledge in C&D glass recycling.
- 02** One of the most interesting findings of the research was the composite panel's behavior in stress generation and pattern of cracking, where there is no propagation in the adjacent layers. This indicates a predisposition of the panels to act as laminated glass and not as an entity. This is happening due to the fact that the layers between them aren't fully fused concluding in a positive result in the safety mechanism of the panel. Nevertheless, complementary to the current study would be the performance of an impact test on a series of specimens to unveil valuable knowledge on the composite panel' setup and mechanical behavior.
- 03** A considerably important issue is related to the safety standards of the recycled cullet. Even if a coating was applied to attribute the resistance and strength of the component, something that was proved attainable, further evaluation is assumed requisite to find the most practicable and promising alternatives. Moreover, the safety strategy could be oriented in terms of reversibility or recyclability of the chosen material or method to allow the glass at the end-of-life to be suitable to return to the closed loop of glassmaking.
- 04** Another indication is the physics of this glass material. A promising and potential concept to be developed in terms of thermal performance, light and sound calculations, and fire safety, essential specifications for a component that is implemented in the facade envelopes and should meet some specific criteria to be utilized.
- 05** Additional research could focus is the design and development of reversible connections for the attachment of the panel in the various applications.
- 06** Finally, the embodied carbon calculations heavily rely on assumptions made due to the lack of information. A more precise investigation of the process in combination with cooperation with the industry could conclude in more accurate numbers. While the assessment of the performance of the casting method utilized with raw material could conclude in a more transparent comparison and understanding.

02 | REFLECTION

02.1 GRADUATION PROCESS

1.1 The relationship between the graduation topic and the master's programme.

The “Building Technology” master track covers a wide spectrum of knowledge and design skills linked to both architecture and engineering. The dominant focus of the program is the sustainable strategy in the scope of the built environment. Moreover, it emphasizes the development of innovative design thinking and the generation and implementation of smart building elements and systems within the limits of efficiency and sustainable approach.

Hardly any other material, that is present not only in our everyday environment but also in the built one, could sufficiently meet the current extensive usage of glass. An existence, so ordinary that we infrequently notice, glass is a material that has always fascinated architects and engineers. It witnessed an immense progression in the architectural and engineering sector, creating the perfect link between indoor and outdoor environment. Glass is a readily recyclable material, that can be remelted and reformed again and again, indefinitely, into articles with the same quality and properties as the original one, nominating it as a perfect candidate in the transition efforts for a low-carbon environment.

The current graduation thesis is mainly related to sustainable material science and glass recycling held by the ongoing research of “Glass & Transparency Group” of TU Delft. Moreover, it aims to further contribute to this quest for novel glass solutions for the built environment, with investigations into the innovative and sustainable glass recycling strategy.

1.2 Elaboration on research method & approach upon the scientific relevance, related to the graduation studio.

The Built environment makes up one of the industrial sections with the highest utilization of energy demand, exploitation of natural resources, and waste generation, causing environmental pressure generated by the construction and demolition sector. This consideration places it, as a substantial field, where sustainable approaches such as reuse and recycling have to take ambitious and pioneering actions. Sizable quantities of various materials and products in the C&D sector and extended construction areas represent the ideal and inviting circumstances, where recycled materials could be exploited in a circular economy. Over and above that, the EU already sets rules and targets in order to make certain this waste is handled in a way that preserves the natural world and circularity is promoted.

Specifically, in the Netherlands a major campaign has been launched in 2016, to drive to a fully circular Dutch economy by 2050. For Dutch, the building sector constitutes a significant part of their financial system. In response to that, specified Agendas set goals for this strategy to be also implemented in the Construction & Demolition industry, which will tackle the environmental, economic, and societal challenges.

Looking at the world of construction, glass panes are all the time used material for façade applications in transparent surfaces of the building envelopes. However, the continuously increasing trend in the architectural and engineering field, towards wider applications of glass surfaces and demand for transparency in the building facades, has spread the need for float glass extended generation. Consequently, the impact on the environment surges, due to illogical energy consumption, increased greenhouse emissions, and the depletion of the limited natural resources. This stresses the need for a well-organized closed-loop recycling system for C&D glass waste.

Generally, the sustainable design graduation studio focuses on innovative design technologies and methods in the scope of the built environment. The current thesis aims to further contribute to this quest for innovation in sustainable glass recycling by focusing on finding circular ways to redefine the production of flat glass with the aim of casting methods and assessing the embodied energy which is included in the life cycle of the new product. So, determined efforts are made, in order to deal with this unsolved problem of flat glass waste, with the assistance of circular principles. The prevention of waste generation, the shift to reuse, remanufacturing, and recycling, along with the ecological design approach, give the right perspectives to use resources efficiently and conclude on positive environmental impacts.

