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Fabrication methods for topology-optimized massive glass structures

Faidra OIKONOMOPOULOU*, Menandros IOANNIDIS[a], Anna Maria KONIARI[a], Telesilla BRISTOGIANNI[a]

[*] Delft University of Technology, Faculty of Architecture + The Built Environment
f.oikonomopoulou@tudelft.nl

[a] Delft University of Technology, Faculty of Architecture + The Built Environment

Abstract

Recent research at TU Delft has highlighted the potential of using structural Topology Optimization (TO) for designing large monolithic cast glass structures of maximized stiffness with minimal mass. The mass efficiency of these structures results in considerably shorter annealing times and, consequently in improved manufacturability in terms of time, energy and cost efficiency. Nonetheless, the geometrical complexity and customization of the resulting forms renders them challenging in terms of fabrication. Exploring the manufacturability of such intricate glass structures, in this paper we discuss the different possible fabrication methods for three-dimensional glass structures of complex and customized geometries, via a review of existing literature, experimental work and prototyping. Specifically, with the aim of addressing all possible manufacturing solutions, we look into the following fabrication methods: (i) casting in disposable moulds; (ii) waterjet cutting and lamination of float glass panes and; (iii) additive manufacturing of glass. We assess these methods based on a set of criteria linked to the structural performance, visual quality, fabrication limitations and sustainability. Accordingly, we discuss the potential, challenges and practical limitations of each fabrication method for real-world applications of TO glass structures. Subsequently, we propose the integration of alternative constraints into the TO formulation, so that customized TO tools that better reflect each fabrication method can be created.

Keywords: topology optimization, glass fabrication methods, construction techniques, customized geometry, cast glass, glass structures, shape complexity, disposable moulds

1. Introduction

Ongoing research at TU Delft [1-3] has highlighted the potential of using structural topology optimization (TO) for the design of monolithic, three-dimensional cast glass structures of complex and customized geometries for architectural and structural applications. By maximizing the stiffness while maintaining minimal mass, the design of monolithic, load-bearing glass structures of substantial dimensions can be achieved with considerably shorter annealing times; the castings of the glass mirror blanks of the giant telescopes are a characteristic such example (fig.1, left) [4]. Promising topology optimized structural glass applications include free-form glass shells and nodes [3], glass slabs, bridges [2] and columns (fig.1). So far, the research has focused on the development of a TO formulation for cast glass structural components that allows for an asymmetric stress behaviour and incorporates constraints to ensure feasible annealing times [1] and, in turn, improved manufacturability in terms of time, energy and cost efficiency. Still, there has been little exploration on the fabrication methods of the resulting complex and customized shapes. Thus, this paper reviews the different possible fabrication methods for three-dimensional glass structures of customized, complex geometries generated by TO. In specific, with the aim of addressing all possible manufacturing solutions we intentionally depart from cast glass as the only possible expression of such geometrically complex forms, and we look as well into alternative fabrication methods (fig. 2). Hence, we explore: (i) casting in disposable moulds; (ii) waterjet cutting and lamination of float glass panes and; (iii) additive manufacturing of glass.

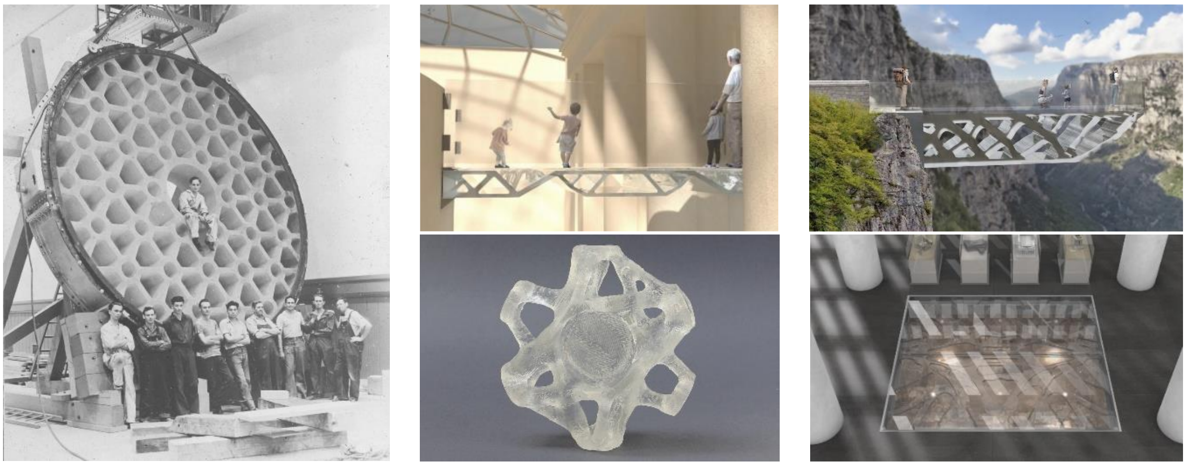

Figure 1. From left clockwise: Cast glass mirror blank of the Hale-1 telescope following a honeycomb structure (image credits: The Rakow Library, Corning Museum of Glass). Impressions of TO cast glass bridges (image credits: A.M. Koniari and M. Ioannidis) and floor (image credits: I. M. Stefanaki), and prototype of a TO cast glass node (image credits: W. Damen).

