9 Conclusions

This dissertation aims to explore the possibilities and constraints of employing cast glass for structural, self-supporting applications in architecture. This chapter summarizes and discusses the main outcomes of the dissertation. Initially, responses to the sub-research questions are given, presenting their particular findings. Based on the latter, a comprehensive answer to the main research question driving the research project is given. Recommendations for further developments in the field are given in Chapter 10.

9.1 Introduction

The prime aim of this research was to investigate and unveil the potential and limitations of using cast glass for structural components. Casting as an alternative manufacturing and fabrication method for structural glass components allows us to escape the 2-dimensionality of float glass; instead we can perceive and design with glass used as a 3-dimensional material. Given the, so far, limited exploration of cast glass in structural applications, an in-depth research of cast glass applications developed in other fields, such as astronomy and art, was essential for understanding the potential and limitations of this manufacturing method. Following, the structural potential of cast glass was demonstrated in this work through the research and development of two distinct structural systems for self-supporting envelopes: adhesively bonded and interlocking. The validation of the proposed systems was conducted mainly through experimental work. This chapter presents the main findings of this work. These are given as responses to the sub-questions first, which summarize the main findings per chapter. These partial outcomes lead to a comprehensive response to the main research question, featured directly after.

9.2 Answers to the sub-questions

1 What are the main practical implications and limitations of employing casting for structural glass elements? (Chapter 2)

In theory, there is no limit in the size of a glass component that can be produced by casting. In practice though, to achieve a financially feasible solution, several factors constrain the size of cast glass components to a few kg in weight. The most decisive factor is the required annealing time, explained in detail in Chapter 2. The annealing time is directly influenced by the thermal expansion coefficient -and thus by the chemical composition and type- of glass, the thickness and geometry of the component and the amount of residual stresses allowed. Indirectly, annealing is influenced by several more parameters related to the geometry of the component but also to the physics of the furnace set-up involved. In brief, the thicker and larger the component, the exponentially longer the annealing time required. Real examples of this effect are the blanks of the giant telescope mirrors, presented in Chapter 3: weighing several tons each, they require from months to years of annealing to prevent the generation of residual stresses. Such a prolonged annealing time may be acceptable for astronomical research, yet it would render a cast glass component financially unjustifiable for architectural and structural applications. A limited mass to a few kg further facilitates practical aspects such as the transportation, handling and buildability of a structure in architecture.

Another restraining factor in the use of cast glass elements for structural applications is the, so far, limited, if any, standardized reference data on the strength of solid cast glass components. In contrast to float glass, there is no standard yet regarding the strength of solid cast glass components. Given that the casting manufacturing process is still not fully standardized/automatized the surface quality is anticipated to be lower than that of float glass. Moreover, due to the lack of customized quality control equipment, it is difficult to determine the amount and size of randomly distributed critical flaws within the cast components. Towards this direction, the inverse scale effect in brittle materials implies that the larger the component, the higher the probability of critical flaws within it, which in turn can result in a decrease in the probabilistic strength. Often, small air bubbles and inclusions, visible by the naked eye, exist in cast glass components. Such defects are unacceptable by the control standards of the float industry. However, given the fact that the most influential flaws are the ones at the surface of the component and considering that the surface area to volume ratio for cast glass is much smaller

TOC

compared to float glass (it is the inner volume that is considerably larger and thus, the defects in the meso-structure), it is anticipated that cast glass has a comparable -yet to some extent reduced- strength compared to standardized float glass. This has so far not been systematically investigated and confirmed. Besides the lack of standardized strength data, there is not yet an accurate through-the-thickness residual stress measurement method for cast glass. Most of the times, the residual stress is qualitatively evaluated though cross polarization.

Accordingly, the experimental validation of structural systems out of cast glass components is considered necessary in order to derive statistical engineering data and ensure their safe structural application.

