1 Introduction to the research

Innovations in glass technologies and engineering over the last decades have altered the way we perceive glass. Combining transparency, durability and a compressive strength exceeding that of concrete and even structural steel, glass has evolved in the engineering world from a brittle, fragile material to a reliable structural component with high compressive load-carrying capacity. At present, the structural applications of glass in architecture are constantly increasing, yet with a considerable geometrical limitation: although glass's fabrication boundaries have been continuously stretching so far, glass structures are still dominated by the limited shapes which can be generated by the combination of the virtually 2-dimensional, planar elements produced by the float industry. Whereas glass panels in float production can stretch more than 20 m in length, the width is restricted to 3.21 or 4.5 m and the maximum commercial thickness is only 25 mm (Lyons 2010; Schittich et al. 2007; Patterson 2011).

Cast glass can overcome the design limitations imposed by the 2-dimensional nature of float glass. By pouring molten glass into moulds, solid 3-dimensional glass components of almost any shape and cross-section can be obtained[1]. Such objects can be shaped to form repetitive units for free-form full-glass structures that do not buckle due to their slender proportions, thus taking full advantage of the high compressive strength of glass; a solution little explored so far. Discouraging factors such as the meticulous and time-consuming annealing process required, the to-date non-standardized production, and the corresponding high manufacturing costs, have limited cast glass to only a handful of realized architectural applications. Consequently, there is a lack of engineering data and a general unawareness of the potential and risks of building with cast glass as a structural material. The load-bearing function of cast glass in architecture remains an unmapped field.

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[1] At present, the largest monolithic pieces of cast glass made -in terms of dimensions- are the blanks of the Giant Magellan Telescope. Each honeycomb disk is 8.4 m in diameter, ranges between 0.43 – 0.89 m in thickness and weighs 16 t. The aforementioned mirror blank together with other characteristic examples of massive cast glass components are presented and discussed in detail in Chapter 3.

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Scope of this research is to explore the structural potential and limitations of solid cast glass components and introduce cast glass as a promising construction material in architecture, indicating both the potential and limitations of this alternative production process for glass in buildings. To achieve this, the research focuses on the development and experimental validation of two new design concepts for self-supporting envelopes made almost entirely of cast glass components: adhesively bonded and interlocking cast glass components.

1.1 Problem definition

1.1.1 Glass as a structural material

According to the *Oxford Dictionary*, glass is a "*hard, brittle substance, typically transparent or translucent, made by fusing sand with soda and lime and cooling rapidly. It is used to make windows, drinking containers, and other articles*". Indeed, transparency and brittleness are the two most well-known properties of glass and the ones that have defined the majority of its applications. Yet, glass has another inherent property that has allowed us to go beyond its traditional use as an infill material, and conceive it as a structural building material: Glass exhibits a compressive strength (stated as 1000 MPa for float soda-lime glass by (Saint Gobain 2016; Weller et al. 2008; Ashby, Jones 2006)) higher than that of most conventional building materials, including concrete and even many types of structural steel[2]. This property together with technological advances that have increased the safety of glass elements -namely the tempering and lamination process- have allowed glass to evolve from a brittle, fragile material to a material for creating structural components with high compressive load-carrying capacity. Indeed, over the last decades glass has been applied for various structural components, such as beams, columns, walls,

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[2] Several guidelines and specifications exist on the strength of structural steel and concrete, with variable values according to the material composition. As an indication, according to (Job, Ramaswamy 2007) a typical high performance concrete has a compressive strength of 85 MPA and according to (Sarkisian 2012) for a typical ultra-high performance concrete the value is 110 MPA. For a typical high-strength structural steel, the yield strength is approx. 450 MPa (Granta Design Limited 2015; Sarkisian 2012), but higher values are also reported.

facades, staircases and even entire envelopes (Fig. 1.1) (Wurm 2007; Nijsse 2003; Schittich et al. 2007). In the quest of maximum transparency, glass's structural boundaries have been continuously stretching (Albus,Robanus 2015). The glass sheets are constantly becoming larger and the connections less, both in size and number (O' Callaghan,Marcin 2009). The long pursued architectural desire for a totally transparent, almost dematerialized structure is finally feasible.

