1 Introduction

The thesis 'COOLFACADE – Architectural integration of solar cooling strategies in the building envelope' aims to shed light on the possibilities and constraints for architectural integration of solar cooling systems in façades, in order to support the design of climate responsive architectural products for office buildings as self-sufficient alternatives to conventional air-conditioning systems.

This first chapter introduces the topics to be addressed throughout the dissertation, stating the main research problem, aim and focus of the study. Moreover, research questions are formulated, with consequent strategy and required methods to provide comprehensive answers to the defined challenges. Finally, the impact of the thesis is discussed in terms of its scientific and societal relevance, aiming to provide new knowledge to close research gaps in the field; but most importantly striving to promote further application of environmentally friendly technologies driven by renewable energy sources in the built environment.

§ 1.1 Background

Cooling needs in the built environment present an important and complex challenge for the design of sustainable buildings and cities. Energy demands for cooling have increased drastically in the last decades, due to societal and economic factors such as higher standards of life and affordability of air conditioning; and environmental aspects such as temperature rise in cities in what is known as urban heat islands, and global climate change (Santamouris, 2016). Total energy projections for the next decades show that energy consumption will keep rising, mostly driven by fast-growing emerging economies (BP, 2016; DOE/EIA, 2016), and cooling energy demands are expected to follow this trend (Jochem & Schade, 2009; OECD/IEA, 2015). As an example, yearly sales of room air conditioning units are expected to grow at 10-15%, going from 100 million worldwide in 2014, to over 1.6 billion by 2050 (Montagnino, 2017). These projections call for strong actions to be taken in order to minimise the impact of cooling needs in global energy consumption.

Initiatives devised to tackle this situation focus on the energy savings potential of the building sector, promoting good practices (ASHRAE, 2011; CIBSE, 2012) and enforcing regulations to reduce the operational energy demand in buildings (EP, 2010). In this regard, there is wide consensus on the application of passive cooling strategies as the first step for the design of sustainable buildings, under a climate responsive approach (Herzog, Krippner, & Lang, 2004; Lechner, 2014). This is particularly relevant in the case of office and commercial buildings, due to the relative importance of heating, ventilation and air conditioning (HVAC) equipment in their total energy consumption, which may reach over 50% in warm climates (Qi, 2006). Hence, their design should consider appropriate adaption to the local microclimate, regarding layout, solar protection, control of internal heat sources, and natural ventilation among other possibilities; before incorporating energy driven building services. Nevertheless, in most cases these systems will still be needed in order to meet comfort requirements; particularly in severe warm climate contexts such as desertic or tropical environments.

Therefore, a second recommended step for the design and operation of commercial buildings is the use of renewable energy sources to cope with the remaining demand in order to meet comfort requirements, avoiding the use of fossil fuels as much as possible (RVO, 2013). However, the quest for sustainable buildings and cities not only considers the use of clean energy sources but environmentally friendly systems as well. Conventional cooling units present an extra complication: the refrigerants used as working fluids within the cooling process have serious environmental impact. The most common refrigerants currently used in vapour compression based air-conditioning are hydrofluorocarbons (HFCs), such as R134a. This is a non-ozone-depleting substance, but with a global warming potential (GWP) 1,430 times that of CO2 (IPCC/TEAP, 2005). Recently, an amendment to the Montreal Protocol was signed, agreeing to phase down these substances over the period of 2019-2036 and 2024-2047 in developed and developing countries respectively (UN, 2016). This represents an important landmark, breaking a vicious cycle between refrigerants that contribute to temperature rise in urban areas, thus increasing the need for them. Moreover, this is regarded as an opportunity for the development of environmentally friendly technological solutions based on alternative cooling processes.

Solar cooling technologies have gained increasing attention these last couple of decades, for their potential to lower indoor temperatures through environmentally friendly cooling processes driven by renewable energy. The principles behind some of these technologies have been researched since as far back as the 1800s, with explicit institutional support after the oil crisis of 1973, through initiatives such as the Solar Heating & Cooling Programme of the International Energy Agency (IEA-SHC, 2016) or the U.S. Department of Energy (DOE, n.d.). The maturity of certain solar cooling technologies has reached advanced levels, being recognised as promising alternatives to traditional vapour compression refrigeration (Goetzler et al., 2014). Nonetheless, building application remains mostly limited to demonstration projects and pilot experiences (Balaras et al., 2007; Henning & Döll, 2012).