2 In what ways can different glass recipes, geometry and fabrication methods affect the manufacturing process and thus the feasibility and marketability of the resulting component, as suggested by relevant pre-existing applications in other fields? (Chapters 2 & 3)

This question sought to investigate the influence of the leading contributing parameters to the feasibility of the resulting cast glass component: the type (composition) of glass used, the desired geometry and the fabrication method. These parameters, analysed in Chapter 2 and highlighted through relevant applications in Chapter 3, should be considered from the design stage in order to make feasible, cost-efficient cast glass components.

Chapter 2 discusses how the alternative glass recipes present, besides distinct mechanical properties, considerable differences in their melting and working temperatures and thermal expansion coefficient. Accordingly, glass compositions with a low thermal expansion coefficient require substantially less annealing time, as they are able to sustain greater temperature deviations between the warmest and the coolest part of the component during cooling; moreover, they result in less shrinkage of the cast element. Under this assumption, we would ideally use 96% silica glass for cast glass structural elements, a glass that presents a thermal expansion coefficient approximately ten times less than that of soda-lime glass. However, the glass recipes with the lowest thermal expansion coefficient, such as 96% silica and fused silica glass, require as well the highest working temperatures, which render them challenging to fabricate – even at those high temperatures they are essentially too viscous to be worked with. The high working temperature increases substantially the manufacturing cost as well. For the above reasons, soda-lime and borosilicate glass are considered the most feasible solutions, for cast glass applications in architecture. They are the least expensive options, have comparatively low melting temperatures and satisfactory mechanical properties. Of the two, borosilicate glass features a more attractive thermal expansion coefficient but comes at a higher cost due to the prerequisite of a higher working temperature. Nonetheless, the considerably shorter annealing time required and the attained high manufacturing accuracy can ultimately render borosilicate glass a competitive solution in terms of overall cost: the manufacturing process can be considerably faster and post-processing can be avoided. Overall, the choice between soda-lime and borosilicate glass should be made taking into account the complete requirements for the component and the case-study, such as dimensional accuracy, climate, fire-resistance, etc.

The overall geometry of the component plays a key-role in defining the annealing time involved. An optimization of the ratio between the mass and stiffness of the component can greatly reduce the required annealing time and consequently the manufacturing cost of the element. Again, this has been well distributed in the fabrication of the giant telescope mirror blanks, analysed in Chapter 3. By creating a honey-comb structure with cavities and slender glass walls, the blank of the Giant Magellan telescope mirror of 16 t weight and 8.4 m in diameter required only 3 months of annealing; that is 4 times less than the annealing time of a solid blank of almost ¼ the diameter and total weight. Such smart geometry could as well be implemented in cast components for architectural, load-bearing purposes. For example, compared to solid ones, glass blocks following the honeycomb principle would be sufficiently rigid, but faster to produce and lightweight, facilitating transportation and handling. To further reduce the annealing time an even mass distribution and a relatively constant thickness of the element is essential. The thickest part of the component governs the annealing schedule. A homogeneous mass distribution and rounded shapes and/or edges are also preferred for preventing the generation of internal residual stresses as they ensure even cooling of the component.

The fabrication method can further reduce the required post-processing, decreasing the manufacturing costs and production time as well. In general, hot pouring is used for the mass fabrication of cast glass components. The choice of mould is relevant to the amount of identical elements produced and the desired accuracy. For mass production, steel or graphite high accuracy moulds are the best choice. Press steel moulds generally achieve a higher degree of accuracy than open moulds and are preferable if no post-processing is necessary. When post-processing is required, open, high-precision steel moulds are the most cost-effective option. For unique, more elaborate or variable components elements, disposable moulds should be chosen due to their low manufacturing cost, even though they require much more time for preparation and necessitate post-processing. A promising new technology in this direction is the fabrication of 3D-printed high-accuracy sand moulds.