FIG. 1.1 The *Apple Store* in New York by *EOC Engineers*

Still, due to the prevalence of the float glass industry, the design of full-glass structures is dominated by the limited forms, shapes and dimensions feasible by virtually two-dimensional, planar elements: either orthogonal or cylindrical in shape and supported by glass fins and beams or braced against buckling using slender, non-glass components. At present, glass panes can stretch more than 20 m in length, yet, their maximum standardized thickness does not exceed 25 mm in float production (Lyons 2010; Schittich et al. 2007; Patterson 2011)[3]. Such a disproportional slenderness ratio renders float glass panes virtually 2D elements that

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[3] Actually, 25 mm thick float glass is produced to a limited extend. An example of float glass produced in 25 mm thickness is by *Linea Azzurra* of AGC (AGC 2019). Float glass is usually manufactured up to 19 mm in thickness (Wurm 2007).

are susceptible to buckling, preventing the use of glass's full compressive capacity, although it is at least an order of magnitude higher than its tensile strength. In essence, a float glass element, even when loaded in compression, will eventually fail due to the initiation of tensile stresses at significantly lower values than its stated compressive strength.

Cast glass can escape the design limitations imposed by the virtually 2D nature of float glass. By pouring molten glass into moulds, solid three-dimensional glass components of considerably larger cross-sections and of virtually any shape can be obtained. Owing to their monolithic nature, such components can form repetitive units for the construction of three-dimensional, self-supporting glass-structures that are not sensitive to buckling, sparing the necessity of additional supporting elements. Certainly, solid cast glass components are a promising solution for engineering pure glass structures of high transparency (Fig. 1.2) that take full advantage of glass's compressive strength.

FIG. 1.2 The Crystal Houses façade in Amsterdam by *MVRDV Architects*, made of adhesively bonded glass blocks. Source: *Daria Scagliola and Stijn Brakke.*

Nonetheless, at present, little and rather sporadic exploration has been made in the use of casting as a manufacturing method for structural glass components in architecture. To a certain extent this is attributed to the existence of only a few realized examples of self-supporting structures from 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 to a general unawareness of the potential of cast glass in structural applications in architecture.

The aim of this research is to bridge the knowledge gap on the use of cast glass in structural components in architecture, and introduce the potential and limitations of this alternative production process. To accomplish this, the current research focuses on the application of solid cast glass components in self-supporting envelopes with no additional, visible, substructure. Accordingly, the research evolves around the design and experimental validation of two new building concepts for self-supporting envelopes purely from cast glass components: adhesively bonded and interlocking cast glass structures.

1.1.2 Cast glass as a structural material: Potential and limitations.

In theory, casting enables us to create monolithic glass elements of any form and cross-section (Fig. 1.4). Such an immense forming potential combined with the high compressive strength of glass offers endless possibilities in the design of monolithic, entirely transparent, structural glass members, e.g. storey-high glass columns (Fig. 1.3) or even entire glass envelopes. Nevertheless, in practice, casting glass in volumes of such a scale requires a meticulous and excessively time-consuming annealing process that can jeopardize the marketability of the components and render them financially unaffordable. To this end, the choices of glass composition, overall dimensions, mass and form of the object are key factors for the total annealing time.