In this regard, several developments in the small-scale range have been promoted through research projects, in an attempt to expand possibilities for application in residential and commercial buildings (Jaehnig, 2009). Furthermore, this has recently led to different explorations of façade integrated concepts by several researchers, as a way to promote widespread application through the development of multifunctional building components (Prieto et al., 2017a). These integrated concepts aim to seize economic and functional benefits derived from the integration of decentralised systems in the façade, while using its exposed area for direct and diffuse solar collection. Moreover, the usual match between peak solar irradiance and peak cooling demands supports harvesting that energy for cooling applications, while blocking solar heat gains under a climate responsive façade design. Nonetheless, while the development of building integrated photovoltaics (BIPV) and building integrated solar thermal collectors (BIST) has resulted in guidelines and commercial components (Escarré et al., 2015; Munari-Probst & Roecker, 2012); fully integrated solar cooling facades are not yet ready for use as architectural products. Current experiences are regarded as relevant and promising standalone concepts but further research is needed to assess their potential within façade design, and identify barriers to overcome to promote the widespread application of solar cooling components in the built environment.

§ 1.2 Problem statement

The research project deals with the integration of solar cooling systems into the building façade as a way to support the development of environmentally friendly cooling processes and the use of renewable energy sources in the built environment. Furthermore, the possibility of using the façade itself as an active heat dissipation system is seen as an opportunity for the development of self-sustaining cooling façade modules to be applied either on new buildings or refurbishment projects in the line of new 'nearly zero' energy standards. Façade integration of decentralised building services has been encouraged by several authors as a path for the development of high performing façades, based on economic and functional advantages. The former refer to construction cost savings through off-site production, and extra leasable space from avoiding complex distribution systems (Franzke et al., 2003; Knaack, Klein, Bilow, & Auer, 2007); while functional benefits range from efficient energy usage by identifying local demands, to higher perceived comfort due to personal control (Mahler & Himmler, 2008).

The underlying hypothesis behind this research project is that self-sufficient solar cooling integrated facades may be a promising alternative to conventional centralised air-conditioning systems used in commercial buildings from warm climates. The fact that experiences with integration and prototypes exist, is regarded as basic proof of the feasibility of such concepts, but they are far from commercial application, and isolated from façade design and development processes. Most research efforts on solar cooling currently deal with the optimisation of the systems in terms of their performance, testing new materials and simplifying their operation to increase reported efficiencies. However, there is a lack of knowledge on the requirements and current limits for widespread façade application.

Therefore, this thesis focuses on the suitability of solar cooling technologies in terms of their potential for façade integration, exploring current possibilities and identifying main constraints for further development of solar cooling integrated architectural products. The potential for façade integration is assessed considering both the architectural requirements for the integration of building services within the façade design and development process; and the potential climate feasibility of self-sufficient integrated concepts, matching current technical possibilities with cooling requirements from several climates under an holistic approach to climate responsive façade design (Figure 1.1).

Given that cooling needs are the main driver of the research, the assessment focuses exclusively on warm climates, ranging from temperate to extreme desertic and tropical environments. Furthermore, although a good climate responsive design should consider all comfort issues for the design of not only the façade system but the entire building; cooling is defined as the main parameter to optimise for purposes of the assessment. Similarly, discussion about design possibilities are constrained to the façade, leaving potential for further optimisation of cooling demands through building level strategies outside the scope of the present research.

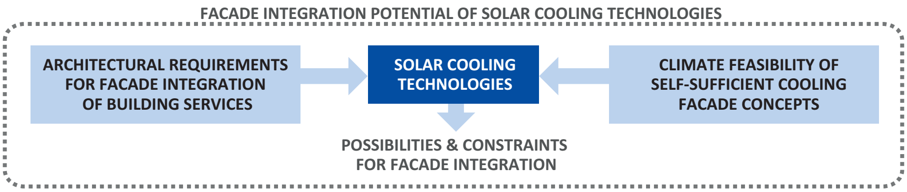


FIGURE 1.1 Main structure and focus of the research project

§ 1.3 Research objectives and questions

§ 1.3.1 Aim

The aim of the research project is to explore the possibilities and constraints for architectural integration of solar cooling strategies in façades, in order to support the design of climate responsive architectural products for office buildings as an alternative to conventional AC systems, without compromising the thermal comfort of users. The main outcome of the dissertation is a systematic assessment of the façade integration potential of selected solar cooling technologies, showcasing current limits for application while identifying main bottlenecks for further development of architectural products.