2. Methodology

To assess the aforementioned methods, we first establish a set of criteria linked to the structural performance, visual quality and fabrication limitations; towards sustainability, the waste generation and recyclability of the glass components are also addressed. Accordingly, we discuss the potential, challenges and limitations of each method based on literature review and on our main observations from experimental and prototyping work. Towards the creation of customized TO tools that better reflect each fabrication method, we propose the integration of alternative constraints into the TO formulation.

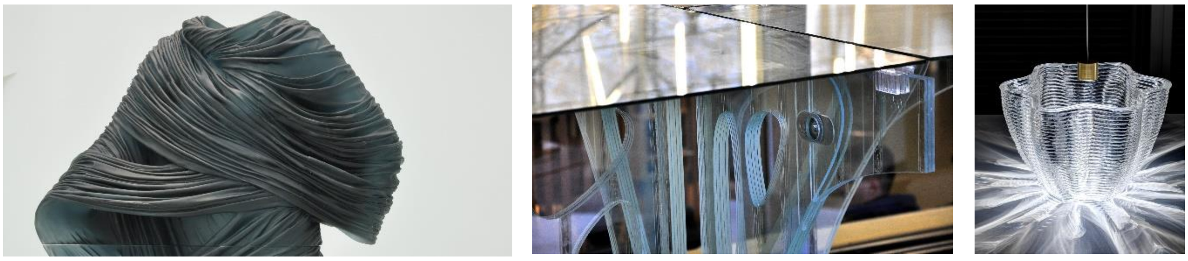

Figure 2: From left to right: Examples of free-form shapes in glass using (i) casting in disposable moulds (sculpture by Karen LaMonte), (ii) waterjet cutting and lamination of float glass panes at a prototype made in TU Delft and (iii) additive manufacturing of glass (image by C. Inamura)

3. Assessment criteria

With the aim of generating customized, complex geometries in glass, the three different fabrication methods are assessed on aspects related to the (i) structural performance, (ii) optical performance, (iii) fabrication limitations and (iv) sustainability. In specific:

(i) structural performance is evaluated in terms of the inherent strength and the integrated redundancy of the resulting glass components/structure;

(ii) optical performance concerns both the resulting transparency, as well as the finishing surface quality of the components (fig.3);

(iii) fabrication limitations are particularly linked to shape and size limitations of the chosen manufacturing methods, need for post processing and ease of fabrication;

(iv) sustainability regards the waste generation during fabrication and the recyclability of the resulting components.

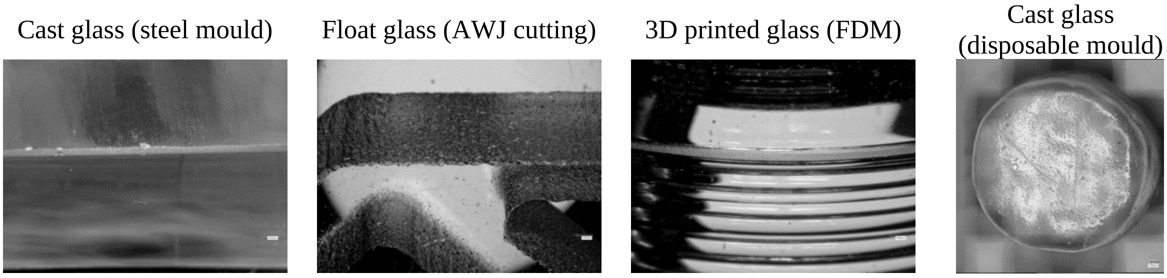
Cast glass (steel mould)
Float glass (AWJ cutting)
3D printed glass (FDM)
Cast glass (disposable mould)

Figure 3: Microscope photos of the finishing surface quality of the different fabrication methods.

As the different assessment criteria are interconnected, they can directly impact each other. For example, the surface finish quality can influence the strength of the glass component, as well as the need for post-processing. Given the novel application of these fabrication methods for structural applications, there are limited if any comparable quantitative data in the forenamed aspects, which can lead to misleading observations. Thus, a qualitative assessment is made as more representative.