3 Which are the current structural systems employed for creating self-supporting structures out of cast glass components? Which are the main advantages and drawbacks of each system? What is the buildability of these systems and which design principles do the glass components follow? (Chapter 4)

In general, the structural use of cast glass in architecture is still in an early stage of development. The custom-made and, to a certain extent, manual fabrication of the cast units together with the lack of a standardized construction method and strength data has currently confined cast glass to just a few load-bearing applications in architecture. Prior to the research conducted for this dissertation, only a few built structures existed, following two structural systems: either a supportive metal substructure was used or a stiff, colourless adhesive for bonding the cast units together was applied. A supportive steel structure is the prevailing solution, offering a relatively easy, fast and possibly reversible, construction. Furthermore, by directing the tensile forces to the metal structure, glass can be mainly loaded in compression, where it exhibits its highest strength. The main disadvantage of this solution is that it compromises the overall level of transparency. Prior to this dissertation, an adhesively bonded glass block system had only been used in the construction of the *Atocha Memorial*, where the cylindrical geometry of the structure contributed significantly in the overall stiffness of the structure. Owing to the colourless nature of the adhesive, such a solution attains a high degree of transparency, yet it results in an irreversible, non-recyclable and challenging construction requiring meticulous and intensive, high accuracy labour.

The few realized projects employ components made by primary casting (hot pouring) and high precision steel moulds, either open or press ones. All projects employed a singular block geometry of less than 10 kg in weight. The limited mass of the units also facilitates the transportation, installation and handling processes. Moreover, a repetitive component geometry is essential for simplifying the production and assembly and for minimizing the manufacturing costs, on account of a limited number of high-precision steel moulds and a standardized production process.

Regarding the overall shape, little exploration has been made in the realized projects on the forms that can be achieved by cast glass. Mainly a simple rectangular form has been favoured, replicating the standard masonry brick modulus. The only exemption is the block modulus of the Atocha Memorial that follows a shape with a concave and a convex shape to allow for the generation of the entire cylindrical structure by a singular unit.

Either borosilicate or soda-lime glass are employed, depending on the project's location and the required dimensional accuracy. A characteristic example is again the *Atocha Memorial*, where with the use of press moulds and borosilicate glass, a ±1.00 mm accuracy was achieved at the manufactured blocks, without the need of any post-processing. In terms of maintenance, systems employing solid cast blocks are fairly maintenance-free, provided that, during construction, there is proper cleaning and then sealing of the joints between the glass blocks.

4 What is the structural potential and which are the main factors that influence the structural performance of an adhesively bonded cast glass system? (Chapter 5)

This question was answered through the research, development and experimental validation of the adhesively bonded system applied on the *Crystal Houses* façade, discussed in Chapter 5. It was experimentally proven that the strength of the adhesively bonded cast block assembly is highly dependent on the adhesive's thickness, therefore on the dimensional accuracy of the components and on proper connections. The overall geometry of the structure also plays a key role, as it can further contribute to the stiffness of the structure and thus, allow for the use of a less rigid (and thicker) adhesive.

The literature review discussed in Chapters 2 and 3 indicated several principles and design criteria for the geometry of the cast glass components; however, the specific case study was an externally assigned project, where the size and shape of the blocks was predetermined by the architects. Hence, there was no exploration of the shaping potential of cast glass in this case study.

The flat geometry of the façade necessitated the use of a stiffer, thinner adhesive compared to the one employed in the *Atocha Memorial*. A UV-curing clear acrylate was chosen for bonding the blocks together due to its colourless nature, high compressive strength and fast curing that facilitates construction. To further reinforce the stiffness of the self-supporting façade, a continuous glass wall with buttresses was proposed, creating a rigid 3-dimensional envelope.

It was experimentally proven that the use of the selected UV-curing, stiff acrylate, allows the assembly to behave monolithically against the anticipated loading and to present a compressive and flexural strength comparable to or better than the strength of typical B80 high performance concrete. Yet, the monolithic structural behaviour is only achieved if the adhesive is evenly distributed in a thickness that corresponds to the optimum bond strength. Visual and structural prototypes demonstrated that when using the specific adhesive, a thicker bond layer results in a decreased bond strength and an inhomogeneous application. It was determined that for the given adhesive, the optimum bond thickness lies between 0.2 and 0.3 mm, indicating that the glass components should meet dimensional tolerances that do not exceed ±0.25 mm in both size and flatness. Given this high level of required accuracy, post-processing of the horizontal (bonding) surfaces of the system was necessary. For that reason, for the fabrication of the blocks, soda-lime glass and open high precision moulds were preferred to decrease the manufacturing costs. Even though in soda-lime glass the thermal stresses occurring are much higher than those for borosilicate glass, the experimental work proved that soda-lime glass blocks can withstand the anticipated rapid temperature changes when applied to an external wall in a temperate climate.