Furthermore, the recommendations and findings obtained from this research are expected to serve as valuable feedback to both façade professionals and cooling system developers. Thus, providing new insights for the integration of new technologies in the façade design and development process; while charting paths for the further development of each solar cooling technology considered in the assessment, based on identified requirements for new applications in the built environment.

§ 1.3.2 Research questions

The research project aims to answer the following research question, regarded as the main driver for an exploration of the current limits of the assessed technologies in terms of their façade integration potential:

To what extent can solar cooling technologies be integrated into the building envelope, in order to meet local thermal requirements through climate responsive integrated façade units, as an alternative to conventional centralised mechanical cooling in office buildings?

To be able to answer the research question, several sub-questions need to be explored. These sub-questions investigate specific aspects of the research project, addressed in different chapters throughout the present dissertation.

1. What is the available knowledge on façade related cooling strategies for office buildings? (Chapter 2)
2. What are the conceptual issues and state-of-the-art components and systems to consider for solar cooling façade integration? (Chapter 3)
3. What are the main perceived problems for building services integration in facades at different stages of the façade design process? (Chapter 4)
4. What are the main perceived barriers for façade integration of solar collection technologies? (Chapter 5)
5. What is the potential impact of the application of passive cooling strategies, on the cooling demands of office buildings in different warm climates? (Chapter 6)
6. What are the current possibilities and technical barriers for the architectural integration of solar cooling technologies in façade systems? (Chapter 7)
7. What is the potential for the application of self-sufficient solar cooling façades in different warm climate contexts, and what is the impact of the climate conditions on façade design possibilities? (Chapter 8)

§ 1.4 Research strategy and methods

In order to assess the potential for application of façade integrated solar cooling concepts, the research follows a straight forward approach, based on three sequential parts. The first part deals with the state-of-the-art in the field and the theoretical framework, laying the groundwork for the following sections. The second part explores different aspects required as input for façade integration; while the third part comprises the evaluation of solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades, based on the inputs identified in the second part.

The overall strategy is shown in the scheme in Figure 1.2, comprising the main parts of the research project and the chapters in each one of them. Hence, the research strategy matches the outline of the dissertation. As stated before, the potential for façade integration of solar cooling technologies is assessed considering two main groups of aspects: architectural requirements from the façade design and development process; and the climate feasibility of self-sufficient integrated façade units. Therefore, both are assessed separately in the second part, leading to parallel explorations within that section, to then converge again in the third and final part for the evaluation of selected technologies.

Each chapter aims to respond one of the sub-questions presented above, supporting the development of the whole research by delivering specific outcomes, connected under an overall research strategy. Besides the main conclusions of the thesis, these particular outcomes are regarded as valuable contributions in each sub-field addressed in the dissertation. Hence, each chapter was conceived as a standalone exploration, using particular research methods and expanding the background related to the specific research problem at hand. Therefore, it was decided to conceive the chapters of the dissertation as scientific articles for publication in peer review academic journals. Despite some redundancy in the chapters' introductions, the benefits derived from the need to focus and clearly communicate partial results through continuous publication in scientific outlets, are regarded as an integral aspect of the research strategy.

As stated, each chapter considers different methods, to address the specific sub-questions. The particular strategy and methods are explained in detail in each chapter, but a brief overview is presented below, discussing the aim and methods from the chapters within each main part in order to understand how they relate to the others and their general role in the overall research scheme.