4. Fabrication methods

4.1. Casting in disposable moulds

Casting enables the creation of virtually any shape and size in glass. Nonetheless, currently in architecture, structural cast glass components are typically limited to solid blocks, similar in size to standard terracotta bricks [5]. This limited size is mainly due to the excessively lengthy annealing time required in massive glass pieces, which can span up to multiple months [4], and can subsequently result in prohibitive energy and manufacturing costs. The component's geometry and selected glass composition are the most influential factors of the annealing time. Essentially, the higher the thermal expansion coefficient of glass and/or the larger the cross-sectional thickness of the component, the exponentially longer the annealing time required. The optimization of the stiffness-to-weight ratio of cast glass components, e.g. via structural TO, and the use of glass compositions of lower thermal expansion coefficient (e.g. borosilicate glass) can greatly reduce the annealing time and subsequently, allow for larger overall dimensions.

For customized and geometrically complex components such as the one resulting using TO, disposable moulds and kiln-casting are preferred over permanent metal moulds and hot-pouring, as they are considerably cheaper and allow for a significantly higher freedom in shape[1]. Prototyping work at TU Delft has pointed towards two alternative disposable mould fabrication methods for kiln-casting: (i) silica-plaster (e.g. Crystal Cast) investment moulds using a was positive model[2] of the desired geometry that is steamed out (lost wax-technique), as shown in fig.4, and (ii) 3D-printed sand moulds (fig.6). The former, typically used in intricate-shaped glass art castings, are in principle laborious and yield

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[1] Considerably more expensive multi-component steel moulds can be used for the casting of complex geometries in glass; nonetheless, such moulds cannot incorporate undercuts.

[2] For highly intricate shapes, the wax positive model can be produced using 3D-printing or sintering of wax. Research in both methods at TU Delft suggests that sintering produces more refined, smooth textures.

compromised dimensional accuracy. An alternative offering higher accuracy, yet also resulting in considerably higher manufacturing costs, is milled alumina-silica fibre ceramic moulds, such as the ones employed in the castings of the giant mirror blanks (see fig.5) [6]. For architectural applications, 3D-printed sand moulds are considered more suitable, due to their low cost, quick production, scalability and high accuracy (up to ± 0.1 mm, defined by the grain size of the sand) [6]. Previous and current experimental work at TU Delft, has shown that 3D-printed sand moulds using inorganic binders are the most promising option for kiln-cast glass components [6]. 3D-printed sand moulds can currently be produced up to 4m x 2m x 1m in dimensions by *Voxeljet printer* VX4000; nonetheless, larger, multi-piece moulds that interlock together can exceed these dimensions.

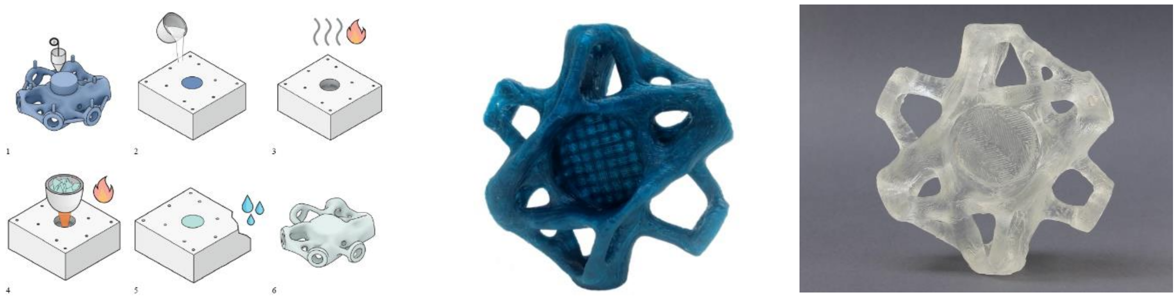

Figure 4: Left: Process of producing a silica-plaster mould process employing a wax positive. Right: Wax model (top) and resulting cast component (right). Image credits: W. Damen

Figure 5: Milled alumina-silica fibre ceramic mould (left) for the casting of the Giant Magellan Telescope mirror blanks and segment of glass produced in such a mould (right)

Figure 6: 3D-printed sand mould and produced glass component

4.1.1. Structural performance

Similarly to float glass panes, cast glass displays isotropic material properties. Glass's brittle failure is typically triggered by inherent flaws. Massive cast glass pieces are prone to the inverse scale effect: the larger the component, the higher the probability of critical flaws within it, thus the lowest its probabilistic strength [7]. In addition, the lack of a large-scale, automated and controlled production and of quality control standards for cast glass, contribute to an increased occurrence of defects compared to the fully-automated and strictly controlled float glass production [5, 8, 9]. The lack of sufficient strength data and of inherent redundancy in the structure, result to a decreased overall strength of cast glass compared to float and enforce the use of increased safety factors. Thermal tempering that can increase glass's tensile strength, is not advised for volumetric glass components, particularly of ones of intricate geometry, due to their bulky and uneven cross-section[3]. All the above, mandate a significant increase in material use when designing with cast glass compared to float.