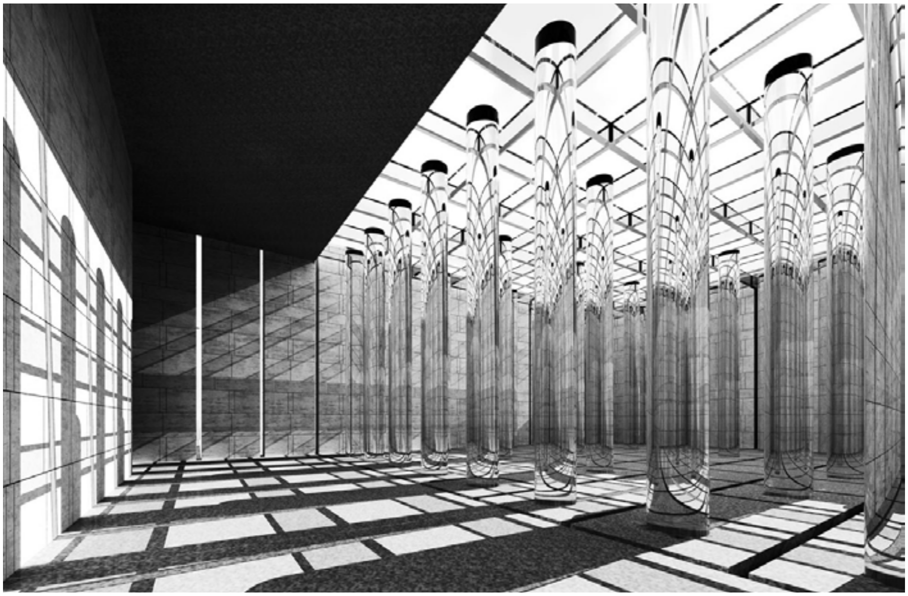

FIG. 1.3 Illustration of *Giuseppe Terragni* and *Pietro Lingeri's* unrealized design for the *Danterium* (1938). Can we cast such solid, transparent glass columns? Source: archeyes.com

FIG. 1.4 Glass casting (hot-pouring)

In specific, based on its composition, commercial glass can be divided into six main families/types: Soda-lime, borosilicate, lead, aluminosilicate, 96% silicate and fused silica glass. Each glass family differs not only in composition, but also in the resulting material properties (Shand, Armistead 1958). Out of these properties, the thermal expansion coefficient plays a key role in determining the cooling rate of the glass component. For example, the considerably higher thermal expansion coefficient ($9*10^{-6}$/K) of soda-lime glass compared to that of borosilicate glass (3.1 - $6*10^{-6}$/K) results in an annealing time that can be more than double in duration. A comparison between the annealing time of the 8.4 kg and 70 mm x 200 mm x 300 mm borosilicate block of the *Atocha Memorial* and the 7.2 kg and 65 mmx 210 mm x 210 mm soda-lime block of the *Crystal Houses* demonstrates this clearly. The latter, although smaller in both dimensions and weight requires circa 36-38 h of annealing (Oikonomopoulou et al. 2017a); almost double the time required for the comparably bigger block of the *Atocha Memorial* which needed 20 h (Goppert et al. 2008).

Mass is another critical aspect. The bigger the component, the exponentially longer the annealing time. This has been well demonstrated in the fields of astronomy and art (Fig. 1.5), where the largest monolithic cast glass objects, made until now, have been manufactured. The 5 m in diameter and 15 tons in weight honeycomb mirror of the *Mt. Palomar Observatory* required 10 months of controlled cooling to remove any residual stresses that could lead to the eventual cracking of the component (Zirker 2005). The *Opposites of White* drum-shaped cast sculptures by artist *Roni Horn*, each 50.8 cm high by 142 cm diameter, required 4 months of controlled annealing to prevent the generation of residual stresses respectively (Kroller-Muller Museum 2007).

FIG. 1.5 Solid glass sculptures by artist *Roni Horn*.

A substantially lighter structure can greatly reduce the annealing time, allowing for the fabrication of larger components in considerably reduced time. This is well illustrated by the evolution in the casting of the blanks of the *Giant Telescope Mirrors* over time, discussed in chapter 3.2. By employing smart geometry, i.e. a honeycomb structure, the four times heavier and more than triple in diameter blank of the *Giant Magellan Telescope* required 4 times less annealing time than a 2.5 m in diameter solid disk.