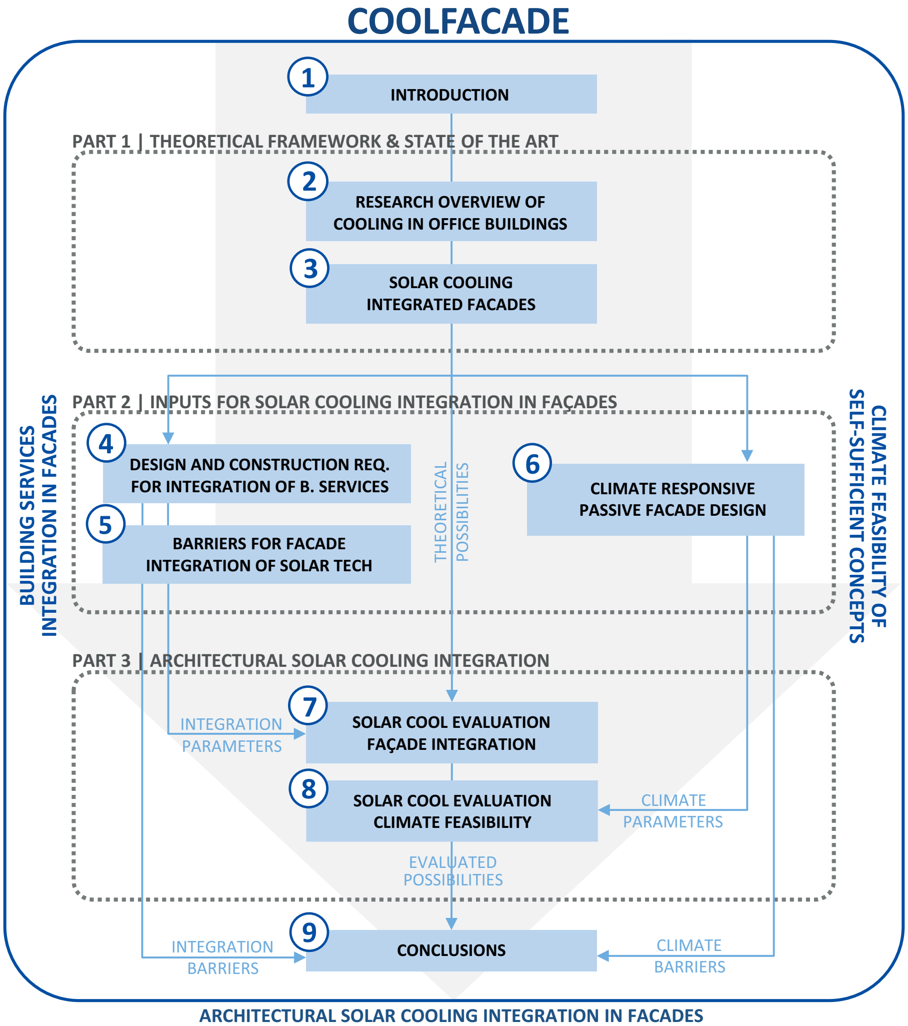


FIGURE 1.2 Research strategy scheme / dissertation outline.

Part 1: Theoretical framework and state-of-the-art

The first part considers two chapters that lay the foundations for the research project, expanding the background while exploring the state-of-the-art within the field. A systematic literature review of cooling research in office buildings is presented in Chapter 2, showcasing a panorama of the scientific knowledge in the field during the last 25 years, based on reported experiences in peer review scientific articles. This chapter is regarded as a general introduction to the topics, expanding the background of the dissertation by identifying knowledge gaps and research trends while contributing to the generation of a reference database of research experiences. On the other hand, Chapter 3 delves specifically in the main themes addressed within the dissertation, proposing a framework for the understanding of solar cooling integrated façades. This considers the theoretical discussion of the concept of architectural façade integration; and the identification of the main working principles and technical components from most common solar cooling technologies, based on a state-of-the-art review. Reported façade concepts and prototypes are also showcased to illustrate current possibilities.

Part 2: Inputs for solar cooling integration in facades

Chapters 4-6 explore different aspects required for façade integration. Chapters 4 and 5 discuss design and construction requirements for integration, while Chapter 6 deals with the response from façade design parameters to various climate conditions. The exploration of design and construction requirements is conducted through the identification of the main perceived problems for the façade integration of building services and solar technologies, by means of a survey addressed to façade professionals. The responses from the survey are interpreted using qualitative content analysis techniques and quantitative descriptive statistics. Chapter 4 presents and discusses the main perceived barriers for the integration of building services, while Chapter 5 deals with the integration of solar collection technologies. On a parallel track, Chapter 6 explores the relation between climate conditions and cooling requirements in office buildings, evaluating the potential impact of several passive cooling strategies for the design of climate responsive façades. As stated in the background, this should be the first step when aiming to decrease cooling demands, before integrating further technology. Thus, the chapter aims to examine the performance extents from the application of passive strategies in various warm climates, through the statistical analysis of reported research experiences, and dynamic energy simulations of a base scenario using specialised software. The outcomes from the chapters in the second part lead directly to the identification of general barriers, while also providing specific input for the evaluations carried out in the third part.