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[3] In thermal tempering of (float) glass, the material is first heat up and then rapidly cooled down, resulting in the outer surfaces being into compression and the inner surfaces being into tension. In volumetric glass components and/or in perplex cross-sections, tempering in a controlled manner would be extremely challenging, due to the considerably larger temperature deviations between the centre and the surfaces of the glass.

A monolithic glass structure lacks redundancy in case of failure. Possible engineering solutions that allow for redundancy, are the lamination of a float glass layer (if possible in terms of shape), or the segmentation of the structure to enable enhanced redundancy against crack propagation. In this direction, cast glass structures made of interlocking units are a promising solution with inherent redundancy [10]. Finally, initial prototype and experimental work at TU Delft suggests that glass beams with embedded metal reinforcement during casting can have increased ductility, exhibit a warning mechanism prior to ultimate fracture and secure a post-failure load-bearing capacity [11].

4.1.2. Optical performance

The monolithic nature of cast glass allows, in principle, for increased transparency. Nonetheless, the transparency of kiln-cast glass elements is affected by several factors, including the type of glass, firing temperature and annealing schedule, type of mould (fig.3) and coatings applied on it, and post processing. Transparency can be increased if a low-iron glass recipe is used that omits any colouring (e.g. of green tint). Transparency is mainly compromised in the finishing surface quality: grains of the disposable moulds tend to adhere to the glass, resulting in an opaque and rough surface, mandating post-processing, which in turn results in compromised dimensional accuracy and higher manufacturing costs. To achieve a fully transparent and smooth finishing quality of glass cast in disposable moulds, the application of mould coatings is necessary. Previous research at ETH focusing on foundry casting in 3D-printed sand moulds fabricated with inorganic binders and coated with a combination of *Zirkofluid* and graphite-water dispersion yielded promising results [12]. Current experimental work at TU Delft focuses on the further investigation of coatings that can yield a completely smooth and transparent surface quality in kiln-casting[4]. So far, series of kiln-cast prototyping experiments in several annealing schedules using two types of 3D-printed sand moulds (quartz or ceramic sand printed with inorganic binder), sponsored by *ExOne*, and a combination of coatings, sponsored by *Hüttenes-Albertus*, indicate that the combinations with the best finishing quality are (i) molds printed with quartz sand coated with *Arkopal B5* and (ii) molds printed with synthetic (ceramic) sand coated with *Crystal Cast* and *Zirkofluid*® 6672 or 1219 (see fig.7). In specific, kiln-casting experiments at 870˚C at the *TU Delft lab* facilities suggest that direct application of *Zirkofluid* coatings on the mold surface lead to partial adhesion of the sand and coating to the glass (fig.7b). When a substrate layer of *Crystal Cast* is added under the coatings it leads to a better surface quality and no sand consolidation (fig.7d-f). Given the above, 3D-printed molds of a material similar to Crystal Cast could as well be a promising solution.

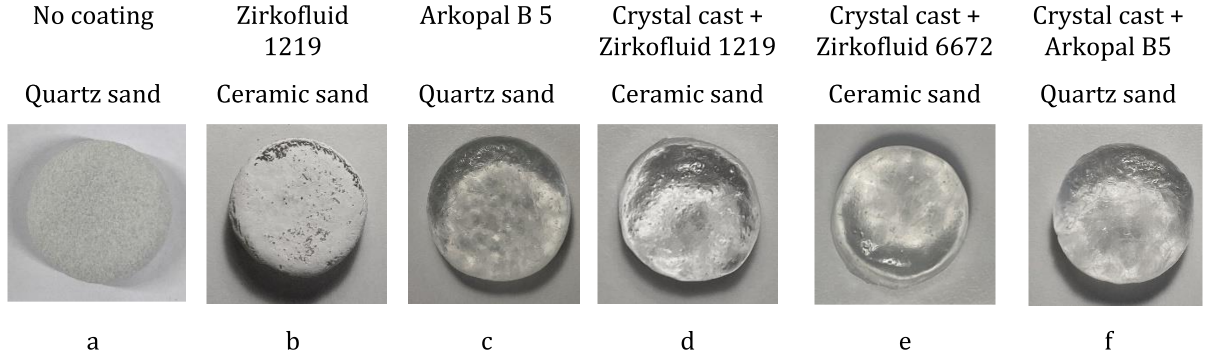

Figure 7: Glass surface of glass specimens kiln-cast at 870˚C in coated 3D printed sand moulds.