If the above mentioned parameters are considered and incorporated from the design stage, structurally efficient cast glass components can be made of various shapes and forms. Currently, there are only a few realized projects utilizing solid cast glass components in a structural way. The most representative projects are the envelopes of the *Atocha Memorial* (Schober et al. 2007), the *Crown Fountain* (Hannah 2009) and the *Optical House* (Hiroshi 2013), discussed in Chapter 4. Another characteristic example is the *Crystal Houses* (Oikonomopoulou et al. 2017a; Oikonomopoulou et al. 2015b), the research and development of which are an integral part of this dissertation, presented in Chapters 5 and 6.

In all four projects, cast glass elements have been limited to a size comparable to the one of standard rectangular terracotta bricks, so that they can be manufactured with an economically feasible annealing schedule. Owing to their substantial cross-sectional area and monolithic nature, solid glass bricks have great potential as structural elements in architecture: They can form repetitive units for the construction of three-dimensional glass structures that are not sensitive to buckling and thus, can take full advantage of glass's high compressive strength, sparing the necessity for an additional supporting structure. Yet, due to the lack of standardized structural specifications and strength data on transparent adhesives, the majority of such projects so far rely on a supporting substructure to ensure rigidity and prevent buckling. Such solutions not only compromise the resulting level of transparency but also do not take full advantage of the inherent strength of glass.

Prior to this dissertation the only realized example of an adhesively bonded, self-supporting, cast glass structure was the *Atocha Memorial*, where solid glass blocks bonded by a transparent UV-curing adhesive form a cylindrical construction. The cylindrical geometry of the *Memorial* plays a key role to the structure's stiffness, eliminating in this case the necessity of additional steel elements for its support (Schober et al. 2007) and allowing for a more elastic (and less rigid) adhesive compared to the one applied at the *Crystal Houses* façade.

From all the above, it is evident that there is still great room for exploration in the field of structural cast glass in architecture; particularly towards creating self-

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supporting or even load-bearing structures purely from cast glass components that circumvent the use of opaque reinforcement elements. Furthermore, little exploration has been made so far on the shaping potential of cast glass in the realized projects. The cast glass components of the realized architectural projects copy the design language of common terracotta masonry bricks – just as many of the marble decorative details in Greek temples are reminiscent of the older wooden connections. Yet, glass as a material has different properties and manufacturing process, compared to standard masonry, stone or concrete, which sequentially call for different forms. The shape of cast glass components can be further improved towards both a more cost- and time-efficient production and assembly combined with an enhanced structural performance.

The current research therefore focuses on broadening the knowledge and spectrum of structural systems made of solid cast glass components in architecture. Accordingly, the structural potential of cast glass is examined from the unit level to the entire structure. To prove the feasibility of cast glass as a structural material, different systems for self-supporting envelopes made of cast glass components are developed, designed and experimentally validated. To exhibit the structural capacity of glass, the goal is to attain glass structures of maximum transparency and of minimum additional elements such as connectors. The following section provides an overview of the research aspects and the applied methodology.

1.2 Research questions and aims

Scope of this research is to develop and experimentally validate new design concepts, from the component's form to the overall structural system that can lead to fully transparent, self-supporting building envelopes made of solid cast glass components. The main research question can be formed as follows:

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 research can be further divided into the following sub-questions:

1. What are the main practical implications and limitations of employing casting for structural glass elements? (Chapter 2)
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)
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)
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)
5. Which are the main engineering challenges involved in an adhesively bonded cast glass system for structural applications? (Chapter 6)
6. Which are the main engineering advantages, principles and design criteria for creating a dry-assembly, interlocking cast glass structure? (Chapter 7)
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)

1.3 Objectives

The objective of this research is to design, develop and validate via experimental testing new design concepts for fully-transparent, self-supporting structures (i.e. envelopes, walls) in architecture utilizing solid cast glass components. Aim is to explore the structural potential of cast glass in architectural applications from the level of the unit to the entire structure.

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1.4 Research Methodology

Fig. 1.6 provides an illustration of the methodology of this thesis. Towards developing new design concepts for self-supporting structures of cast glass components, initially an extended literature study and field research is conducted on the commonly applied glass types/compositions and their properties, casting production methods and mould types. Characteristic examples of cast glass structures, not only in the field of architecture but also in other areas such as astronomy and art, are analysed and assessed with comparative data charts, in order to exhibit both the limitations and the potential of cast glass. Accordingly, preliminary conclusions are drawn that help establish design criteria.