Proper connection design is also essential for ensuring the desired structural performance in a cast glass block system. If properly supported, one solid glass block can carry the entire load of the façade without cracking. If, however, the blocks come to direct contact with each other or with another hard material, micro-asperities induce stress concentration at the surface of the components which can trigger crack initiation and propagation at comparatively low compressive loads.

5 Which are the main engineering challenges involved in an adhesively bonded cast glass system for structural applications? (Chapter 6)

The engineering challenges of an adhesively bonded cast glass system were discussed in detail in Chapter 6 through the real application of the developed system at the *Crystal Houses façade*. It was demonstrated that most of the engineering problems involved are generated by the relatively low thickness of rigid adhesives, combined with the architectural prerequisite of high visual performance. The fundamental difference between the developed adhesive system and a conventional mortar system is that a mortar layer can compensate for the intolerances in size of the bricks, while a rigid adhesive cannot; this leads to a meticulous and strictly controlled building process. Strict tolerances are essential not only per layer of construction but for the entire structure.

Moreover, in contrast to conventional masonry, in an adhesively bonded glass system, any flaws in the bonding layer are entirely visible. To attain imperceptible connections in the structure, the development of a bonding method for the homogeneous and flawless application of the adhesive is necessary.

An inherent challenge of an adhesively bonded cast glass system is the irreversible nature of the involved stiff adhesive that leads to a permanent, non-circular structure. Although local repairs using controlled heat are possible, overall the blocks cannot be retrieved intact at the end-of-life of the building, nor can they be easily recycled due to adhesive contamination. Taking into account the global drive towards increased circularity and reuse of building materials, this is a crucial aspect to address and improve in future applications of this system.

6 Which are the main engineering advantages, principles and design criteria for creating a dry-assembly, interlocking cast glass structure? (Chapter 7)

This question sought to define the engineering concept of a novel structural system out of interlocking cast glass blocks and establish the design criteria for shaping the components. This new structural system was triggered by the drawbacks of the developed adhesively bonded system, as a promising solution that circumvents all the inherent challenges of the latter. Owing to its segmented nature and dry-assembly, the proposed system offers several engineering advantages such as an improved toughness resistance, a visible deformation prior to failure, localized failure and a reversible construction that allows for easily retrievable and thus, reusable and recyclable components. Even though it is anticipated that such a system will present a reduced stiffness compared to an adhesively bonded cast glass structure, it provides a structure of enhanced safety. In specific, the fragmentation of the structure is expected to diminish the influence of individual critical flaws for the structure as a whole. The nature of the interlocking system confines any local failure to the cracked unit – cracks do not propagate to the rest of the structure, as would be the case in the monolithic variant. This in turn offers the possibility to dimension the assembly without considering the possible occurrence of critical flaws in the glass; hence, a reduced safety factor can be applied in the glass construction. Ironically, the safety of the structure is further supported by the low bending stiffness of such an assembly: The anticipated visible deformation and the pseudo-ductile behaviour of such a system upon excessive loading can provide a warning mechanism prior to failure.

Another benefit of an interlocking system is its relatively easy buildability due to the self-aligning nature of the components. To further simplify the assembly process -and reduce the manufacturing costs- components following a multifunctional geometry are recommended. To attain reversibility a soft, preferably transparent, dry-interlayer is proposed as an intermediary between the individual components. The interlayer, in addition to ensuring an even stress distribution by accommodating by deformation the surface-asperities of the blocks, can also compensate for the size tolerances of the individual components in its thickness. To stabilize and restrain the overall structure a constraint frame is necessary, which can be engineered for minimal visual intrusion.