4.1.3. Fabrication limitations

The use of disposable moulds allows for great freedom in the shape and size of the cast glass components, as exhibited in existing cast glass art pieces of massive dimensions and/or of highly

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[4] Compared to foundry casting, kiln-casting requires a considerably more prolonged heating cycle of the moulds.

intricate shapes [4]. The use of interlocking 3D-printed sand moulds can enable considerably large castings; the potential size of a structure utilizing such moulds has been exhibited in concrete castings, such as the *SMART SLAB* by ETH, where 3D-printed sand moulds were used for the underlying formwork [13]. In essence, the size of the glass casting is confined to the size of the kiln. Even so, custom-made kilns can be built to accommodate large castings, as proved by the castings of the *Giant Magellan Telescope* and of multi-ton glass sculptures by *Roni Horn* [4]. The component's annealing time can be considered the governing factor in limiting the glass component's overall size. Castings of massive cast glass blanks requiring up to 1 year of annealing have been recorded [4], yet such prolonged times would be prohibitive for applications in the built environment. Nonetheless, with the aid of TO, the generation of massive pieces of optimized stiffness-to-mass ratio can be achieved, which in turn can yield feasible annealing times and associated energy costs.

There are limitations in relation to shape though. Shape limitations are greatly linked to the proper annealing of the glass component and to the mould's geometry and strength. For example, abrupt changes in the component's thickness should be avoided as they would result in uneven cooling of the glass. The size and geometry of overhangs, and of very thin voids, should be as well associated with the mould's strength. Furthermore, the use of a mould hinders completely enclosed cavities.

Post-processing, in particular polishing, may be necessary to obtain the desired smooth, glossy finishing surface and to omit dimensional deviations due to the natural shrinkage of glass occurring during cooling [14]. The effect of natural shrinkage can be reduced in some cases by employing spin-casting [4]. Polishing can be challenging in cavities that are not easily accessible by the relevant equipment.

4.1.4. Sustainability

Being monolithic, cast glass can be recycled in a closed-loop. Its recyclability can be compromised, if a sacrificial layer is laminated for safety/redundancy, due to contamination by the lamination foil. The ability to cast directly the desired shape prevents the generation of glass waste. Finally, in the case of 3D-printed sand moulds, their water dissolvable composition enables the remaining sand to be reused.

4.2. Waterjet cutting and bonding of float glass panes

By abrasive waterjet (AWJ) cutting and bonding together multiple float glass layers, freeform, layered 3D glass structures can be made. In this process, three distinct fabrication steps are involved: The float glass production, the waterjet-cutting of the individual glass panes to the desired shape, and finally their bonding or lamination. In specific, AWJ cutting is a subtractive manufacturing method, used for a broad range of materials, including metals, stone and glass; it employs high-pressure waterjets with fine abrasive grains to cut the workpiece material. A computer-controlled head and nozzle with up to 5-axis allow for precise cutting under varying angles and the flow rate and abrasive size can be adjusted for optimal cutting and surface quality of the edge [15]. AWJ cutting of glass panes can lead to rough or non-perpendicular edges (kerf angle, see fig.3), necessitating the post-processing (polishing) of the edge in order to avoid undesirable stress concentrations. Once the individual sheets are AWJ-cut, they should be bonded together. Extensive literature research suggests that industrially fabricated examples using lamination are typically confined to 5-6 layers; one of the largest known multi-layer laminations is the 11-layered *Glass Wippe* by EOC Engineers. Multi-layered structures, such as the horizontally-layered glass sheet sculptures of the 6 m high *Glass Sphinx* (NL) and the 3 m high *Glass Angel* (NL), and the vertically-layered *Laminata House* (NL) opted out of lamination, but also of a conventional adhesive application, as structural glass adhesives are yet to be developed for bonding large surfaces of glass in stacked configurations [16]. Instead adhesive tapes were used for assembling the Glass Angel [17] and the Glass Sphinx [18]; in *Laminata House*, the individual sheets were cut and pre-adhered on site in sets of 10 using a 2-component silicon compound, then installed in place using a silicone-based sealant.