Subsequently, design proposals are made regarding the component's form, structural system and type of connection or bonding media.

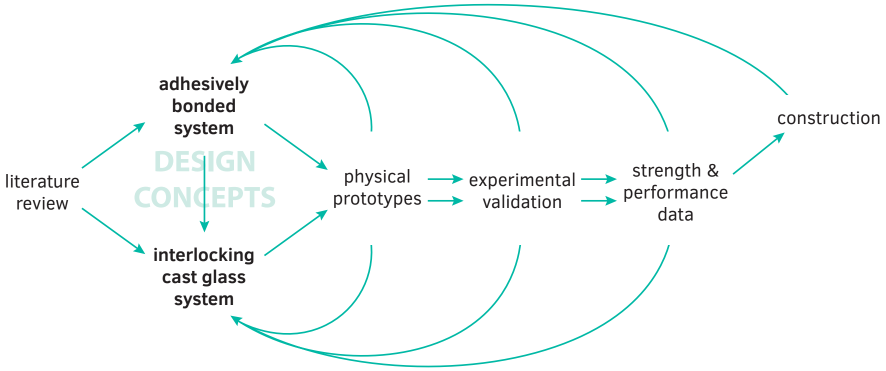

FIG. 1.6 Methodology diagram of the thesis.

The main body of the dissertation presents the research, development and experimental validation of 2 different design concepts: an adhesively bonded glass brick system and a system out of dry-assembly, interlocking cast glass components. The former is developed and eventually applied in a real case-study, the *Crystal Houses façade* in Amsterdam designed by MVRDV. The author of this dissertation has been deeply involved in the research, development and construction of the realized adhesively bonded cast brick façade. Having the opportunity to be at the frontline of realizing this cutting-edge project was a unique learning process. It has been a long, challenging, often stressful, yet rewarding and irreplaceable experience to observe one's research scaling up from a few bonded bricks to, eventually, a 10 x 12 m façade that received several engineering and architectural awards. Having spent more than 18 months in research and 7 entire months at the construction site as a quality control engineer gave the author a rare insight in all the practical implications involved in such a project. The *Crystal Houses façade*, bonded by a rigid, colourless adhesive of virtually zero thickness, manifests the potential of cast glass in architecture but also points out the engineering challenges resulting from a permanent construction of extreme accuracy and intensive and meticulous labour. Achieving the desired dimensional accuracy and visual performance proved to be an even bigger challenge than obtaining the desired structural performance.

It was the engineering challenges and irreversible nature of this system that have led to the second design concept: Interlocking cast glass components that are stacked with the aid of a transparent dry interlayer, circumventing the use of adhesives. This allows for a reversible, reconfigurable, recyclable and easily-assembled structure that circumvents the aforementioned challenges and results as well to a more sustainable construction system: eventually the components can be easily demounted and recycled again, as they are contaminant-free. This system is yet to be applied in reality, but can be a promising answer for future inspiring structures, from small-scale furniture to full-glass columns and complete building envelopes.

Integral part of the research is the fabrication and engineering of full-scale prototypes and the experimental validation of the final design concepts. Numerous physical prototypes have been made to assess various critical aspects for the feasibility of the proposed systems. These include among others the visual performance, ease of fabrication, ease of assembly and end of life scheme of the proposed design concepts and corresponding glass components. To evaluate and quantify the structural behaviour of the presented systems, series of prototypes have been experimentally tested until failure so that statistical data can be derived regarding each proposed system's performance.