Taking into consideration both the physical principles of interlocking and glass casting, several design criteria are established for defining the geometry of the cast glass components: Components of limited volume are proposed to reduce the annealing time, facilitate the handling and construction and increase the fracture toughness of the system. Geometries following rounded shapes or/and edges, smooth interlocking mechanisms, an even mass distribution and consistent thickness are preferred for preventing the generation of uncontrolled residual stresses and improve the shear capacity of the system. Units following a multifunctional geometry that allows for multiple different configurations keep the manufacturing costs lower and can speed up the construction.

7 What is the potential of an interlocking system out of cast glass blocks for structural applications in architecture and which are the main factors that influence its structural performance? (Chapter 8)

The experimental and numerical investigation of an interlocking system out of osteomorphic glass blocks was presented in detail in Chapter 8. Although further validation of the system is necessary for applying it in a real construction, the findings of this chapter manifest that an interlocking system is a feasible solution for cast glass structures that can tackle all the downsides of the existing systems utilizing cast glass blocks. It allows for a reversible, almost fully-transparent system of enhanced safety, firstly due to its fragmented nature that allows for localized failure and secondly, due to its pseudo-ductile behaviour that provides visible warnings prior to failure.

As indicated by the numerical and experimental research, the structural potential of such a system is influenced by multiple, interlinked factors. These include the geometry and dimensional accuracy of the glass blocks and especially of the interlocking mechanism, the choice of interlayer material and its thickness and the amount of pre-stress applied.

In specific, it was proven numerically that a decrease in the height of the block lowers its shear capacity and alters the system's failure mechanism: a lower brick is more susceptible to cracking by bending, whereas for higher brick variants the shear lock failure is proven to be more critical. It was also shown that an increased amplitude height of the interlocking mechanism leads to increased shear capacity, decreased uplifting effects and failure at considerably smaller deformation. These latter findings were confirmed experimentally by out-of-plane shear tests in assemblies of kiln-cast blocks of different amplitudes. As a disadvantage, higher amplitudes were proven to be more prone to critical dimensional deviations that can lead to peak stresses due to insufficient contact between the components and the interlayer, but also to induced eccentricity during the assembly of the system. The steeper curvature of the higher amplitudes, combined with the dimensional tolerances, can lead to the sliding of one component in relation to the others and thus, to an initial misalignment of the assembly. A solution to this is the design of an interlocking mechanism with multiple locks, enhancing the self-aligning capacity of the unit.

The dimensional tolerances of the interlocking mechanism of the glass blocks also play a key-role in the choice of interlayer material and its thickness and to this extent, to the overall performance and stiffness of the assembly. As the experiments indicated, interlayers with lower tear strength tend to fail at the spots of the interlocking geometry where there is a steep curvature change. More importantly, poor manufacturing tolerances of the glass blocks and particularly in their interlocking geometry necessitate the application of thicker interlayers. If the interlayer cannot accommodate the dimensional tolerances, failure can eventually occur due to the partial contact of the glass blocks and the interlayer that leads to concentrated stresses. In principle, the thicker the interlayer the stiffer it is, yet impairing the overall stiffness of the assembly and making it more prone to buckling. On the other hand, thinner interlayers ensure a better stiffness of the assembly but if they are too thin, they may result to unequal material distribution and thus bare a higher risk of local failure. The Shore Hardness of the interlayer is also crucial for the overall stiffness. In this direction, the conducted experiments suggested that interlayers with a Shore Hardness in the range of 70A – 80A are a good candidate for real applications.

The amount of pre-stress applied to constrain such a system plays an essential role to the overall stiffness of the construction as well. Due to time and financial limitations the effect of pre-stressing was not examined in this work. Yet, the results of the out-of-plane shear tests on assemblies of osteomorphic blocks indicated a low strength due to the low bending stiffness of the assembly, which can be attributed to several factors, such as the dimensional tolerances of the kiln-cast blocks, (therefore requiring) the use of a 6 mm thick interlayer and the low pre-stress applied at the constraining steel frame. It is anticipated that higher amounts of pre-stress can increase the stiffness of the system, yet this is to be validated.