4.2.1. Structural performance

The structural properties of float glass are well-documented with engineering values provided by several standards (e.g. DIN 18008, EN 16612:2019, NEN 2608:2014, ASTM E1300-00). Owing to the highly automated process and strict quality control in float glass production, float glass presents the highest engineering strength values (for soda-lime glass) among the three discussed fabrication methods. The tensile strength of float glass can be further increased via tempering. The inherent redundancy due to the bonding/lamination of multiple layers and the well-documented, predictable strength of float glass lead to the use of reduced safety factors in this case. The strength can, however, be compromised due to edge flaws introduced by AWJ-cutting; although these can be minimized by post-processing/polishing the edges. It should be noted that layered glass structures are in essence, anisotropic: they present considerably higher strength in parallel to the glass panes than in (long-term) loads perpendicular to the laminate, where, an effective thickness of the laminated or bonded glass should be considered [19].

4.2.2. Optical performance

In principle, float glass panes are of high optical quality. Yet, the transparency of a freeform, layered glass component made of float panes depends on the number and orientation of the glass layers, the overall shape and the viewing angle. In specific, a structure can be perceived as fully transparent when viewed perpendicular to the laminates, and completely opaque when seen parallel to the laminates. Polishing of the cut edges (fig.3) is essential for obtaining a smooth finish surface.

4.2.3. Fabrication limitations

A variety of machinery and materials are used in this method, resulting overall in a complex and costly process. Although individual glass panes can size up to 24m x 3.21m, further size limitations are imposed by the subsequent processing steps. Although AWJ typically has a cutting table of 4m x 2m, it can be customized to accommodate larger sizes. For example, the *yc waterjet* company has produced customized AWJ cutting tables up to 4m x 12m in size for 3-axis AWJ and 3m x 8m for 5-axis AWJ. The total thickness of the layered glass structure is subject to the type of bonding: lamination can be easily achieved for 5-6 layers of glass (each of a max. 25 mm thickness), and has been recorded for up to 11 layers. Beyond this number of layers, a customized adhesive solution should be followed, further adding to the costs and possibly affecting the overall strength.

In terms of shape freedom, a major limitation is that the desired geometry should be made by the bonding of virtually flat elements. In addition, the lamination or bonding process can render challenging the creation of undercuts and voids, as uneven pressure loads can occur during the lamination, which can lead to the eventual failure of the glass. Overall, lamination of multiple layers is challenging and can increase considerably the overall fabrication cost. If the glass sheets are bonded together with an adhesive, its uncontrollable overflow in non-accessible areas can compromise the final visual result. If an adhesive tape is used instead, the tape lines can be visible. Lastly, considerable accumulated dimensional offsets can occur, even with the high accuracy level of float glass thickness and the use of thin tape, as in the example of the *Glass Sphinx* where an accumulated height offset of 4 cm was recorded [20]. Finally, as the AWJ cutting results in a rough surface, subject as well to edge flaws, post-processing of the edge is necessary, which can be challenging in hard-to-access areas of the cut glass piece.

4.2.4. Sustainability

The subtractive nature of AWJ results in considerable glass waste. The discarded cut-out glass pieces, can be recycled by remelting; although this is an energy-intensive process. Once assembled, laminated/ bonded glass components are in principle hard to recycle, due to the difficult separation method and the inevitable contamination of the glass by the interlayers/adhesives.

4.3. Additive manufacturing (AM) of glass

Additive manufacturing (AM) of glass is still in an early stage of development, yet it displays great potential for the fabrication of freeform glass structures. Several AM methods have been explored, but most concern smaller elements [21]. The prevailing AM method for bigger glass elements is *Fused Deposition Modelling* (FDM). FDM involves a continuous filament feeding through a computer-controlled heated nozzle; it is the only method so far with available, yet limited, structural data on glass [22]. Such an AM method for printing silica glass, G3DP, was first developed by *Micron3DP* and *MIT*. G3DP is based on a dual heated chamber concept. The upper part, essentially a kiln cartridge, operates at ~1040°C and pours the molten glass through a nozzle to the desired shape. The object is built within the lower annealing chamber which keeps the glass hot enough so that the next layer of structure adheres to it while the glass can cool down controllably. A second version, G3DP2, allowed for more accurate prints and improvements in speed and printable volume. It includes a digitally integrated thermal control system to accompany the various stages of glass forming and a 4-axis motion control system for flow control, spatial accuracy and precision and faster production rates with continuous deposition of up to 30 kg of molten glass [23]. Up to now, AM of glass has been confined to small-scale objects. The largest in scale project is the *Glass II* [24], which concerns the fabrication of 3m-tall free-standing, pre-stressed hollow glass columns of intricate geometry, each consisting of 15 segments [25].

