

**DESIGN OF EFFECTIVE
SOLAR ARCHITECTURAL SKINS
FOR VISUAL ENGAGEMENT**

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Abstract

Architectural skins can enhance people's experience of urban spaces through a captivating design and can improve the energy performance of buildings by generating energy from renewable resources. Designing building envelopes that can attract attention and interest entails understanding architecture's communicative role and aspects of vision. This points at potentially eye-catching features and at examples of building skins that display them, such as media facades, with their challenges and opportunities. The latter include the possibility of integrating photovoltaic technologies into the building envelope, which involves a compromise between efficiency and aesthetic quality. This research explores the design of architectural skins that can stimulate visual engagement by deploying solar technologies effectively.

Designing solar building envelopes could draw from research on vision and media façade design as well as consider the potential of emerging photovoltaic-based technologies for building integration. Exploratory and open-ended, this research merges knowledge from different disciplines to suggest a framework for conceiving solar architectural skins that can trigger visual engagement while generating energy efficiently. It adopts a mixed-methods approach combining an interdisciplinary literature review underpinned by the analysis of case studies with the design of a concept for a photovoltaic façade. The design involves people in the process and is facilitated by digital prototyping techniques. These include a virtual reality experiment completed by observations and interviews for evaluating participants' responses to a concept generated with parametric simulations and visualisations.

The resulting framework for conceiving effective solar architectural skins that may stimulate visual engagement can support the early creative process through a set of aspects to be pondered and possible methods to be used. It may be helpful to those intending to integrate solar technologies into captivating building skins at an early stage of their design by focusing on visual and energy aspects. It is also open to refinement with continuing exploration considering further aspects, such as economics or technology and design development, which fall outside of the scope of this research. The proposed holistic approach that draws from different disciplines with design inspiration from media architecture invites consideration of emerging solar technologies with improved performance, which may also produce stimulating

visual effects on architectural skins. It promotes the use of participatory VR research in the design of solar envelopes for visual engagement from an early stage and encourages further exploration on the communicative potential of solar architectural skins as well as innovative thinking towards developments in technology and design.

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Accompanying Material

DVD: 2 Short Videos

1. *Example of Test Animation Produced by the Author while Generating a Concept for a Solar Architectural Skin*
2. *360° Video Produced by the Author to Evaluate People's Visual Engagement with a Solar Architectural Skin*

The role of the videos in this research is explained in Chapter 7 and Chapter 8 of the thesis. The one-minute long 360° video is to be played on a smartphone embedding a gyroscopic sensor and an accelerometer, by using a VR viewing application such as VRTV VR Video Player (Google, 2018) and a headset compatible with Google Cardboard (Google, n. d.).

Nomenclature

AR	augmented reality
BAPV	Building Attached Photovoltaic
BIPV	Building Integrated Photovoltaic
c-Si	crystalline silicon
CdTe	cadmium telluride
CIGS	copper indium gallium diselenide
CPC	compound parabolic concentrator
CPV	concentrating photovoltaic
CPVT	photovoltaic thermal concentrator
GaAs	gallium arsenide
LED	light-emitting diode
PCM	phase change material
PV	photovoltaic
PV/T or PVT	photovoltaic-thermal
VR	virtual reality

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Declaration

I declare that the research contained in this thesis, unless otherwise formally indicated within the text, is the original work of the author. The thesis has not been previously submitted to this or any other university for a degree, and does not incorporate any material already submitted for a degree.

Signed

A solid black rectangular box used to redact the signature of the author.

Eleonora Nicoletti

Dated 23 January 2020

Chapter 1: Introduction

1.1 Chapter Overview

Visually captivating building exteriors such as media facades can enhance the quality of urban spaces, but present operational drawbacks including high energy use. On the other hand, integrating solar technologies into the envelope can improve a building's energy performance towards 'nearly zero-energy' standards. This chapter introduces and summarises the research undertaken, which investigates the potential for designing architectural skins that can engage passers-by visually and collect solar energy effectively.

The second section outlines the context of the investigation, lying within the research fields of visually engaging architectural skins and solar building envelopes, which draw knowledge from multiple disciplines.

The third section states the research problem, reflecting the gap in knowledge identified within the research context, and presents the research questions guiding the exploration.

The fourth section briefly introduces the aims of the research, which intends to create a framework aiding the early design of visually engaging architectural skins that deploy solar technologies in effective ways. It also presents the scope and the limitations of the research, which being a PhD project is subject to time and funding constraints.

The fifth section outlines the research approach adopted, introducing the methods used and the structure of the thesis which mirrors the process of the investigation.

The sixth section provides a summary of the chapter contents, drawing its conclusions.

1.2 Research Context

As presented in the next chapter, architecture can be thought of as a form of communication, in which the physical features of spaces can be associated with meanings and induce people's fondness for places. While all senses contribute to the experience of urban environments, influencing people's perception of architecture, vision appears to play a prominent role for most people. Visually engaging architectural skins, capable of attracting people's attention and interest as well as of stimulating reactions, can improve the quality of publicly used spaces.

Such building skins embed eye-catching qualities of shape, colour, three-dimensionality and motion. The latter appears to be the strongest visual attractor according to research on the psychology and neuroscience of visual perception. Motion can manifest in various forms, including illusory movement.

Visually striking features such as figures, patterns and motion can be recognised in architectural envelopes indicated as ‘media facades’, referring to luminous (see fig. 1.) and kinetic building skins (see fig. 2.), as exemplified below. These are articulated in modular configurations which facilitate the display of visual content, but can present considerable operational downsides, such as the intensive use of electric power, not conforming with requirements for nearly zero-energy buildings, as well as issues related to cost and maintenance. Such problems may be reduced by employing less electrically operated components in a variety of ways, such as exploiting specific material behaviours or atmospheric conditions, optical phenomena and visual illusions to convey a sense of motion. Creating motion impressions through static building skin systems appears to be a particularly accessible and potentially more effective way of minimising operational issues associated with dynamic architectural exteriors.



Fig. 1. *realities:united*, SPOTS, 2005 (Photo © Bernd Hiepe | Artistic Content Displayed © Nina Fischer & Moruan El Sani)

Figure removed due to copyright restrictions

Fig. 2. *MegaFaces by Asif Khan*

The performance of building envelopes can also be improved through the integration of solar technologies. These supply buildings with electricity and heat from solar energy, which contributes to reducing carbon emissions that are believed responsible for global warming. Solar technologies may be embedded in architectural skins according to designs that display visually engaging features. This suggests the possibility of supplying buildings with renewable energy produced onsite through captivating exteriors that can improve the quality of publicly used spaces. For instance, there exist solar modules with enhanced aesthetics, particularly characterised by the presence of colour and patterns. However, there seems to be a trade-off between optimising energy capture by photovoltaic and solar thermal arrays, which are usually dark in colour and uniformly shaped, and

enhancing their appearance.

There is a significant body of research directed at ameliorating the performance of solar technologies and their deployment on building envelopes. Further visual improvements on solar architectural skins may become possible thanks to solar technologies for building integration that are currently less established or still under development. These include solar modules with three-dimensional configurations, and low-concentration optical devices which can increase the energy output of photovoltaics by reflecting, refracting or emitting light.

Guidance in the design of functional and aesthetically pleasing building-integrated solar arrays has been provided by previous research, including studies conducted as part of the International Energy Agency's project '*IEA SHC Task 41: Solar Energy and Architecture*' (Farkas, 2013; Munari Probst & Roecker, 2013). However, existing frameworks for designing solar architectural skins are not aimed specifically at stimulating visual engagement, nor do they try to encompass promising technologies that are still in development but may become viable in the future. Additionally, the suitability of a solar envelope for a building always depends on multiple factors including characteristics of the particular location and climate. An understanding of existing and developing solar technologies, and of the strategies to successfully embed them in architectural skins, can orient architects' choices in generating novel concepts of visually captivating solar façades.

1.3 Research Problem

As outlined in the previous section, there is a considerable body of research on the design of architectural skins for visual engagement and on the integration of solar technologies into building envelopes. Nonetheless, the two research fields have yet to be combined. A knowledge gap may be identified in a foundation drawn from multiple disciplines for the process of creating visually engaging designs of architectural skins that deploy solar technologies in effective ways. This can be achieved by connecting information from different fields of knowledge, ranging from the psychology and neuroscience of visual perception to media architecture and solar technologies for building integration. Filling this research gap appears important to facilitate designs that can both enhance the quality of exterior urban spaces, contributing to a sense of place, and improve the performance of buildings towards 'nearly zero-energy' standards that all new properties in the European Union are expected to comply with by 2020 (2010/31/EU, article 9).

To outline an approach that aids the design of effective solar architectural skins for visual engagement, the following research questions are to be answered.

1. How can architectural skins produce visual engagement with minimal energy use?
2. How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?
3. How can novel concepts of effective solar architectural skins be designed to produce visual engagement?

The three 'how can' questions reveal the exploratory nature of the research, towards suggesting directions for the design of novel architectural skins that can stimulate visual engagement by deploying solar technologies successfully.