TOC

It was also demonstrated that the complicated geometry of the interlocking blocks results in the generation of peak localized stresses at considerably lower nominal compressive stress values compared to blocks of flat geometry. This, in combination with the reduced stiffness of the assembly due to the relatively soft interlayer, lead to the conclusion that an interlocking assembly would present a lower strength compared to an adhesively bonded system made out of rectangular cast glass blocks. Yet, as the experiments indicated, the visible deflection and pseudo-ductile behaviour of the interlocking assembly in combination with localized failure and resistance to crack propagation lead to a structure with increased safety, providing visible warning mechanisms and a redundancy prior to failure.

Moreover, upon failure, the assemblies would still have a significant residual strength and upon load removal they would self-realign towards their original configuration. The extent of the ability of the system to self-realign was not investigated in detail and should be further validated in the future. The experiments also showed that internal flaws (within the meso-structure of the blocks) or defects at locations that are not anticipated to be subject to peak stresses, do not seem to influence the overall performance of the assembly.

Several more aspects need to be further studied and engineered in order to realize this system in the built environment, yet the results so far strongly support the feasibility of this novel type of construction utilizing solid cast components.

9.3 Main research question

What is the potential of using cast glass elements as structural components for the generation of self-supporting envelopes without the need of opaque reinforcement elements?

The driving force of the research project was to investigate the potential of cast glass components in architectural, structural applications. Prior to this research, little and rather sporadic exploration had been made in the use of casting as a manufacturing method for structural glass components in architecture. At present, there are only a few realized examples of self-supporting structures made of solid cast glass elements. The, so far, limited demand has in turn led to the absence of a standardized manufacturing process, to a lack of consistent engineering data and building guidelines, and to a general unawareness of the potential of cast glass in structural applications in architecture.

A short, simplified answer to the main research question is that cast glass has a great potential for structural applications due to its ability to form 3-dimensional glass structures that are shaped to eliminate the risk of buckling due to slender proportions. The monolithic nature and substantial cross-section of cast glass components combined with the inherent compressive strength of glass allow us to escape the design limitations imposed by the, essentially, 2-dimensional nature of float glass. To demonstrate this potential, this work focused on the development and experimental validation of two distinct structural/building systems for self-supporting envelopes employing almost solely cast glass elements. These proved that to take full advantage of cast glass structural components certain requirements should be met, linked to the manufacturing process but also the means of assembly of the individual cast glass elements. These requirements have been discussed thoroughly by forming the answers in the sub-questions, each of which focuses on a specific aspect of the main research problem.

An inherent advantage of casting is that it provides great freedom in the size and shape of the resulting component; although there are practical limitations in the geometry largely due to the meticulous and lengthy annealing procedure involved. These limitations are explained in the answers of sub-questions 1 and 2. Accordingly, in architectural applications solid cast glass components have been currently commercialized up to the size range and modulus of standard masonry bricks. Such elements can be used as repetitive components to form self-supporting, 3-dimensional all-glass structures of undisturbed transparency.

Cast glass exhibits a great shaping potential, allowing us to create forms beyond the standardized brick modulus. Although the shaping potential of cast glass could not be fully explored in this work, design criteria in respect to casting were established and accordingly interlocking forms following curved shapes were developed. The first results of the study on the shapes and geometry of cast glass components have been presented in Chapter 7, demonstrating that casting as a manufacturing method and glass as a material *can* and *should* be made following different forms than the ones adopted for other building materials that have been produced by different methods.

To achieve load-bearing cast glass structures, it is essential to use an intermediate material between the individual glass elements. This intermedium influences the stiffness of the structure; equally importantly, it ensures even load distribution over

TOC

the glass components and prevents early failure due to peak stresses on surface micro-asperities triggered by glass-to-glass contact. To maximize transparency this intermedium should be colourless; moreover, any secondary supportive substructure should be minimized. Accordingly, the main contribution of this research work is the development of two distinct systems for self-supporting envelopes of maximized transparency: an adhesively bonded glass block system, using a colourless adhesive as an intermedium and an interlocking cast glass block system, employing a colourless dry interlayer. Although, in this work, both systems have been developed for self-supporting envelopes, they can, in principle, be applied on other compressive members as well, such as columns or arches as demonstrated in the cited case studies.