4.3.1. Structural Performance

AM glass components present anisotropic structural performance. [26] states a 40% difference between the major and minor axis. Loading perpendicular to the plane of the layer (major axis) displays the best performance. More extensive, yet still limited, testing has been performed by [22] in annealed and chemically tempered samples under 3-point bending, suggesting a tensile strength of 51 MPa in the major axis and 41 MPa in minor axis for annealed glass; whereas chemically-strengthened glass samples presented high deviation in the strength, leading to inconclusive results. Due to the small size of the tested samples, the high variation in the resulting values and the use of 3-point instead of 4-point bending tests (which would result in less favourable flexural strength values), in the work of [22] a safety factor of 10 is used. Moreover, the interface between two consecutive layers can display poorer mechanical properties than the rest of the volume. Improper adhesion of the layers can lead to delamination and failure of the sample, as shown by preliminary 3-point bending tests parallel to the layers conducted by [26]. However, the layered structure may be able to stop slow-crack growth. Still, to derive engineering strength values for 3D printed glass components extensive experimental validation remains necessary.

4.3.2. Optical Performance

Similarly to laminated glass components, due to its visible layering, 3D-printed glass using FDM displays directional transparency (see fig.2 and fig.3). In order to achieve the desired, glossy result, the finishing surfaces (top and bottom sides) should be polished using cerium oxide [26].

4.3.3. Fabrication Limitations

3D-printing of glass has a high potential in creating components with complex inner features. Yet, it can only occur within a highly controlled annealing chamber; hence, similarly to cast glass, the glass object is confined to the size of the annealing chamber. Contrary to kiln-casting, two kilns are required in this method, one for the printing cartridge and one for the annealing of the printed object. Currently, the maximum printable area is 320 mm x 320 mm x 350 mm with a flow rate of 5.2 kg/h [22] and a max. capacity of 30 kg of glass [23]. For an element of 10kg in weight, 1 hour is needed for the printing and 8 hours for annealing [25]. Further shape limitations linked to FDM, include overhang limitations which may necessitate supports, and the generation of shapes that can be produced by a continuous thread.

4.3.4. Sustainability

3D-printed glass can be considered a 100% recyclable and waste-free production method.

5. Conclusions

Table 1 provides a qualitative comparison of the different fabrication methods for complex, customized structural cast glass components, such as the ones derived using TO.

Table 1: Qualitative comparison of the different fabrication methods

Criteria		Cast	Waterjet cutting and bonding of float glass	Additive manufacturing
Structural	strength	+ medium	++ high	- low
	redundancy	- no	++ high	- no
Optical	resulting transparency	++ high	+ medium - low	- low
	finishing quality	- medium-low	++ high	+ medium
Fabrication limitations	size freedom	++ high	+ medium	- low
	shape freedom	++ high	+ medium	+ medium
	post-processing	- high	+ medium	++ medium-low
	fabrication cost	- high	+ medium	- high
Sustainability	waste generation	++ low	- high	++ low
	recyclability	++ high	- low	++ high

Waterjet cutting and bonding of float glass presents the best structural performance overall, mainly due to the well-documented and highly controlled properties of float glass, and the inherent redundancy of a multi-layered solution. Adding to the above the possibility of increasing the tensile strength of the components by tempering and the use of reduced safety factors compared to the other two methods, this fabrication method probably yields the most lightweight structure. On the downside, transparency in this case is subject to the directionality of the layers. Moreover, there are considerable limitations in both the size and the shape of the resulting piece. It is also considered the least sustainable solution, as it produces substantial glass waste and the final component cannot be easily recycled back to glass.

Cast glass is the preferred solution in terms of resulting transparency, sustainability, shape and size freedom. The governing restriction size-wise is the annealing time, which, however, can be considerably reduced by an optimized geometry and by choosing a glass composition of low thermal expansion coefficient. An inherent disadvantage is that post-processing of the finishing glass surface is essential, due to the use of disposable moulds for the fabrication of customized components; although, research at both ETH and TU Delft on mould coatings already yields promising results towards obtaining a good surface quality directly in demoulding. In terms of structural performance, cast glass components present lower strength values compared to float. This is attributed to the less controlled casting process and the lack of relevant quality standards, as well as to the inverse scale effect in large glass components. All the above result in the use of increased safety factors, which in turn yield a heavier structure compared to float glass. A monolithic glass structure lacks redundancy, but different engineering approaches, such as segmentation or lamination of a sacrificial layer, could improve the safety of the structure.

Lastly, AM of glass, although still at experimental stage, is perhaps the most sustainable solution as it results in virtually zero waste; it can potentially require the least post-processing as well. Yet, this method results in visible layering of the deposited glass, compromising the overall transparency, presents the lowest structural performance and is subject to multiple fabrication limitations; although some of them, such as limitations in size, can be linked to its infant stage of development.