1.4 Aims, Scope and Limitations of the Research

Building on existing knowledge, this research aims to outline a framework that can facilitate the design of novel, visually engaging architectural skins characterised by the effective deployment of solar technologies, pointing at directions for further investigations on the subject. The proposed approach to the design of solar building skins may be employed by architectural practitioners and researchers, as well as by architecture students, potentially influencing future design and research.

Exploratory in nature, this study finds its context in research on visually engaging architectural skins and on building-integrated solar technologies, thus it has an interdisciplinary scope. It looks into how visual engagement may be stimulated through designs of solar architectural skins, which may improve the experience of urban spaces as well as the energy performance of buildings. Therefore, it connects seemingly disparate subjects by exploring them with an architectural perspective. It considers findings from the scientific study of vision, involving the psychology and neuroscience of visual perception which includes physiological and cognitive aspects. It relates them to research on visually dynamic building skins, encompassing topics such as 'media facades', 'kinetic facades' and 'responsive facades', and links those to research on the architectural integration of solar technologies. The study ultimately focuses on the deployment of photovoltaic-based technologies in the early stage of architectural design, considering their visual characteristics which may stimulate engagement but also energy aspects that are intrinsic to such technologies. Other aspects fall outside of the scope of the

exploration, thus even when they are touched upon, they are investigated in much less depth. Researching responses to solar building skins beyond what is indicative of visual engagement or identifying correlations between them and characteristics of a population is not part of the aims of this project. Developing technologies or designs is beyond the scope of this research which explores, instead, possibilities for the architectural deployment of existing and emerging solar technologies as it can be envisioned in early design. Economic aspects are not part of the scope of the present study, but they are considered to some extent as they propel the development of alternative photovoltaic-based technologies and impact design choices about their architectural integration. It is also noted in the thesis that the design of visually communicative architectural skins can be motivated by commercial purposes, such as representing brands or displaying advertising, and may bring economic benefits to urban areas.

In the attempt to blend media façade design with solar façade design and to suggest a framework leading to novel concepts of solar architectural skins, the research provides a comprehensive overview of the topics involved rather than examining each of them in depth. For this reason, and due to the time and resource constraints of the PhD project, several topics are touched on that might require further investigation in the future. For instance, the state-of-the-art solar technologies for building integration are broadly presented including those that are less established or still in development but appear promising in terms of performance and future architectural application. The information on solar technologies is reviewed by the researcher from an architectural design perspective, which inevitably determines a selection of the aspects that are most relevant to the design of buildings, with a special focus on the visual impact of their exteriors. Therefore, solar technologies are presented with an emphasis on qualitative rather than on quantitative characteristics yet considering their performance in terms of energy generation as this is important in informing decision-making when it comes to designing effective solar architectural skins.

While both electricity and heat from solar energy can be utilised in buildings, through photovoltaic and solar thermal systems respectively, this research leans more towards applications of solar technologies which appear to allow greater design flexibility in the creation of visually engaging effects on architectural skins. Hence, the research focuses more on the architectural integration of photovoltaics, considering their potential enhancement with low-concentration devices and other

strategies. This does not deny the possibility of deploying solar thermal arrays and other systems in captivating façade designs, but rather recognises the existence of more complex problems which can be better investigated through further research.

Additionally, this project does not examine thoroughly or in depth the communicative potential of solar architectural skins. For instance, it does not fully explore the possible ways of displaying motion through solar architectural skins, or their benefits and drawbacks. It ultimately focuses on the potential for creating motion impressions through static systems which may have operational advantages, leaving the exploration of kinetic solar skins to further studies that may continue existing work on solar tracking facades and on the integration of photovoltaics in light-emitting and kinetic media facades.

The impossibility of exploring in detail a wider range of strategies and technologies for designing captivating solar envelopes has been mainly determined by the limited timeframe of the research, conducted by a single person with restricted resources. The ongoing status of research on solar technologies also poses limits to the completeness of the analysis carried out, as new findings are constantly published in this field. Such constraints have also informed the choice of including a single practical design example in the research project, applying the outlined approach to the design of solar architectural skins for visual engagement. For the same reasons, the exploration only focuses on the initial stage of designing solar architectural skins, rather than on developing concepts to a detailed stage. This would require a higher level of analysis of all the aspects involved, as well as further testing of prototypes or materials, the availability of more time and resources, and different types of expertise beyond architecture. Therefore, this research does not intend to develop new technologies or designs to an advanced stage, but only aims to delineate a novel approach to dealing with the complexity of conceiving effective solar architectural skins for visual engagement.

Considering the characteristics of solar technologies, the proposed approach is largely based on the scientific study of vision as well as on research on media architecture. It is aimed at facilitating the creation of architectural skin designs embedding solar technologies, that can attract visual attention and interest as well as stimulate reactions. The suggested approach is applied to an early design example in which multiple variables are handled and ideas are tested through digital prototyping techniques, including parametric simulations, visualisations and virtual

reality, to overcome limitations in time and resources. This uncovers several challenges and opens the way to further research.

1.5 Research Approach and Structure

As revealed by its questions, this research is exploratory and open-ended, as it hints at new possibilities for the design of solar architectural skins aimed at stimulating visual engagement. Its exploratory aim to create a design framework starting from a broad, interdisciplinary knowledge base implies that the study demands to be undertaken with a holistic approach and diverse methods. These complement each other in a form of triangulation which strengthens the validity of the study. Hence, the research is conducted through a combined strategy with a predominantly naturalistic paradigmatic stance.

The combined strategy integrates secondary qualitative and case study research with primary, practice-based simulation and experimental research. Drawing from research in seemingly disparate fields, ranging from the psychology and neuroscience of visual perception to media architecture and solar technologies for building integration, a broad knowledge base is created through qualitative research in the form of literature review, and it is further expanded through the analysis of fifteen case studies of visually captivating architectural skins. These are selected for visually stimulating characteristics which could be applied potentially to the design of effective solar building skins. The emerging links between concepts lead to outlining a framework for the design of effective solar architectural skins capable of producing visual engagement. Inviting consideration of multiple factors and of a range of possible design solutions including visual features and technologies, the suggested model is applied to the early design of a solar architectural skin for an arts centre in Doha, Qatar. Rather than conducting interviews with user groups prior to the design, this process entails testing a concept proposal based on the theory drawn from combined disciplines, through observations of people's reactions and interviews with them after the design concept is created. This is found appropriate to evaluate a design's capacity for attracting people's gaze and attention.

The design experiment entails using multiple methods that range from algorithmic 3D modelling techniques using Rhino and Grasshopper, to parametric simulations of insolation levels using the Ladybug plugin for Grasshopper and rendering with V-Ray for Rhino. The latter is also employed to create a virtual reality experience involving fifteen participants, whose reactions to the proposed design are observed, recorded and better understood through interviews conducted afterwards. While the

digital tools within Grasshopper allow the researcher to handle multiple variables in the design, virtual reality enables the evaluation of participants' responses to the proposed solar skin, which can be considered relatively realistic due to the immersive character of the experience. While participants are informed about the distinctive traits of the simulation in virtual reality and of its potential side effects, the latter are avoided through preventive strategies including caution in design.

The structure of the thesis reflects the research process. Following this introductory chapter which briefly outlines the contents of the thesis, the second chapter provides an overview of the state-of-the-art research on the design of visually engaging architectural skins. It starts from an introduction of architecture's communicative role and of the importance of visual perception in the experience of urban spaces, to then identify the features that can influence the attractiveness of architectural skins. It reviews the literature on visually captivating building envelopes, such as 'media facades', 'kinetic facades' and 'responsive facades', particularly from a design and technology perspective, to uncover the challenges related to the design of these architectural skins and to hint at potential solutions.

The third chapter provides an overview of the state-of-the-art solar technologies for integration into architectural skins, including a review of design criteria outlined by researchers and of concepts in development. Constraints and opportunities for enhancing the effectiveness of solar building envelopes are examined, hinting at potential strategies for novel designs of effective solar architectural skins capable of stimulating visual engagement.

The fourth chapter presents the methodology adopted in this research and how it has been formulated. Besides providing a general overview of architectural research as the context, the chapter illustrates the exploratory nature of this project with its aims, target audience, expected impact and research questions. It describes how the research idea originated and developed, informing the choice of a mixed methods approach. The chapter explains and justifies the chosen strategy integrating secondary qualitative and case study research with primary simulation and experimental research, as well as the rejection of certain strategies and methods.

The fifth chapter illustrates fifteen case studies based on secondary sources, exemplifying visually captivating designs of architectural skins selected for their capacity of producing motion impressions in ways that could potentially be applied

to the design of effective solar building envelopes triggering visual engagement. The case studies are analysed in a descriptive and explorative manner from a compositional and technology perspective, leading to an indication of potential directions for the visual design of novel solar architectural skins.

The sixth chapter expands on the topics examined through the literature review and analysis of case studies, outlining a framework for the design of effective solar architectural skins capable of triggering visual engagement, to be utilised in a practical design experiment.