1.3 The relationship between research & design.

Main part of the current thesis is the concept “Design thHo Research”. The review of an extensive literature into various sectors from glass technology, glass recyclability, and architectural glass waste to the mapping of the current recycling process of flat glass, in order to recommend suitable solutions to overcome any barriers rest on the path to sustainability. For the time being, it is obvious that a linear flat glass waste chain incurs, so the need to switch towards a circular life-cycle of such waste is rising. The growing interest, in this transition to closed-loop recycling, can be also seen and encouraged by float glass industries and different actors in the whole construction sector.

After gathering an extensive amount of information and data, which were cross-referenced between numerous studies and authors, the primary foundation was set. That served as the starting point for the experiments, indicative variables, design considerations, and criteria.

Nevertheless, the purpose of this research is to develop and experimentally verify with the aid of casting, not only new design concepts and engineering their fabrication in accordance with the design criteria, but also an ideal recycling collection system for cullets coming from the C&D sector. These recycled panels are introduced by means of closed-loop alternatives that extend the service life of these products, establishing at the same time the foundation for a circular life-cycle of architectural glass. This is achieved by experimentally testing the recyclability of different flat glass waste used instead of raw material, as monolithic thick-walled components are created for built environment applications, produced through the casting method. According to the literature, higher thickness compared to the conventional thin-walled glass is able to tolerate a higher contamination rate, something that is also verified through the experiments exploration and experimental studies prior to mine, held by the TUDelft Researchers.

The final results of the material exploration indicated some promising and interesting outputs, even if it is based only on a specified number of casting samples. Recycling C&D cullet is an ambitious path to meet the market's needs, while it contributes to the circular economy performance based on natural resources reuse. Design and specifications, for new facade components with the use of glass recycling, will take us a step closer to the national program «Circular Netherlands in 2050» that aids to reach pioneering material savings and become zero waste in the construction sector. Moreover, the current thesis provides the guideline for further performing laboratory scientific studies on the recycling of flat glass waste.

1.4 The way that research approach worked out and led to the aimed results.

The well-organized and prioritized literature review according to new findings, most important authors, cross-referenced information, and understanding of the current obstacles and limitations of C&D glass waste, assisted me to make the whole study effort to work out properly. Accordingly, the findings of the bibliographic search were classified into the three main parts of the literature body of my thesis, which was no other than the glass technology, glass recyclability, and deep exploration of the C&D glass waste stream. These laid the foundation to draw conclusions on how to proceed with my experiments and which parts of them to determine carefully.

However, owing to the labor-intensive and time-consuming experimental process in the laboratory, limited the number of specimens to be tested. Moreover, further exploration could be held on the compatibility tests in the final composite glass panel, along with the design of a unique connection system for its implementation in the built environment. Additionally, a coherent indication in the safety evaluation of such components would also be essential.

02.2 SOCIAL IMPACT

2.1 The relationship between the graduation project and the wider social, professional, and scientific framework.

Nowadays, the contemporary world is moving towards more robust and sustainably efficient environments on account of the present climate emergency, the abatement of nonrenewable energy, and the shortage of natural resources. The whole ideology, infrastructure, and legal system are crucial to alter all the more!

Glass is one of the oldest synthetic materials, which carved its path into human activity, not only in everyday life but also in the scientific and technological aspects. A widely used material, likewise in the building industry, its production continues ascending, causing a significant environmental impact. Even if the glass is a material totally recyclable in theory, and the recycling of it has been conducted since its discovery, only a small part gets

recycled mainly by the packaging industry. Essentially, glass waste remains a significant unresolved problem and a considerable part refers to float glass, mainly used for architectural purposes, coming from the construction and demolition sector. This results from the fact that there is not a proper recycling system for such waste and also most of the discarded cullet fail to pass the quality standards due to contamination, as set by the current rigid float glass generation process, aftereffects from coatings, lamination, adhesives or incompatibility to the recipe, closing their life-cycle in the landfill.

With the growing demand for glass and the waste that comes from the Construction & Demolition sector, it is deemed necessary to explore the possibilities and potentials of investigating and mapping a closed-loop recycling system that will provide us the needful sustainable material to be applied for new concepts for the built environment. It is really important to mention that this upcycling system in examination is a new approach based on data coming from the industries and glass experts, and not many experiments have been done in this field. As it is in the aftermath, this experimental approach may be really challenging but it would give great potential while probing new data through a case study, and start filling the scientific gap that exists at the present time. The mapping of this upcycling method, in combination with the research-based exploration through material casting tests, provides the next step for a deeper understanding of the float glass upcycling process. Any development within this field could act as a guideline and inspiration for future reference and investigation for architects, engineers, scientists, and the glass industry.

Moreover, the development of responsible manufacture and consumption is capable of attaining results with remarkable social, financial, and last but not least benefits related to ecosystems' value chain. Consequently, glass recycling in the C&D field qualifies the mitigation of human demand in nature and its footprint by putting away energy and natural resources, while it introduces locally new job offers.

2.2 Ethical issues or dilemmas encountered doing the research.

The primary scope of the research is to explore the most possible and at the same time efficient scenarios of C&D glass recycling on the fabrication of the panel. Every step and part indicated moments in which choices had to be made. Through the research, various challenges were explored until reaching the desired result. Considering the findings, and outlining the available options with arguments, led me in every decision that I had to make until the end. Even if often, this was mainly a chain of fortune events and afterward just the decisions made based on the results, due to the lack of background knowledge on this topic and the fact that I was working almost blindly.