6. Discussion

Based on the prioritized performance criteria, the most suitable fabrication method can already be pre-selected, as shown in fig.8. Accordingly, to create practical tools that better reflect the needs of the chosen manufacturing method, different adjustments can be incorporated to the TO formulation (fig.8).

Regarding structural performance, the isotropic or anisotropic nature, the risk of defects during the fabrication, as well as compromises in the surface quality can reduce the structural integrity of the final component. Therefore, they largely influence the applied limits for tensile and compressive strength through relevant increased or decreased safety factors, while they also affect the selection of the appropriate material failure criterion in the TO formulation [27, 28].

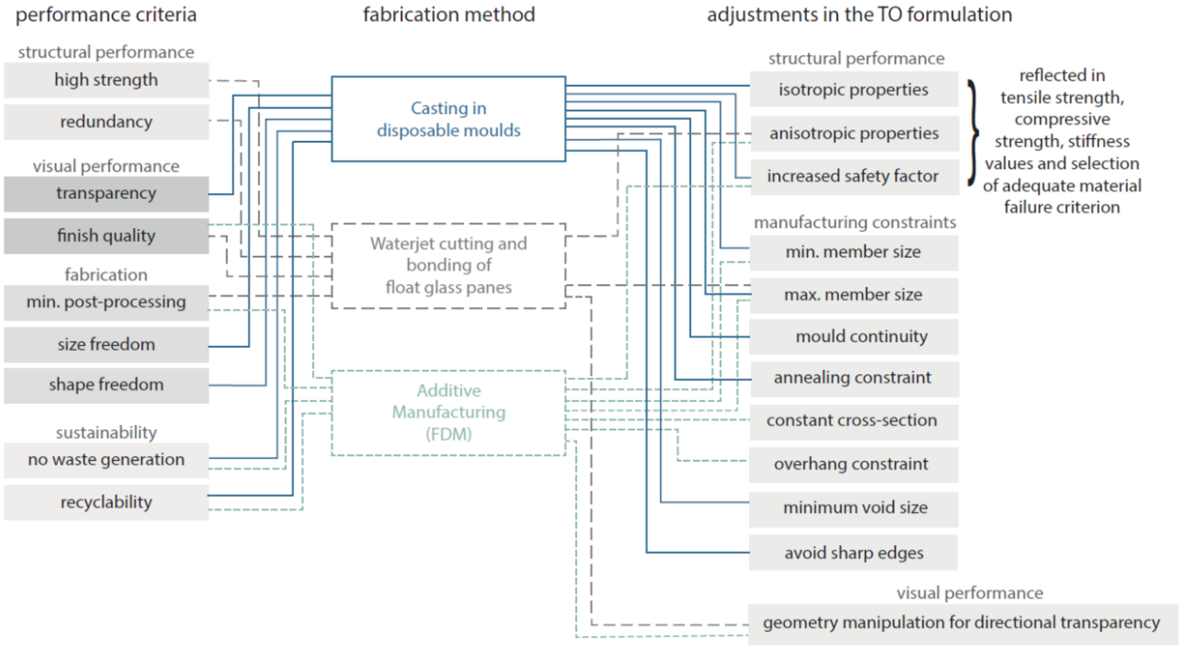

Figure 8: Flowchart showing how the prioritized performance criteria impacts the selection of the most suitable fabrication method, which in turn is reflected in the integration of different constraints in the TO formulation.

Additionally, different practical fabrication-related aspects need to be addressed according to each method. These are related primarily to the size of each member that composes the total complex geometry. Particularly, in the case of 3D printing, the cross section should have a constant dimension that can be created with the available nozzle size, while in waterjet cutting, a minimum member size should be ensured to avoid breakage during the cutting process. In the case of casting, both minimum and maximum member size constraints should be applied. In the latter case, the maximum cross section size should consider both the annealing time limit and the need for an even and smooth gradient of thickness in the geometry [1]. The need for homogeneous mass is also related to the need for elimination of sharp edges in the shape, since these cool down faster than the overall geometry leading to cracks directly in the cooling process. Moreover, a minimum void size should be applied to ensure a sufficient mold thickness to resist the hydrostatic pressure thar arises through casting. Both minimum member and minimum void size can be incorporated with multiple phase projection [29], while the maximum dimension can be applied through the maximum length scale constraint[1, 30]. Lastly, it is also important to eliminate closed cavities in order to ensure mold continuity and allow for effective demolding after casting. This can be applied through the Virtual Temperature Method [31].

In the case of 3D printing, additional aspects that should be considered in the TO formulation are the need to ensure a continuous thread, as well as restrictions in critical overhang angle, which is already studied in similar applications with AM techniques. Lastly, in all cases, the TO formulation can be adapted to comply with design criteria that can ensure directional transparency in the geometry.

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