The seventh chapter describes the primary, practice-based research process of generating a concept for a solar skin aimed at producing visual engagement, following the suggested framework, for a real site in Doha, Qatar. This is the Fire Station Artist in Residence, an arts centre belonging to Qatar Museums, where the researcher worked for some time in 2017. The iterative design process is presented as characterised by the use of digital prototyping techniques including parametric simulations and visualisations.

The eighth chapter presents the primary, practice-based research process of evaluating a solar skin's capacity for triggering visual engagement, utilising the design concept proposed for the Fire Station Artist in Residence in Doha. This is conducted through a virtual reality experiment involving people, in which their responses to the proposed design are observed by the researcher and further understood thanks to their feedback.

The ninth chapter discusses the results of the research, commenting on them in relation to the aims of the project and refining the design framework previously outlined. It highlights aspects which emerged throughout the research that are relevant to the design of effective solar architectural skins for visual engagement and identifies opportunities for further work in design and research.

The tenth chapter draws the conclusions of the study, clarifying its outcomes in relation to its aims as well as its original contribution to knowledge, and indicating possible directions for future research.

1.6 Conclusions

This chapter has provided a general overview of the research undertaken. It has introduced the context of the research and the identified gap in knowledge, then stating the research problem and presenting the research questions, as well as the

aims of the investigation, its scope and its limitations. It has been highlighted that the research is rooted in multiple fields of knowledge ranging from visual perception and media architecture to solar technologies for building integration. By building on existing knowledge, this research intends to outline a framework capable of aiding the early design of novel, visually engaging architectural skins which deploy solar technologies in effective ways, and to hint at directions for further explorations on the subject. Therefore, the research is mainly directed at practitioners and researchers as well as students in the field of architecture.

The research strategies and methods employed have also been presented briefly as a composite methodology that combines secondary qualitative and case study research with primary simulation and experimental research. Complementing each other in a form of triangulation that strengthens the validity of the study, the mixed methods used include literature review, analysis of case studies, parametric modelling, visualisations, virtual reality simulation, observations and interviews.

The next chapter examines part of the research context, reviewing literature on the topic of visually engaging architectural skins.

Chapter 2: Visually Engaging Architectural Skins

2.1 Chapter Overview

This chapter provides an overview of research on visual engagement in relation to the design of architectural skins. It frames the context of the present exploration through the review of relevant literature and introduces the direction pursued in the current study.

The second section approaches the subject from an understanding of architecture's communicative role to then consider the importance of visual perception in the experience of urban spaces.

The third section narrows the focus to the aspect of visual engagement. It clarifies its meaning and identifies features that may stimulate it when they are displayed on architectural skins.

Showing how visually engaging features can be displayed on building envelopes, media facades are the topic reviewed in the fourth section. This considers potential benefits of media facades, their technologies and design aspects as well as their drawbacks and possible solutions.

The fifth section draws the conclusions of this chapter, clarifying the intent of the present research.

2.2 Architecture as Communication

Architecture's communicative role has been explored by several researchers from various fields of expertise and from different perspectives. For instance, Botwina & Botwina (2012) reviewed the literature on the aspect of 'meaning' in architecture, mentioning, among others, the semiotician Umberto Eco (Leach, 2005:173-195) who recognised the discipline as a complex communicative system conveying meanings subjected to multiple interpretations (Botwina & Botwina, 2012:222-224). Similarly, Gawlikowska (2013) pointed out that by being a society's reaction to changing contexts, architecture and urban spaces communicate, although the efficacy of the communication is subject to people's reception and interpretation ability (Gawlikowska, 2013). Research into 'sense of place', intended as 'an emotional relationship between people and places', highlighted that this affection is produced by both the physical characteristics of a setting and the activities and

meanings people associate with it (Najafi & Shariff, 2011). Thus, the fulfilment of architecture's communicative role depends on people's perception.

Several studies examined how people perceive architectural and urban spaces. Boyle (2011) provided a review of the prominent literature on sensory design of the built environment, citing works by Juhani Pallasmaa, Peter Zumthor and others (Boyle, 2011). Pallasmaa (2005) in particular criticised the predominance of vision at the expense of the other senses in the current experience of architecture (Pallasmaa, 2005:30-31). On the other hand, the same author suggested that 'unfocused vision' could favour a restored balance between the senses (Pallasmaa 2005:35-36). According to Pallasmaa (2000), due to 'the power of the eye' over the other senses, architecture is perceived as a mere visual image instead of being appreciated by 'the eye, ear, nose, skin, tongue, skeleton and muscle' collaborating together (Pallasmaa, 2000:78). The relevance of a multisensory experience of architecture emerged also from Zumthor's concept of 'atmosphere' (Zumthor, 2006). Nonetheless, the amount of sensory stimulation in a setting may affect people's well-being, as both too much and too little stimulation in the environment were said to produce stress (Evans & Cohen 1987:578). Furthermore, it may be observed that the extent to which senses other than sight appreciate architecture depends on the distance from which a certain setting is experienced.

Despite the importance of all senses in influencing people's perception of architecture, vision appears to have a major role, at least for sighted people. Belova (2006) wrote that despite the intertwining of the senses in the human experience of spaces, 'organisational artefacts continue to have a strong appeal to our visual senses' (Belova, 2006:94). According to the same author, 'the viewer engages with the image on a bodily level', as viewing a space can evoke 'sensual feelings' and can invite further exploration (Belova, 2006:97). Suggesting the example of colours that can 'feel', for instance, 'warm' or 'cold', and largely referring to Merleau-Ponty, she described viewing as an 'actively responsive' way to bodily engage with an environment and to understand it (Belova, 2006:100-105). By studying the sensory experience of spaces in relation to tourism, Rahman et al. (2016) pointed out that visual stimuli play an important motivational role before, during and after a vacation (Rahman et al., 2016:TOC-120). Moreover, the healthcare design expert Roger S. Ulrich claimed that 'vision is by far our most important sense in terms of yielding information about outdoor environments' (Ulrich, 1979:17). Therefore, vision is

highly significant in the experience of open urban spaces and of architectural exteriors.

The above considerations do not apply to visually impaired people who perceive spaces through senses other than sight. There are various types of visual impairment, from total to partial blindness, such as being able to distinguish only light, having only lateral or central vision, or having blurred vision. Visually impaired people retrieve spatial information largely through their haptic and orienting abilities. Visual features of spaces may be perceived only by those visually impaired who are partially sighted, whereas memories of visual experiences can influence spatial perception in people whose blindness is not congenital or acquired very early in life (Dischinger, 2000:91-94). People with visual impairment use auditory stimuli from the environment to obtain spatial information (Nagahata, 1998; Dischinger, 2000:156), constructing 'cognitive maps' to which haptic and olfactory stimuli may contribute (Papadopoulos et al., 2012). The importance of auditory and other non-visual sensory stimuli should be considered in the inclusive design of public spaces and buildings (Rychtarikova et al., 2012). However, the present research focuses on visual information which remains highly relevant to the perception of architecture for most people.

Given the importance of vision in the human experience of spaces, it can be evinced that in urban environments building facades play an eminent communicative role. Krampen (1989) showed how façade surface layouts can convey different 'affective meanings' depending on the presence or absence, as well as on the distribution, of decorative elements (Krampen, 1989:135). Evaluating the quality of urban environments based on pedestrian dynamic and static actions, Gehl (2011) mentioned 'active frontages' among the spatial features capable of enhancing pedestrian flow (Gehl 2011, cited in Campos, 2012:125-126). A study examining pedestrians' reactions in an urban site characterised by a blank façade and in one with open and more dynamic building fronts showed that people's psychological state was positively affected by the environment with lively facades capable of attracting their attention (Ellard, 2015). Another study which analysed pedestrians' visual engagement in street environments using eye-tracking suggested that building facades can attract people's gaze particularly when they are 'transparent and permeable' and offer 'human-scaled opportunities for engagement' (Simpson et al., 2019). Therefore, some features on architectural skins may make them more

visually stimulating, triggering people's responses and improving their experience of urban spaces.

2.3 Visual Engagement with Architectural Skins

Research on urban design aesthetics revealed that the appreciation of building exteriors involves perceptual and cognitive components. It includes the perception of 'formal' aspects referring to the compositional 'structure', such as qualities of shape, scale, colour, lighting, and rhythm, as well as 'semantic' aspects concerning the 'content' or meaning conveyed. Both formal and semantic attributes of exteriors were found to determine whether public spaces are perceived as enjoyable. While compositions characterised by order and familiarity were associated with 'pleasantness' and 'relaxation', designs featuring 'complexity' and 'atypicality' were found to trigger 'interest and excitement' (Nasar, 1994). The latter type of designs appears to relate more closely to the capacity of attracting people's attention and stimulating reactions, which can be thought of as 'visual engagement'.

2.3.1 Defining Visual Engagement

The verb 'engage' itself refers to the action of attracting 'someone's interest or attention' (Oxford University Press, 2019b). Thus, visual engagement can be defined as the attraction of people's visual attention and interest. It can be observed that the capacity for stimulating visual engagement enables building exteriors to be noticed and therefore allows them to convey meanings. Therefore, it deserves special consideration in the exploration of architectural skins' communicative role.