The ethical issue that I faced was not about how this new knowledge would be handled, provided that would not hurt human life, built environment and ecosystem –they will only benefit from such a study–, but it mainly had to do not be shown inadequate in the research that I committed myself in, and with responsibility and proper research to give reliable results to promote them within the spectrum of truth and error avoidance, while providing at the same time expanding knowledge of the topic of flat glass closed-loop recycling. However, driven by sustainability and circular strategy, every result is accompanied by experimental validation and shows the potential and limits of recycled cast glass products.

2.3 The extent that research results are applicable in practice.

At first sight, the current research prioritizes the upcycling of glass coming from the float line. With the growing demand for this material, and the waste that comes from the Construction & Demolition sector, it is deemed necessary to explore the possibilities and potentials of investigating and mapping a closed-loop recycling system that will provide us the needful sustainable material to be applied for new concepts in the built environment. Glass recycling is qualified to convert the manufacturing industry to its supreme productiveness with the smallest damage to the ecosystem through waste generation and concludes in significant environmental benefits. It is really important to mention that this upcycling system in examination is a new approach based on data, coming from the industry, glass experts, and small but ambitious efforts that have been done in this field to overcome any barriers rest on the path to sustainability.

Recycling this cullet is an ambitious path to meet the market's needs, while it contributes to the circular economy performance, based on natural resources reuse. Design and specifications, for these new facade components with the use of glass recycling, take us a step closer to the national program «Circular Netherlands in 2050» that aids to reach pioneering material savings and become zero waste in the construction sector.

With the aim of the cast glass method, the manufacture of the glazed panel is achieved through a more flexible process with small-scale production and a bigger thickness of the object, which actually is able to tolerate more

contamination and impurity rates than thin-walled glass. Moreover, it minimizes logistical and environmental costs of waste collection and transportation. The final product applicability can be met not only on a facade envelope but also in other architectural elements such as glazed floors and inner partition walls.

02.3 PERSONAL REFLECTION

The past eight months, in which I am involved with my graduation thesis, have been a unique and exciting learning experience with ups and downs in the whole study and research process. This timeframe and needed tasks would not be possible without the assistance and encouragement of many people. People that come from my familiar environment provided me support, and my professors shared their knowledge, expertise, enthusiasm, and wondering about the evolution of my research topic on C&D glass waste up-cycling. They always stood by my side to inspire me, providing another perspective on every aspect, and finally keeping my feet on the ground when I lacked motivation and obstacles rested in my experimental research.

In general, working on a thesis like this is an experience like no other before. The exciting world of glass is not something that I was accustomed to, since my background is based on architectural design and expression. However, due to the fact that the more I read about glass as a material, the more fascinated I become about it, acting as an encouragement to get one more step at a time. However, the road to this was not easy.

My topic choices posed various challenges that I had to go through, and solve within a relatively limited amount of time, since investigating and developing the up-, and recycling feasibility of float glass, in order to create a glazed facade panel made from recycled glass coming from Construction & Demolition cullet, considering at the same moment the embodied energy that it possesses, is not a simple task. This effort is combined by many different but linked together topics, commencing glass technology, glass families and composition, production techniques, glass waste classification, and their recyclability, problems, and limitations in the current existing or not recycling systems and simultaneously, the selection of C&D glass waste, which constitutes a significant waste stream, its mass quantities of flat glass that are either landfilled or diverted to a next-use market, for instance, aggregate. Nevertheless, even if this type of glass is of a great number around us, small efforts have been made by the float industry such as the glass waste to be used as high-quality cullet in the glass sheets production. The aforementioned fact implies that there is a lack of data and figures on the market, making my efforts to further unveil the possibilities of recycled glass more challenging. This also entails the mapping of an ideal recycling collection system for cullets coming from the built environment and the life cycle assessment of the embodied energy, which is included in the life cycle of the new product and is needed to complete my thesis approach, to be a little more difficult and time-consuming, but not unattainable research.

As far as the preliminary results of my research are concerned, there is a constant evolution and experimentation in the opportunities that recycled glass cullets are given with every firing exploration. They comprehend and extended literature review on every aspect of glass technology and recycling with the right programming, enthusiasm, additional knowledge, and the instructive assistance, which helped me to adapt to each new normal, in order to support my work and my ideas, to point out better directions for the optimal result of the recycled C&D glass panel. All these also helped my whole approach to the research and the experimental process to be more recreational and enjoyable, in combination with the inspiring feedback from my mentors, and the out-of-the-box conversations and thoughts.

Apart from the whole experience and if the final result is successful or not, the process seemed to be a steep learning curve. Here, I taught myself to look into the things that are possible to be done in a way, instead of letting myself be led by the difficulties and challenging situations I fell into. The whole process made me more optimistic about the next steps in recycling float glass within the sustainable closed-loop approach.

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