As already mentioned, the described adhesively bonded glass block system has been developed in collaboration with, and support by, the industry. All conducted experiments are made with industrially fabricated glass blocks of high dimensional accuracy. The provided results can be used as design guidelines for future applications. The second, interlocking system was developed within research context only and was funded through a *4TU.bouw* research grant and self-funding. Thus, all experiments conducted are made utilizing manually fabricated glass blocks at the *Glass & Transparency Lab*. These blocks present considerably lower dimensional tolerances and surface quality compared to the ones produced by the industry, which can have a significant influence in the structural performance of such a

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system. Hence, in this case, the experiments aim to provide a qualitative comparison of different variables that influence the system but should not be used as strength values. To provide further insight on the effect of these factors in the structural behaviour and capacity of such a system, a numerical model has also been made. Compared to the presented adhesively bonded system, the interlocking system is still under development and further research is necessary for its real application in the built environment.

Still, the findings of both concepts prove their feasibility and highlight their advantages and drawbacks. Based on the results, suggestions are made for future research directions towards the further exploration of the potential of cast glass in structures.

1.5 Societal and Scientific Relevance

The applicability of glass in structures is continuously ascending, as the transparency and high compressive strength of the material render it the optimum choice for realizing diaphanous structural components that allow for both light transmittance and space continuity. Yet, so far, engineers and architects alike tend to think of glass as a virtually 2D, brittle material susceptible to buckling and spontaneous failure. In this direction, this research aims to introduce a new method for building with glass that enables the realization of safe, self-supporting full-glass structures that can take full advantage of the compressive strength of glass. By casting, solid glass elements of high transparency and strength can be made, offering a vast potential in the realization of 3D transparent elements and structures that so far have been considered unrealistic. Glass is no more a 2D material but a three-dimensional solid. Despite glass's brittleness, solid glass components are robust, have an improved buckling resistance due to their geometry and are hence, safe to use. Moreover, a solid glass block has competitive or even superior compressive strength to that of conventional building materials such as concrete and steel (see Chapter 1.1). Thus, this research aims as well to introduce a shift in the mentality of structural engineering by introducing cast glass as a new building material. To this end, experimental work is conducted in order to provide scientific data on both the performance of cast glass components as well as on the performance of the developed structural systems employing these cast glass components. This data can be used as a guideline for the applicability of the developed systems in reality.

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Taking into account that the construction and logistics of a project involving cast glass components can face the most critical aspects for its feasibility, the actual construction of the *Crystal Houses* façade provides great insight on the engineering challenges involved in such a system. The real application of the developed system provides valuable input for the development of a second, demountable glass system that circumvents the use of adhesives and the relevant challenges, allowing for an easily-assembled and reversible structure. Such a system in turn can result in great reduction in the involved costs, construction time and most importantly, lead to a more sustainable, circular solution compared to an adhesively bonded structure. More specifically, in the developed interlocking, dry-assembly glass system, the re-use of the cast glass components is addressed as a design guideline, as well as the use of waste glass as raw material. Moreover, the design for disassembly of this novel system allows the easy reuse, repurpose or recycle of the components at the end of life of the specific application.

1.6 Outline of the dissertation

Fig. 1.7 presents the outline of this dissertation. The dissertation consists of 4 parts, each with a specific focus. Part I provides the *Introduction to the Research* and contains the current Chapter 1. Part II focuses on the *Theoretical Framework* of the research, which includes Chapters 2-4. In specific, Chapter 2 focuses on the main materials and production methods for cast glass. Following, Chapter 3 provides an overview and comparative assessment of existing large-scale non-architectural cast glass applications. Finally, Chapter 4 discusses the structural use of cast glass in architecture through both existing projects and the systems developed in this research. Part III presents the *design and experimental validation* of the two structural systems developed within the framework of this study. In specific, Chapter 5 focuses on the research, development and experimental validation of an adhesively bonded system utilizing solid cast glass blocks. The investigated system has been successfully applied to the *Crystal Houses Façade* in Amsterdam. Chapter 6 discusses all the challenges and innovations necessary for the realization of the façade. Based on the aforementioned challenges, a new concept for glass structures out of dry-assembled interlocking cast glass components is presented in Chapter 7. Chapter 8 provides the numerical and experimental validation of the interlocking glass system. Finally, Part IV, comprising Chapters 9 and 10, presents an *integrated discussion of the research results*. This part provides the conclusions from the

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research, a discussion on the production and design aspects of cast glass structural components for other applications besides self-supporting envelopes, as well as recommendations for future studies.