While being related to aesthetics, the perspective in which the appearance of buildings is studied with a focus on their communicative potential does not necessarily support the belief that architecture should be beautiful, which was advocated by Vitruvius (Pollio et al., 1914:17). Aesthetic approaches to architecture broadly encompass a variety of considerations on formal aspects rather than on functional features. Although they are related to the study of perception and of communication they are largely concerned with the appreciation and with the pleasantness of artefacts (Lang, 1984). Judgements of interest and beauty may not be produced by the same features, as suggested by a study which recorded people's eye movement in the perception of architectural facades (Hasse & Weber, 2012). Whilst the visual perception of a building exterior may lead to the formation of a judgement on its appearance in the viewer and to the interpretation of meanings, the artefact has to be noticed first, or in other words, it needs to attract at least gaze

and attention. Thus, visual engagement is a key event which initiates people's experience of architectural skins from the outside of buildings.

As in the design of buildings visual aspects can be understood as functional (Bafna et al., 2009), communication can be seen as a function of the envelope, the fulfilment of which depends on its capacity for stimulating visual engagement. This has a physiological basis, involving functions of the eye and of the brain. Therefore, an understanding of how architectural skins may attract visual attention and interest needs to be gained by drawing from the scientific study of vision rather than from philosophy.

2.3.2 Understanding Visual Engagement through Visual Perception

2.3.2.1 Understanding Visual Perception

The exploration of how visual engagement may be stimulated through building skins entails gaining an overall understanding of how visual perception works, which several theories attempted to explain, as summarised by Gordon (2004). Among others, the phenomenological approach of Gestalt psychologists interpreted visual perception as a dynamic process enabling the distinction of whole figures against backgrounds. The Empiricists, and particularly Richard Gregory, illustrated perception as a selective process involving knowledge, similar to the activity of forming and testing hypotheses, and occurring when neural events are triggered by stimulated sensory receptors. On the other hand, Gibson's theory of 'direct perception' questioned the nature of perception as a process mediated by the perceiver's internal constructs. It emphasised the role of the environment with its abundant stimuli, in which the active perceiver is immersed, as well as of omnipresent motion, of light as carrier of information and of 'invariants' as properties of visual stimuli remaining constant despite the changes occurring in the perceiver or in the surroundings. To address complex problems such as those of shape and motion perception, a computational approach was also proposed, but criticised by some for associating perceivers with computers and for neglecting subjective aspects of perception. Although no theory seems to have yet explained visual perception thoroughly, the various suggested models have contributed to our comprehension of visual perception as an active process, which is based on both psychological and neurophysiological evidence. With recent research techniques like fMRI scans and spatial frequency analysis, neurophysiology has unveiled key neural mechanisms underlying some aspects of visual perception such as colour vision, showing how change is essential to perception. The introduction of virtual

reality experiments has also uncovered possibilities in the study of visual perception (Gordon, 2004). Therefore, investigating the physiology of visual perception advanced our comprehension of it.

With consideration of its physiological basis, human vision is understood in the neurosciences as a process that starts when light signals are transduced by retinal rods and cones photoreceptors into electrical responses (Andoni et al., 2014:367; Burns & Pugh, 2014:7). Falling onto the retina, light signals derive from the interaction of objects and materials with light (Anderson, 2014:653). They trigger responses from photoreceptors that produce representations of the environment within the visual nervous system through increasingly more intricate networks of neurons at progressively higher levels of information processing (Lindsey & Brown, 2014:511). The multiplicity, arrangement and diversity of cone photoreceptors, of which three different classes have been identified on the human retina, determine the ability to perceive colours (Hofer & Williams, 2014:469). These only emerge inside the human mind as the spectral composition of light is mapped onto colour representations within the visual system (Lindsey & Brown, 2014:511). On the other hand, the capacity to see three-dimensional space has been attributed to the characteristics of binocular vision creating two retinal images with disparities that enable the distinction of stereoscopic depth (Lester, 2013:29; Freeman, 2014; Parker, 2014:397; Schor, 2014:809), and to monocular sources of information including texture gradients, perspective cues and the partial overlap of visual stimuli or occlusion (Lester, 2013:30; Ware, 2013:240; Schor, 2014:821). Moreover, human vision has been found to be intrinsically active and dynamic, as it involves various kinds of eye movements and it is subject to external, stimulus-based influences but also internal influences from the brain of the viewer, which makes visual perception a selective process (Hoffman, 1998; Ware, 2013:140-142; McCamy et al., 2014). Thus, the study visual perception involves physiological and cognitive aspects.

Visual perception has been studied in cognitive science. Since the process of retrieving information from the visual field is a form of selection (Hoffman, 1998), the features triggering visual perception have been investigated within research on visual attention, or 'the aspect of vision most closely associated with conscious visual experience' (Rensink, 2010:69-70). As Driver (2001) pointed out, attention is a broad subject that has been studied in psychology and in neuroscience (Driver, 2001:73). In his literature review on attention, he stated that 'what we see, hear, feel and remember depends not only on the information entering our senses, but also

upon which aspects of this we choose to attend' (Driver, 2001:53). He presented psychological approaches including Broadbent's 'filter theory' from 1958 to later revisions, which mainly identified two different stages in human perception: a 'preattentive' stage characterised by the reception of physical stimuli, and a subsequent 'attentive' stage involving more abstract properties (Driver, 2001:54). In the 1980s, Anne Treisman developed her 'feature integration theory' focusing specifically on vision and indicating various features of visual stimuli that are noticed 'preattentively', or without attention, in contrast with combinations of features that require attention to be perceived (Driver, 2001:63). Wolfe (2000) identified four types of vision, respectively happening before, with, after and without attention, asserting that what attention does is enabling the 'binding' of features individually perceived preattentively (Wolfe, 2000). Some groups of features can also be perceived preattentively or in what is now known as 'early vision', the neural mechanisms of which include the retinotopic system (Rensink, 2010:69). Pashler (1995) pointed at attention as a 'precondition of conscious awareness' and highlighted its physical constraints related to the types of stimuli and our physical apparatuses (Pashler, 1995:72). Hence, some visual features can attract gaze more easily, which may be a precursor to attention.

Neuroscience research methods supported psychological research on attention by introducing measurements of increased blood flow in different areas of the visual cortex in response to specific stimuli (Driver, 2001:71-72). According to Rensink (2010), observations on the effects of cortical damage of different sorts led to the suggestion of two possible kinds of attention besides the type concerned with change detection and identified as 'coherent' attention. 'Ambient' and 'focused' attention respectively indicate the 'selective access' to chaotic visual information and the 'selective creation' of structured representations (Rensink, 2010:71). Several studies on attention were based on the evaluation of eye movements of the viewers, which can reveal shifts in attention (Borji & Itti, 2013:186), although there is evidence that these may sometimes occur without any eye motion (Driver, 2001:65). Thus, while there can be different types of attention, this may not be proved by gaze.

Visual attention has also been studied for applications in fields such as the computing of cognitive systems, computer vision and robotics, as pointed out by Borji & Itti (2013). These authors presented the distinction between two types of attention, that, in the prevailing view, are combined to direct people's behaviour.

Based on the salient physical features of a scene, 'bottom-up' attention is said to be fast and involuntary, whereas, influenced by knowledge, expectations and targets, 'top-down' attention appears to be slow and voluntary (Borji & Itti, 2013:187-188). Bottom-up and top-down processes have been alternatively indicated as 'overt' and 'covert' attention respectively (Hoffman, 1998; Borji & Itti, 2013; Schall, 2014). It was highlighted that the saliency of visual stimuli depends on their background, and that there is an agreement among psychology researchers on stages of cognitive processes, involving memory at a 'sensory', 'short-term' and 'long-term' level (Fu et al., 2014:2-3). It was also suggested that substantial processing of viewed objects can occur without attention, as a form of 'implicit perception', rapidly associating the visual experience with semantic and emotional aspects, and accelerating the transition to attentive recognition (Rensink, 2010:72). Therefore, the attraction of visual attention depends on both features of the environment and subjective influences on the viewer.

2.3.2.2 Visually Engaging Features for Architectural Skins

Given the impact of both the physical characteristics of a setting and the knowledge combined with the ongoing activities of the viewers on attracting their visual attention, the possibility of identifying visually engaging features with universal validity seems unlikely. Canosa (2005) highlighted that the saliency of visual features is modulated by the viewer's preference for specific objects determined by an ongoing task, which was identified as 'perceptual conspicuity' (Canosa, 2005). Wang et al. (2014) described how pedestrians moving in an urban environment are guided by both 'goal-directed' and explorative behaviours. The latter are influenced by visually captivating features on the way to a destination, such as 'window displays and street performance', causing people to wander and sometimes to stop by a visual attractor for some time (Wang et al., 2014:24). Nevertheless, the salience of features in an urban space can be limited by a too high concentration of visual stimuli, like in shopping environments where human perception is reduced (Wang et al., 2014:25). Thus, an artefact's capacity for stimulating visual engagement is affected by the presence of other visual attractors in the surrounding environment and by the viewer's goals.