Part 3: Architectural solar cooling integration

The third and final part of the dissertation incorporates the outcomes from the previous chapters for the evaluation of selected solar cooling technologies in terms of current possibilities and constraints for the development of integrated façades. Theoretical possibilities are obtained from the framework proposed in Chapter 3, which are evaluated considering parameters defined in the second part, in two sequential assessments. Chapter 7 shows the qualitative evaluation of the façade integration potential of several solar cooling technologies, based on a comprehensive review of key aspects of each technology and their prospects to overcome identified barriers for façade integration of building services. Finally, Chapter 8 explores the feasibility of the application of integrated concepts in several climates, throughout numerical calculations based on climate data and building scenarios simulated with specialised software. Base scenarios are obtained from Chapter 6, and further evaluations are conducted considering limited design variations. The outcome from the final part aims to show current possibilities and identify main limitations under a systematic assessment, drafting recommendations for the further development of façade integrated architectural products.

§ 1.5 Research impact

§ 1.5.1 Societal relevance

The foremost aspect when discussing the societal relevance of the research project refers to the aforementioned pressing need to decrease cooling demands in the built environment. Furthermore, the exploration and promotion of environmentally friendly cooling processes driven by renewable energy sources should accelerate their widespread application, with the consequent important decrease of the global warming potential of buildings.

On a building scale, energy savings comprise economic benefits in the long run. The integration of self-sufficient solar cooling modules within a climate responsive façade design considers the possibility to achieve zero or nearly-zero energy consumption from the grid. Moreover, on a more general note regarding potential economic benefits, the exploration of new technologies and their possibilities for façade integration could jumpstart the development of new architectural products and business models for new applications in the built environment. In turn, this not only would generate profit for the stakeholders, but also job opportunities and impact on the building industry.

Lastly, the use of decentralised building services has been encouraged based on health and comfort issues. The inherent possibility of direct control suited to local demands has shown improvements in the perceived indoor comfort (Mahler & Himmler, 2008); while the use of centralised equipment has been linked to indoor air quality complaints due to lack of maintenance of coils, filters and cooling towers (Bluyssen, 2009). Moreover, the use of desiccant based solar cooling systems has been proven to enhance indoor air quality in humid environments by avoiding condensation in the cooling process and absorbing pollutants and bacteria (Sahlot & Riffat, 2016). Furthermore, the link between the well-being of workers and their productivity levels is widely accepted, translating social and health issues into economic benefits for the company (Vischer, 2007).