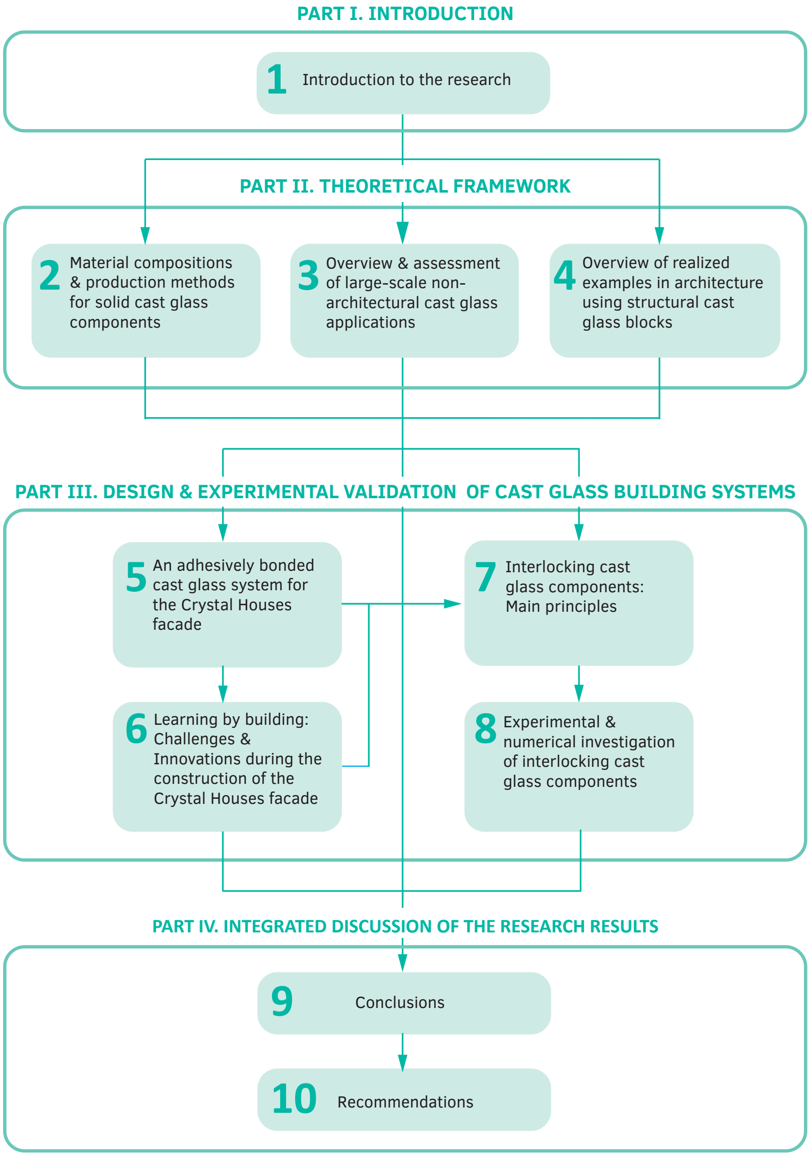

FIG. 1.7 Research strategy scheme / dissertation outline

Casting of soda-lime glass blocks at *Poesia* Factory in Italy

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Casting

To give a shape to (a substance) by pouring in liquid or plastic form into a mould and letting harden without pressure

Definition by the Merriam-Webster Dictionary

[1] An object at or near finished shape obtained by solidification of a substance in a mould.
[2] Pouring molten metal into a mould to produce an object of desired shape.

Definition by the Engineering Dictionary

Casting method

Casting is a method where a solid material is dissolved,
heated to suitable temperature
(generally treated to change its chemical structure),
and is then added into a mould or cavity,
which keeps it in a proper form during solidification.
As a result, in just one step, complex or simple designs
can be created from any material that can be dissolved.
The end product can have nearly any setting the designer needs.