More specifically, the selected rigid UV-curing adhesive allows the adhesively bonded system to ensure a relatively monolithic behaviour under the anticipated forces and a high transparency level. Nonetheless, the resulting structure is irreversible and requires a meticulous and intensive construction of extremely high dimensional accuracy (Chapters 5 and 6). Essentially, in order to ensure a rigid connection, an adhesive of virtually zero thickness is necessary, which cannot accommodate any dimensional tolerances in the size and shape of the individual blocks but also of the entire construction. This in turn results in multiple engineering challenges during the construction of such a system.

In comparison, the developed interlocking system presents a relatively reduced ultimate load-carrying capacity and presents more distortion in terms of transparency; yet it is a reversible, easily assembled system that offers inherent safety due to its fragmented nature and visible deformation prior to failure (Chapters 7 and 8). Several factors influence the stiffness and structural behaviour of such a system, such as the geometry of the blocks and of the interlocking mechanism, the choice of interlayer, the amount of pre-stress applied. Dimensional tolerances of the building blocks are also critical in this case as thicker interlayers lead to a reduction in the overall stiffness of the assembly.

The findings on both systems have been positively received by the international architectural and engineering community. Specifically, the presented adhesively-bonded cast block system was realized at the *Crystal Houses façade*, which received numerous awards by the structural engineering society, including the *Outstanding Innovation Award* by the *Society of Façade Engineers* in 2016. Still, *the Crystal Houses façade* is merely a first real-scale prototype of the developed adhesively bonded system. The actual construction of the façade provided invaluable feedback on the engineering challenges and practicalities involved in such a system, giving room for new suggestions. This triggered the development of the 2nd presented system with interlocking glass blocks. Due to time and financial limitations, this second system was developed in less detail and to an earlier stage compared to the adhesively bonded one. Although future work is necessary to apply this system in the built environment, the results so far demonstrate its feasibility. The interlocking cast glass block system, utilizing recycled cast glass components, although not yet applied in practice, has been exhibited in *The Venice Design 2018* and *Dutch Design Week 2018* and was nominated for the *New Material Award 2018*. An important spin-off discovery from the interlocking system is the potential of using waste glass for creating circular structural cast glass components. This was briefly discussed in Chapter 7.6, - the extensive research on this topic remains out of the scope of this thesis.

Even though cast glass has, so far, been rarely applied in structural applications, the development of new building systems and their experimental validation presented in this work provide a strong basis for further developments and applications in a range of compressive structures. At present, the most considerable drawbacks hindering the marketability of cast glass components are (a) the economic barriers imposed by their customized production and application and (b) the lack of standardized strength data and building guidelines. Thus, even if cast glass elements have proved to be suitable structural components, several economic aspects and logistics need to be tackled and performance issues need to be further explored in order to make cast glass a competitive manufacturing method compared to float production for structural components. The support of the building industry for turning cast glass into a competitive manufacturing method and the support of the architectural community for an increased demand are essential for further applying cast glass components in structures and achieving a standardized production method that can greatly reduce the manufacturing cost and improve the quality of cast glass components.