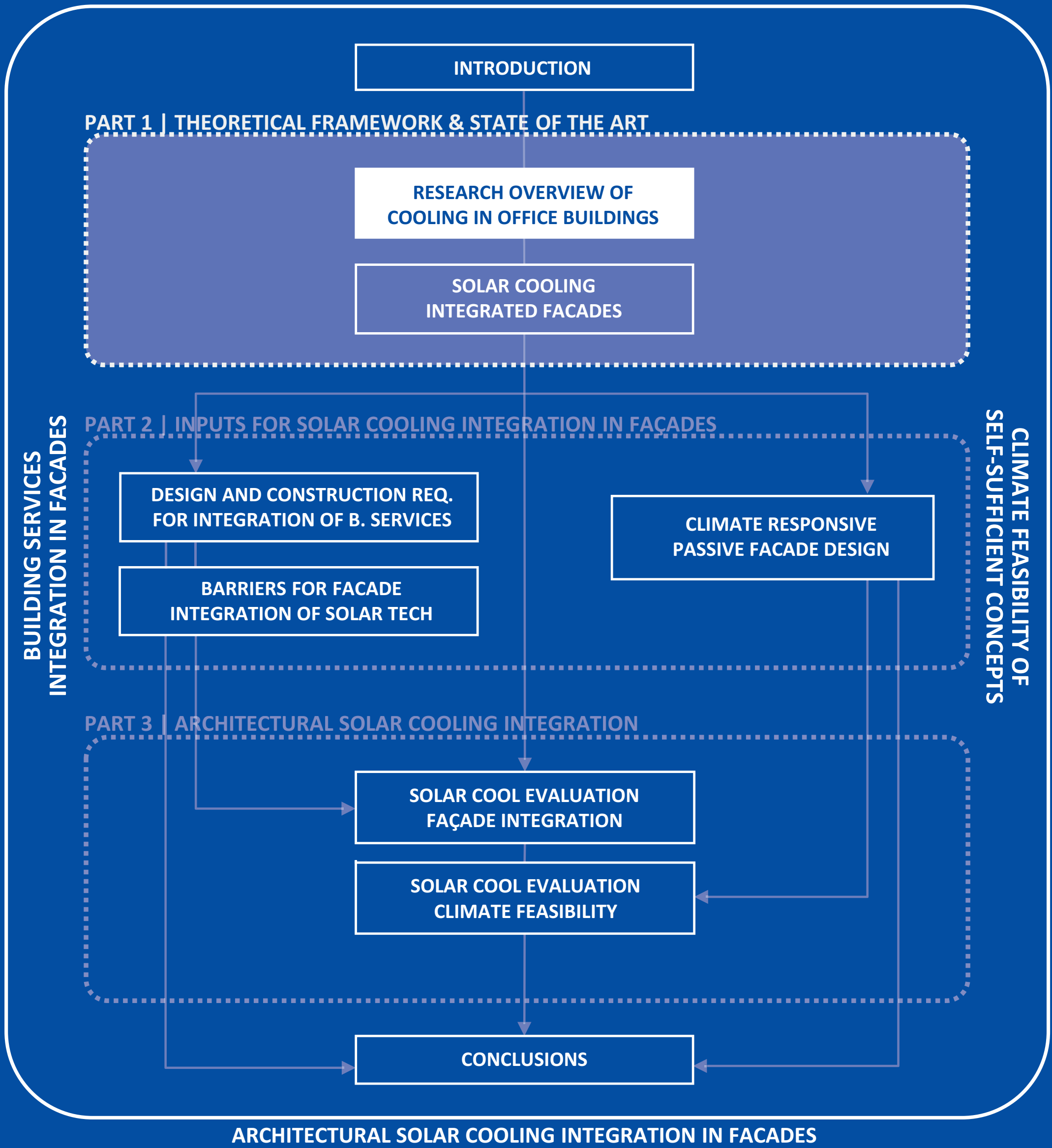
§ 1.5.2 Scientific relevance

The research project seeks to expand current knowledge in the field of façade design, focusing on the development of new architectural products based on their cooling performance, and the integration of new technologies and building services. The assessment of current possibilities and limitations for façade integration of solar cooling technologies under a systematic approach, is regarded as a relevant contribution to the field, guiding further research and development on specific technologies and façade design and construction. Furthermore, the methodology designed for the assessment may be useful not only for the case of solar cooling, but also as a path to evaluate the potential for façade integration of new technologies and innovative building systems.

Besides the central aim, the research also deals with specific research gaps, advancing the knowledge in sub-fields explored throughout the thesis. Therefore, the results from the survey presented in Chapters 4 and 5 aim to provide insights on general issues within the façade design and construction process, besides contributing to the main aim of this research project. The construction industry has been openly criticised by its poor performance and outdated production methods (Woudhuysen & Abley, 2004), so examining the façade development process itself seems relevant in the current agenda towards sustainability. Similarly, the cross-climate examination of the potential savings derived by the application of passive cooling strategies showcased in Chapter 6, is expected to serve as useful referential information in early design stages. Hence, encouraging their application in office buildings, not only as a stepping stone for solar cooling integration but as a basic aspect of all new buildings and refurbishment projects.

Finally, it is worth mentioning that throughout the dissertation, there is a conscious aspiration to make use of available scientific knowledge, based on a comprehensive panorama of the state-of-the-art on both research experiences and technical solutions within the field of study. Hence, the research project not only references and discusses previous studies, but aims to use them as valuable input for the analyses, complementing this data with new information to fill scientific gaps and defining future steps for the development of integrated façade concepts for architectural application.

COOLFACADE



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