While the factors behind the preattentive extraction of visual features from a view are still to be understood (Huang, 2015:43), the available knowledge has been applied in visual communication. Literature in this field, concerning graphic designs in print and screen media, may indicate some characteristics that commonly tend to

attract viewers' attention. This may hint at some potential guidelines for the design of visually engaging building skins as well. Lester (2013) presented colour, form, depth and movement as the 'principal qualities of images' capable of triggering quick responses from the cells in the human visual cortex. He praised the thoughtful creation of contrast between two colours to attract visual attention, advising to avoid colour combinations that can be difficult to look at, such as red and green. He also highlighted how the above qualities of visual communications can be invested with both subjective and collective meanings. For instance, the perception of colours can be influenced by memorable experiences associated with them, straight lines may convey a message of rigidity, curves may appear graceful, and lines grouped to form textures can evoke haptic sensations (Lester, 2013:18-38).

Ware (2013) provided guidelines for graphic designs of all kinds, including web-based applications, grounded in the science of vision and perception. Presenting a set of principles for effective visual designs, he emphasised the characteristics that make representations stand out, demonstrating the importance of creating compelling visual communications that can be grasped instantly, as saccadic eye movements cause discontinuities in visual perception. He explained that although top-down mechanisms affect the selection of what we see, some visual attributes are particularly 'salient' and excite neural activity more than others. Recognising that various features and even some combinations of qualities can be perceived in early vision, Ware pointed out that there are different levels of salience: the strongest impact derives from aspects of colour, form, spatial position and motion, and the more an object differs from its context, the more it stands out (Ware, 2013:141-162). He also stressed the ability of the visual brain to identify patterns (Ware, 2013:179), especially in the two dimensions (Ware, 2013:291) as well as the communicative effectiveness of evocative elements such as silhouettes (Ware, 2013:299-303) and facial expressions conveying emotions (Ware, 2013:308-310). The importance of 'salience' in visual perception was confirmed by Schall (2014), who defined it as the distinctiveness of elements in relation to their context, which can derive from visual features of colour, form, depth and motion and be modulated by the viewer's expectations and objectives (Schall, 2014:907). Thus, architectural skins may be noticed more easily when they display features that stand out from their surroundings with colours, shapes in two or three dimensions, movement and more complex elements such as patterns and figures.

2.3.2.3 Understanding Visual Motion

There seems to be a consensus on the importance of motion in attracting visual attention. The capacity of the visual system to rapidly detect motion has been highlighted by multiple authors and associated with survival instinct (Arnheim, 1974:372; Hoffman, 1998; Lester, 2013:38; Ware, 2013:176). Arnheim (1974) also claimed that dynamic displays or performances are more captivating than static art forms (Arnheim, 1974:372). Presenting some neural mechanisms behind visual attention in a wide range of species, Krauzlis (2014) showed that motion is generally a 'highly salient cue' for detecting dangers and potential prey. Most visual features tend to be irrelevant in comparison with motion and the appearance or disappearance of stimuli (Krauzlis, 2014:326). Hence, displaying motion on architectural skins is likely to make them visually engaging.

Various types of motion can be recognised. Investigating motion perception, Gibson (1954) associated optical stimulation with mathematical transformations. He classified movement into 'rigid motion' which includes translations and rotations; 'elastic motion' referring to scaling, deformations and perspective alterations; and 'disjunctive motion' comprising 'multiple movements' (Gibson, 1954:312). Lester (2013) distinguished four different types of motion: 'real', 'apparent', 'graphic' and 'implied'. While 'real' motion means actual, physical movement, 'apparent' motion refers to the impression of movement produced by still images quickly displayed in sequence as in motion picture films. This is attributed to the 'persistence of vision' resulting from the time required by the visual system to perceive images. 'Graphic' movement is created by a designer arranging elements in compositions to direct viewers' gaze in a specific direction, whereas 'implied' motion is perceived in individual, stationary visual designs as exemplified by Optical Art works. These induce 'visual vibration' through line-based patterns with high-contrast or juxtaposed complementary colours (Lester, 2013:38-39). The indication of motion types beyond actual movement suggests possibilities also for the design of visually engaging architectural skins and invites further exploration of motion perception.

Although motion is difficult to study in isolation due to its strong interaction with the visual features of form and position (Burr, 2014:763), according to Snowden & Freeman (2004) motion perception is fairly understood, thanks to contributions from different research fields such as neurophysiology, psychophysics, psychology and computational modelling (Snowden & Freeman, 2004:R831). Besides being caused by actual movements, the impression of motion can be produced in various ways.

Kim & Blake (2007) showed that the brain activity triggered by paintings conveying a sense of movement is the same as that associated with real motion (Kim & Blake, 2007). The 'motion aftereffect' occurs when after observing for a certain time objects moving in a specific direction, we look at stationary objects and perceive these as moving in the opposite direction (Snowden & Freeman, 2004:R829). As previously mentioned by citing Lester (2013), 'apparent motion' takes place when a sequence of static representations displaying slight changes in progression produces a kinetic impression (Ramachandran & Anstis, 1986:102). When certain colours and patterns within a static composition generate the human perception of motion, the psychological and physiological phenomenon is indicated as 'illusory motion' (Chi et al., 2008). This can be influenced by characteristics such as the luminance variation of static elements (Conway et al., 2005), but also by differences between actual and perceived objects' depth experienced by moving viewers (Papathomas, 2007).

Visual illusions, in general, have been the subject of scientific investigation, which has provided insights into the processes of vision. Defining illusions as 'errors of perception' (Gregory, 1997a:1121), Gregory distinguished illusions with a physical cause, such as a light disturbance, from those occurring due to cognitive factors or 'misapplied knowledge' in the interpretation of sensory stimuli. He also proposed a classification of illusions based on the appearance, identifying 'ambiguities', 'distortions', 'paradoxes' and 'fictions' (Gregory, 1997a; Gregory, 1997b). Among illusions with a physical cause, as opposed to those identified as 'perceptual', Gregory (1968) discerned 'optical' and 'sensory' illusions, the former of which result from the reflection or refraction of light, whereas the latter are produced by protracted or excessive stimulation of sensory organs (Gregory, 1968:279-280). As the perception of building exteriors largely depends on the interaction of sunlight with façade surfaces and our visual system, exploring optical illusions which can convey a sense of motion and potentially trigger visual engagement appears particularly relevant to the present research.

Various types of illusory motion have been examined by researchers and exploited in the arts. Gori et al. (2011) examined the illusion experienced in front of square wave gratings by viewers moving their head back and forth, and highlighted how the perceived distortion and expansion of the viewed pattern varies with changes of luminance contrast (Gori et al., 2011). As pointed out by Ernst (2010), the perceived motion of low-contrast stimuli is slower than that of high-contrast stimuli, and the

speed of the illusion appears reduced while a viewer walks (Ernst, 2010:R357). The painting *Enigma* by Leviant (see fig. 3.) was reported to produce the illusion of rotational motion (Kumar & Glaser, 2006:1947). A study by Zanker & Walker (2004) aimed to explain the mechanisms behind the motion illusion produced by Op Art paintings such as those by Bridget Riley, whose experiments created kinetic impressions from static, black and white patterns. It concluded that saccadic eye movements are crucial to perceive the illusion (Zanker & Walker, 2004), an example of which is provided by Riley's painting *Fall* (see fig. 4.).

Figure removed due to copyright restrictions

Fig. 3. '*Enigma*' by Leviant (1981)

Figure removed due to copyright restrictions

Fig. 4. '*Fall*' by Bridget Riley (1963)

As summarised by Chen et al. (2015), Optical Art induces the brain to generate wrong information, recognising illusions through the retina. Considering such art as 'kinetic', the same authors described it as 'participatory and interactive', since the

viewers play an active role in creating the impression of motion by changing viewpoints. They referred to art by Jesús Rafael Soto who produced motion illusions through criss-cross wire structures (see fig. 5.), and by Yaacov Agam who utilised static patterns on angled planes (see fig. 6.) to be experienced by viewers through changes of viewpoints (Chen et al., 2015:926-927).

Figure removed due to copyright restrictions

Fig. 5. *Example of Artwork by Jesús Rafael Soto (1965)*

Figure removed due to copyright restrictions

Fig. 6. *'Star of David' by Yaacov Agam (1983)*

Motion impressions can also be associated with stereoscopic depth. Papathomas (2007) described as ‘pseudomoving’ those stationary art pieces that appear to move due to the observers’ motion, referring particularly to the illusions based on differences between physical and perceived motion as in stereograms and in works by Patrick Hughes and Dick Termes. As the author stated, this type of illusory motion is especially effective when the visual stimuli are three-dimensional (Papathomas, 2007:91). In Patrick Hughes’ work, the viewer perceives a reversed depth suggested by scenes painted on three-dimensional shapes, as well as motion while moving in front of the artwork (Papathomas, 2007:80), which is distinctive of his *Reverspectives* (see fig. 7.). Dick Termes’ works are painted spheres which produce the impression of depth reversal and motion caused by transformations of the image on the retina due to head and eye movements (Papathomas, 2007:82-84). This visual effect is typical of *Termespheres* (see fig. 8.). Hence, architectural skins with three-dimensional configurations may also be designed to seemingly display change to moving viewers.