Definition by the Engineering Articles
(www.engineerinigarticles.org)

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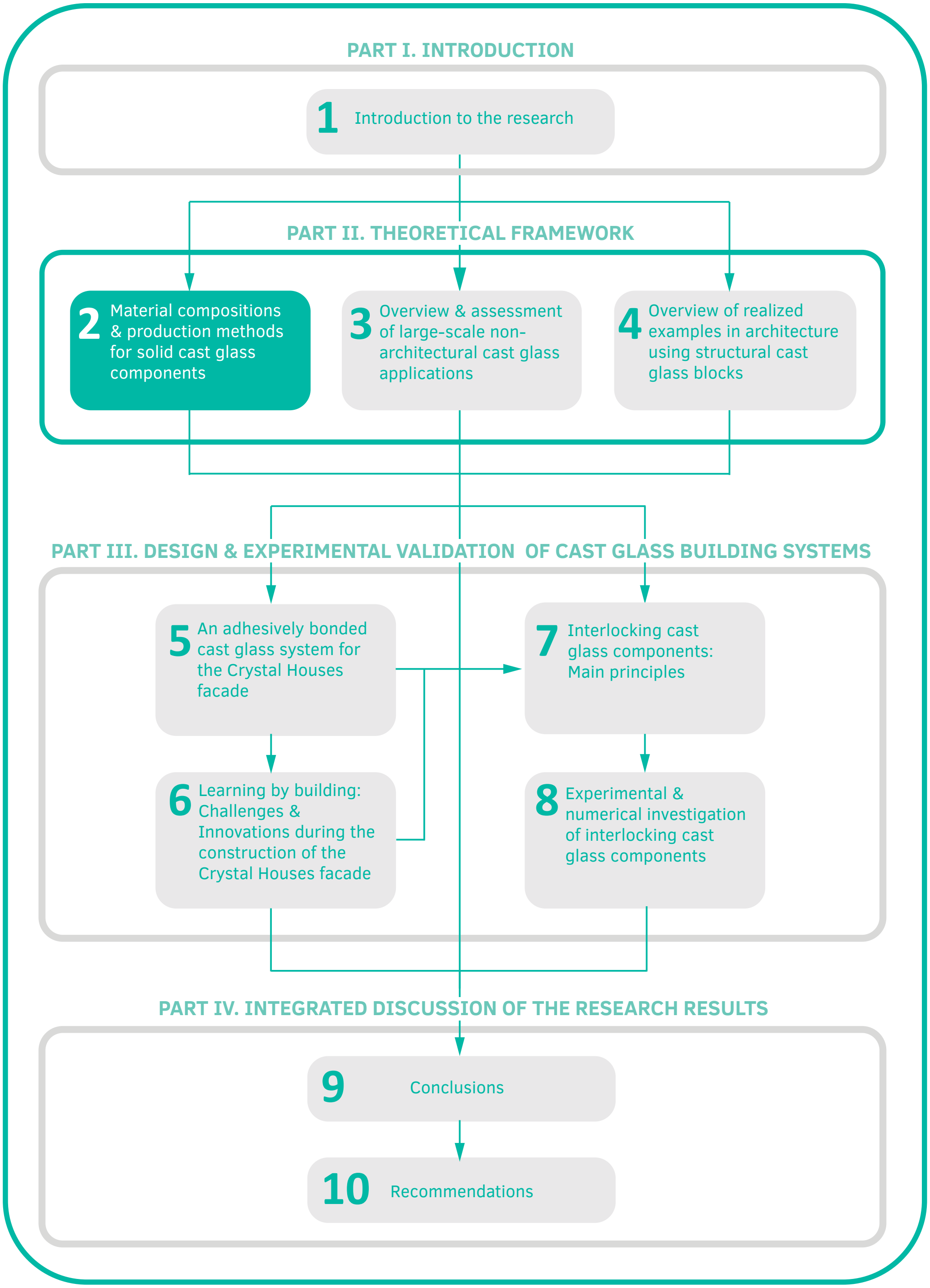
Exploring the third dimension of glass



Solid cast glass components and assemblies for structural applications

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