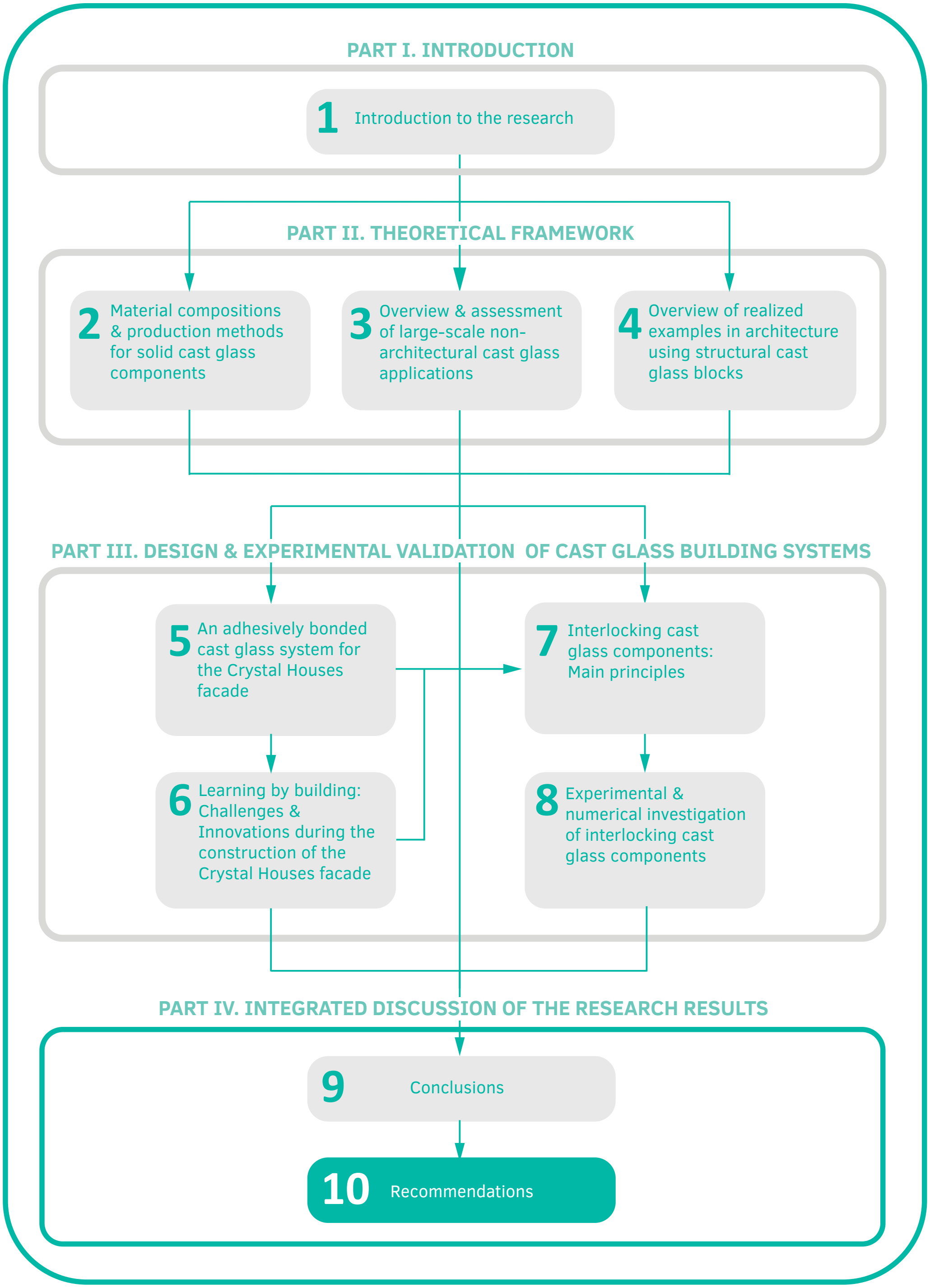
TOC

Prototype of a topologically optimized cast glass node for a grid shell application by (Damen 2019)

TOC

TOC

Exploring the third dimension of glass



PART I. INTRODUCTION

1 Introduction to the research

PART II. THEORETICAL FRAMEWORK

2 Material compositions & production methods for solid cast glass components

3 Overview & assessment of large-scale non-architectural cast glass applications

4 Overview of realized examples in architecture using structural cast glass blocks

PART III. DESIGN & EXPERIMENTAL VALIDATION OF CAST GLASS BUILDING SYSTEMS

5 An adhesively bonded cast glass system for the Crystal Houses facade

6 Learning by building: Challenges & Innovations during the construction of the Crystal Houses facade

7 Interlocking cast glass components: Main principles

8 Experimental & numerical investigation of interlocking cast glass components

PART IV. INTEGRATED DISCUSSION OF THE RESEARCH RESULTS

9 Conclusions

10 Recommendations

Solid cast glass components and assemblies for structural applications

TOC