Fig. 7. ‘New York Flowers’ by Patrick Hughes (2014)



Fig. 8. ‘Reflecting Through’ by Dick Termes, www.termespheres.com (2006)

Examples of motion illusions have also been explored through computer-based visualisation approaches. Conway et al. (2005) examined the illusion *Rotating*

Snakes by Akiyoshi Kitaoka (see fig. 9.), a modification of the ‘peripheral drift illusion’ characterised by circular patterns with ‘sawtooth luminance gradients’ which produce the impression of motion when observed in the periphery (Faubert & Herbert, 1999). In Kitaoka’s *Rotating Snakes*, rotational motion is perceived with eye movements in the direction set by coloured elements, from black to blue, white and yellow, or from black to dark grey, white and light grey in the achromatic version (Conway et al., 2005:5651). Fermüller et al. (2010) also analysed *Rotating Snakes* by Kitaoka, as well as another example of his illusions characterised by asymmetrical luminance gradients. They explained them as mainly caused by a wrong estimation of motion due to fixational eye movements (Fermüller et al. 2010:315). Some authors proposed computational methods to generate ‘self-animated images’, like Kitaoka’s *Rotating Snakes*, from vector fields (Chi et al., 2008; Nascimento & Lewiner, 2013). Wei (2006) provided a detailed description of a method to effectively render the motion of flow fields through static images, based on coloured patterns of convex shapes, such as circles or ovals, each surrounded by a thin, partly white and partly black border, that appear to move in the direction set by the black border sides (Wei, 2006). It can be thus evinced that the impression of motion can be produced through certain colour or luminance combinations, which may find application in the design of captivating architectural skins.

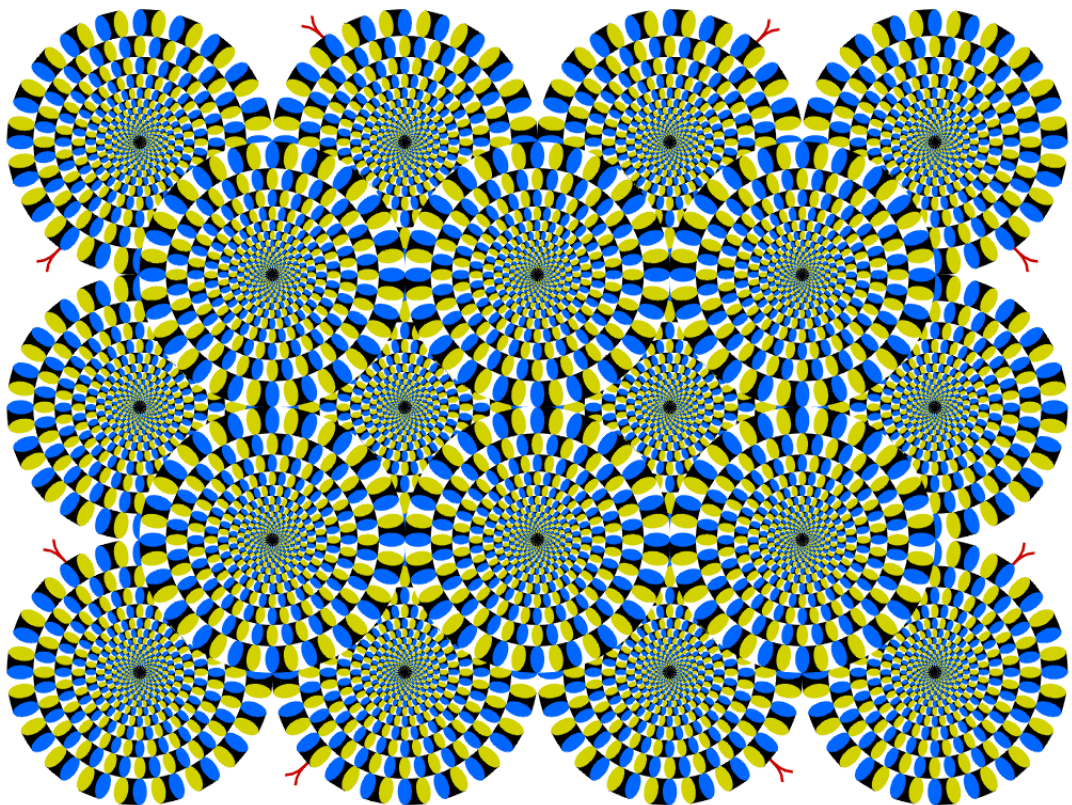


Fig. 9. ‘*Rotating Snakes*’ by Akiyoshi Kitaoka (2003)

While identifying potential visual attractors is important, recognising the flaws of visual perception appears also relevant to the design of visual media and thus of architectural skins. Limitations of vision include 'saccadic suppression', referring to the incapacity to perceive minor events occurring during saccadic eye movements (Ware, 2013:175; McCamy et al., 2014:849), as well as the inability to see colours and small objects at the periphery of the visual field (Ware, 2013:175) where motion detection is sharp instead (Gibson, 1954:307). Additionally, perception at the periphery seems even more limited in highly stressed viewers, who tend to focus on the centre of the visual field in a phenomenon called 'tunnel vision' (Ware, 2013:173-174). Hence, perceptual limitations related to peripheral vision and eye movements should be considered in the design of building exteriors aimed at stimulating visual engagement. Motion is likely to be noticed even when it is not at the centre of the visual field.

It also emerged that certain striped patterns and flickering lights can be perceived as disturbing, inducing not just illusions of colours, forms and movement but also headaches and even seizures in people with photosensitive epilepsy (Wilkins et al., 1984). People with certain ocular or neurological conditions, such as dry eyes, migraine, depression and traumatic brain injury, were found to experience discomfort when exposed to luminous visual stimuli, which is indicated as 'photophobia' (Digre & Brennan, 2012).

Particularly patterns like those distinctive of the Op Art movement, such as in Bridget Riley's work, were found to produce an impression of motion that can cause discomfort and headaches (Wilkins et al., 1984). It appears that most people can find distressing to view visual stimuli such as 'periodic patterns' with 'stripes and text', 'flickering patterns' and some 'colour combinations', which is indicated as 'visual discomfort'. This is determined by parameters such as pattern size, contrast, the relative width of stripes and spacing, and particularly spatial frequency (O'Hare & Hibbard, 2011:1767). The latter depends on the width of alternate light and dark stripes and is measured as the 'number of changes per degree of visual angle' (Gordon, 2004:92). It was pointed out that visual discomfort could 'reflect hyperexcitation of the visual cortex', and that knowing its causes may help prevent negative effects on sensitive individuals, increase workers' productivity and avoid certain types of media content (O'Hare & Hibbard, 2011:1776).

Stein & Kapoula (2012) showed that looking at an image characterised by 'mid-range spatial frequencies' can be 'uncomfortable' or even 'dangerous'. On the other

hand, the more spatial frequencies in a visual composition approach those in natural images, the more it seems to be perceived as pleasing. In Western cultures, text is an example of uncomfortable images as it is characterised by high contrast at mid-range spatial frequencies, which is less true for Eastern languages such as Arabic and Chinese. Relatively large spacing makes a text clearer (Stein & Kapoula, 2012:64-67). Therefore, in the design of architectural skins framing public spaces, it seems appropriate to consider that certain visual stimuli may cause visual discomfort to some people. Potentially disturbing visual stimuli include certain patterns that produce the illusion of motion.

In summary, while perception involves both physiological and cognitive aspects, there are features that can be included in architectural skin designs to make them potentially visually engaging. Among such features which include qualities of form in the three dimensions, colour, patterns and evocative figures, motion has a high potential for producing visual engagement, or in other words, for attracting visual attention and interest. Displaying motion does not necessarily involve actual movement. A motion impression can be produced by static visual compositions involving, for instance, certain colour or luminance combinations, or the interplay of three-dimensional elements and viewers' movement. Although there are perceptual limitations to be considered in design, which include reduced visual perception at the periphery and during saccadic eye movements, motion is detected even when it is marginal in a scene. There may also be a risk of inducing discomfort in some people by displaying some luminous stimuli or particular repetitive patterns characterised by high contrast. Hence, it is to be explored how visually engaging features can be embedded in architectural façade designs.

2.4 Visually Engaging Features as Media Façades

2.4.1 Defining Media Façades

Visually engaging features such as patterns, figures, qualities of forms, colours, three-dimensionality and motion can be recognised in architectural skins identified as 'media facades.' These were defined by Ebsen (2010) as a way of covering building surfaces with digital 'pixels' (Ebsen, 2010:98). Similarly, Al-Azhari et al. (2014) explained them as based on 'the idea of designing or modifying the architecture of buildings, using their surface as giant public screens' (Al-Azhari et al., 2014:818). Media facades are a manifestation of the broader phenomenon called 'media architecture' which Ebsen (2010) described as the application of 'screen-technology in new spatial configurations in practices of architecture and art'

(Ebsen, 2010:98). According to Sade (2014), media architecture represents the release of pixels from the constraint of a conventional display, to place them 'in respect to the formal qualities of architectural structures and surfaces', which does not need to obstruct the view on buildings or the landscape (Sade, 2014:58). Media facades do not need to be at the centre of our perception, since they can act as 'ambient media' at the periphery of people's attention (Sade, 2014:61). Gielen (2015) identified the distinctive character of media facades in the representation of digital content through a 'matrix of components' that dynamically change their appearance (Gielen, 2015:146). Hence, a distinctive characteristic of media facades is some form of display through a modular configuration, an example of which is the skin of the *Ars Electronica Center* (see fig. 10.) in Linz (Leeb, 2009).

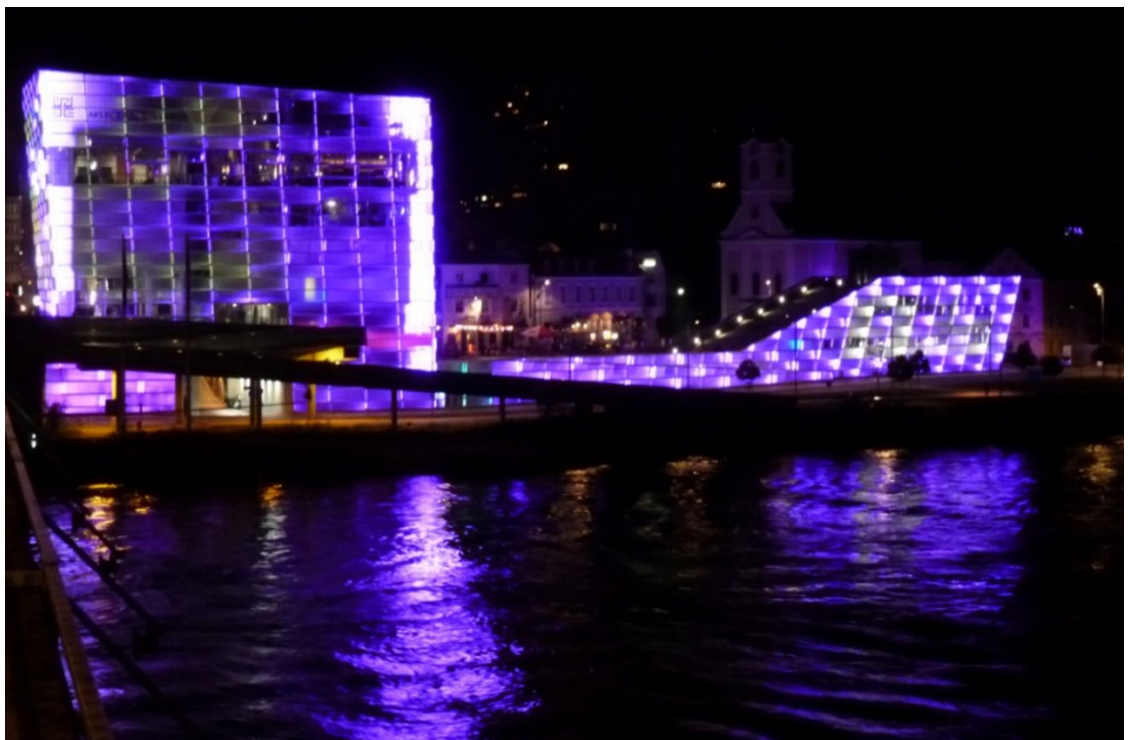


Fig. 10. *Ars Electronica Center* (2011)

Media architecture has been related to the development of electric lighting, signs and advertisement, particularly boosted by the advent of programmable LED light sources. However, dynamic effects distinguish it from static 'exterior illumination' indicated as 'light architecture' (Zielinska-Dabkowska, 2014:101-102). On the other hand, Krajina (2009) linked media facades to the much older art of mosaic. He argued that the logic of communication is based on the same principle of assembling small coloured pieces to compose images that are visible from a certain distance. Yet, in media façades 'the stones are exchanged for bulbs' and are visually

controllable (Krajina, 2009:422). Therefore, the visual display which characterises media facades has a dynamic component to it.

Media building skins have not always been employed with the primary goal to improve the quality of public spaces. Such urban media have been used most commonly to display advertising and news (Fritsch & Dalsgaard, 2008:1). To reduce their 'polluting' impact on public environments, researchers have looked into solutions for creating non-commercial installations (Hinrichs et al., 2013:25). Hence, media façades may be designed alternatively with the main intent to enhance urban open spaces.

2.4.2 Potential Benefits of Media Façades

Besides having evidently commercial applications, media recognisable as 'media architecture' were found capable of improving the quality of public spaces. McQuire (2008) highlighted their capacity to engage wide audiences without the restrictions imposed by less accessible environments such as art galleries (McQuire, 2008:149). Malpas (2008) recognised in the use of new media the potential to reveal the 'character' of places (Malpas, 2008:207). Similarly, Al-Azhari et al. (2014) highlighted media facades' ability to capture pedestrians' visual attention contributing to the quality of a place (Al-Azhari et al., 2014). In reference to interactive public displays, Veenstra et al. (2015) suggested that these media can make urban spaces more appealing by attracting people to specific locations and by stimulating inter-human interaction (Veenstra et al., 2015:20). This may also produce economic advantages in the context, for instance, of urban development and regeneration projects or in relation to tourism, although examining this potential in depth goes beyond the scope of the present research.

A significant body of research supports the idea that media building skins can improve people's experience of urban environments. According to Weiner (2010), media architecture can enhance the communicative role of public spaces with new dimensions in public interaction (Weiner, 2010:103). Jang & Kim (2014) pointed at media facades as 'a prominent social medium' with great potential (Jang & Kim, 2014:7). Albrecht et al. (2015) argued that digital facades can exploit their full potential to positively impact public life by displaying more inclusive types of content such as 'user-generated contributions' besides visual art (Albrecht et al., 2015). Anshuman (2005) argued that, unlike conventional intelligent facades, interactive media skins can enhance social participation and engagement in urban environments (Anshuman, 2005:19). According to Moloney (2006), 'the transition of

the traditionally static building envelope to an interactive skin presents an opportunity for architecture to forge a new form of engagement with contemporary culture' (Moloney, 2006:684). Memarovic et al. (2012) mentioned research on public displays showing how these can facilitate civic involvement and inter-human interaction, also demonstrating how they can meet some of people's needs for engagement in public environments (Memarovic et al., 2012).

People's needs in public spaces were illustrated in detail by Carr et al. (1992) and were identified as 'comfort', 'relaxation', 'passive engagement', 'active engagement' and 'discovery' (Carr et al., 1992). While 'comfort' and 'relaxation' express the satisfaction of necessities such as those of 'food, drink, shelter', or 'a place to rest', and similar demands, the other needs refer to progressively more deep forms of involvement. 'Passive engagement' describes an 'encounter with the setting' without active participation, embodied by the act of observing and stimulated by attractive features in the public space. 'Active engagement' is manifested through direct interaction with the physical space and with other people, while 'discovery' represents the need for exploration (Carr et al., 2007:231-238). Thus, as suggested by Memarovic et al. (2012) about public displays, media facades may be designed to meet some of the above needs in public spaces.

2.4.3 Media Façades: Technologies and Design

Media facades identify a broad range of architectural envelopes. Gasparini (2013) offered a review of the synonyms and interpretations used to refer to media architecture and media facades, including 'urban screens', 'light architecture', 'interactive architecture', 'kinetic architecture' and 'responsive architecture' (Gasparini, 2013). Haeusler (2009) proposed a categorisation of media facades based on the technologies employed. He identified 'mechanical facades', 'front projection facades', 'rear projection facades', 'window animations', 'illuminant facades' and 'display facades' (Haeusler, 2009). 'Mechanical facades' perform ever-changing visual effects through the physical movement of their components. 'Front projection facades' involve the use of external video projectors to display media content onto building skins. 'Rear projection facades' utilise projectors integrated into the building behind its skin to present graphics onto translucent surfaces of the envelope. 'Window animations' turn existing windows into luminous pixels to compose digital visual messages. 'Illuminant' and 'display' facades are characterised by light-emitting elements and video screens respectively (Haeusler 2009, cited in Wiethoff & Gehring, 2012:309).

Light-emitting media facades seem to have particularly exploited programmable, colourful lighting that can continuously change the displayed visual content to attract people's attention (Moghaddam & Ibrahim, 2016:263). On the other hand, 'kinetic' facades are characterised by physical motion which modifies the appearance of the envelope without affecting its 'structural integrity'. Facades indicated as 'responsive' have the ability to respond to variations in the environment through either a change in their material characteristics altering the skin form or through local modifications for adaptive energy control in reaction to external conditions (Sharaidin, 2014:IX).

The subject of people's interaction with media architecture has also been widely explored. The 'spatial layout' of a location was found to influence the type of interactions stimulated by public displays (Behrens et al., 2013). Dalton et al. (2013) highlighted that the viewing angle is crucial to making a public display visible, which is a precondition for interaction (Dalton et al., 2013). Tomitsch et al. (2008) defined the 'layers' that compose architectural space as a 'medium for expression', and provided a classification of its 'embodiments' based on the type of engagement produced, distinguishing 'expressive medium', 'responsive space' and 'social actor'. In their view, an 'expressive medium' is perceived by passers-by and can stimulate inter-human interactions without providing technology to support them. On the contrary, a 'responsive space' is capable of actively interacting with visitors. A 'social actor' is not just interactive, but even imitates some aspects of living beings (Tomitsch et al., 2008). Similarly, Moghaddam & Ibrahim (2016) underlined the distinction between 'expressive', 'reactive' and 'interactive' media facades, only the latter of which were praised by the authors as truly engaging (Moghaddam & Ibrahim, 2016:260). A differentiation between 'expressive' and 'interactive' skins was also proposed by other researchers (Park et al., 2011:307). Thus, media facades can have different degrees of visibility or interactivity.

In their study of the features of interaction with media facades, Brynskov et al. (2009) observed different styles of interaction. In their view, 'basic exploration' describes the behaviour of people simply passing and noticing the artefact, while 'visual engagement' refers to the reaction of those who passed and interacted with the façade. Instead, 'embodied engagement' involves an active approach and 'use' of the medium (Brynskov et al., 2009). Other research mentioned responses to large media displays ranging from mere 'passing by' and 'viewing and reacting' to more deep involvement (Al-Azhari et al., 2014:820). In their study showing how public displays can be used to meet people's needs in public spaces, Memarovic et al.

(2012) observed quick responses identified as 'passive engagement', such as those named 'read 'n' go', 'glimpse interactions' or 'stop-read'. They also noticed 'active engagement' reactions that they called 'active reading', 'read 'n' interact' and 'social triangulation', meaning direct inter-human interaction encouraged by the display (Memarovic et al., 2012). Therefore, media facades can trigger various types of reactions in passers-by, corresponding to increasing levels of engagement with the artefacts.

Some authors researching media façade design highlighted the aspect of motion. According to Park et al. (2011), the goal of media façade design is integrating movement into static architecture, which raises difficulties such as colour combinations and careful placing of electronics (Park et al., 2011:309). Moloney (2006) recognised in the design of kinetics the 'common ground' between responsive building skins and computer-controlled media facades, proposing a framework that classified the 'tectonic' of dynamic architectural skins as 'passive', 'active', 'physical', and 'electronic' (Moloney, 2006). By identifying 'passive' kinetics in architecture, the same author highlighted that motion can be simply caused by the viewer's movement or by changed environmental conditions (Moloney, 2007).

Studies on media facades proposed some criteria for their design. Distinguishing 'interface' and 'content', Halskov & Ebsen (2013) outlined a framework for the design of complex media façade interfaces through a definition of their key features, identified as 'scale', 'shape', 'pixel configuration', 'pixel shape', and 'light quality'. 'Pixel shape' indicates the form of the single pixels and 'pixel configuration' identifies the way pixels are distributed, potentially forming complex patterns rather than a simple grid as in conventional displays. 'Light quality' determines the brightness of the skin and the smoothness of its colours (Halskov & Ebsen, 2013:664-665). Park et al. (2011) proposed a 'tectonic model' for the design of interactive skins, based on the analysis of media architecture precedents. They distinguished visual aspects, such as the speed or acceleration of the movement displayed, from material and physical aspects including the use of electronic or mechanical components. These are characterised respectively by colour and light or by motion which can be 'linear', 'rotational' and 'radial'. The same authors indicated 'modularity' as a distinctive feature of these media surfaces and identified among the properties of an interactive skin 'granularity' and 'continuity', referring to the components' size and uninterrupted distribution respectively (Park et al., 2011:308-310).

Other research examined specifically the design of kinetic architectural skins, an example of which is the dynamic front of the Arab World Institute in Paris (see fig. 11.). Moloney (2011) explored the subject of kinetic facades with a visual approach. He reviewed the relevant literature and analysed morphological aspects to provide a foundation for the design of kinetic patterns through digital animation techniques, in a deliberately abstract way that did not take materials into account. As part of his study, he distinguished low-control kinetic systems, reacting directly to variations in the environment, from high-control systems programmed with computers. He identified a range of movement types for architectural facades, from simple transformations such as 'translation', 'rotation' and 'scaling', to deformations due to material properties, and combinations of these. He used the term 'granularity' to describe how the number of parts in a skin relates to the whole surface, and identified the temporal variables to consider in the design of kinetic facades, such as 'acceleration' and 'rhythm', highlighting that motion is not perceived in a visual field if no change is detected for longer than 2 or 3 seconds (Moloney, 2011:85-87).

Figure removed due to copyright restrictions

Fig. 11. *Façade of the Arab World Institute*

Further research explored the design of kinetic architectural skins with a greater focus on environmental aspects. Sharaidin (2014) investigated the design of environment responsive kinetic facades, starting from a review of the precedents in

the field. He identified five types of motion for adaptive facades and proposed a design and testing methodology for early design stages that involved both digital simulations and physical prototyping. His approach showed the importance of testing kinetic façade concepts with materials to evaluate their effectiveness. The types of motion examined by the researcher identified a series of experiments involving mechanisms ranging from those typical of ‘pulley systems’, to ‘scissor structures’, inflatable elements, and flexible components activated through a shape-changing material (Sharaidin, 2014). Fiorito et al. (2016) provided a review of innovative, dynamic solar shading devices essential for the optimisation of buildings’ energy performance and the occupants’ comfort. They presented a range of possible movement types involving rotations and translations (Fiorito et al., 2016:869). Therefore, media facades of kinetic type may be designed to produce environmental benefits.

2.4.4 Drawbacks of Media Façades

2.4.4.1 General Challenges

Despite their potential for enhancing people’s experience of urban spaces, media facades were found to present some challenges. Dalsgaard & Halskov (2010) pointed at the need for developing new media facade interfaces that can be more robust and stable, as well as suitable content for the medium. They also indicated the need for better integration of media facades into existing environments, for balancing interests among stakeholders and for fitting media façades into the combined situations of specific urban locations. They invited consideration of the potential transformation in social connections and of unpredicted uses of media facades (Dalsgaard & Halskov, 2010:2280).

Media facades were found to have multiple problems. For instance, they may cause ‘display blindness’, identifying the phenomenon occurring when passers-by ‘pay little or no attention to public displays’ (Memarovic et al., 2015:7). Other stimuli in urban settings may compete with public displays and divert people’s attention from them (Memarovic et al., 2014). Zielinska-Dabkowska (2014) pointed at several other issues. She lamented the lack of regulations regarding the use of colour and motion in media architecture in Europe. She also emphasised the importance of a preventive analysis of the context in order to locate media architecture appropriately and to avoid unsuitable installations in historical centres as well as traffic accidents caused by drivers’ distraction. Due to their brightness, necessary to make them stand out within an already illuminated context, media facades can also contribute

to 'light pollution', or excessive artificial lighting in urban areas that can negatively affect not just flora and fauna, but also human health and on climate change (Zielinska-Dabkowska, 2014:103-106). Kinetic façade systems present substantial disadvantages as well, since they require high initial investments and continuous maintenance (Alotaibi, 2015:2). They involve high costs, kinetic components that are scarcely reliable, deficient control systems and even aesthetic issues (Moloney et al., 2017:191). Hence, media facades have significant downsides, including considerable energy use, and there seems to be room for improvement in the design of visually engaging architectural skins.

2.4.4.2 Energy Issue and Possible Solutions

A major drawback of the most common media architecture systems is their high energy demand, which can be partly attenuated with the use of energy-efficient technologies and by limiting the hours of operation (Zielinska-Dabkowska, 2014:106). Kinetic facades also tend to require an energy source to power their functioning (Decker & Zarzycki, 2014:180), as their mechanical systems can entail considerable energy costs and complexity (Khoo et al., 2011:399). Buildings are responsible for more than one third of energy use in the world (International Energy Agency, 2013:1), which should not be worsened by employing energy-intensive façade systems.

The need to improve buildings' energy performance started to be addressed at an international level. The urgency to reduce carbon emissions, that have been identified as causes of global warming (Van Nes et al., 2015; Stips et al., 2016), was confirmed by the *Paris Agreement* at the 'United Nations Framework Convention on Climate Change' (United Nations, 2015). The European Directive on Energy Efficiency highlighted the need for increased retrofitting of existing buildings to improve energy savings (2012/27/EU, paragraph 17). By the end of 2020 all new buildings in the European Union are also expected to be 'nearly zero-energy buildings' using energy from renewable sources (2010/31/EU, article 9). Building envelope renovations that include solar thermal and photovoltaic installations are recommended to improve the energy performance of existing properties (Mohelníková & Mišák, 2006:152). It was also found that renovating with 'eco-friendly' materials is more sustainable than demolishing and rebuilding. In particular, a photovoltaic façade designed for the energy retrofit of a low-performance block of flats typically erected between the 1950s and the 1990s demonstrated the potential to transform it into a 'zero-energy building' while improving its appearance and its

commercial value (Evola & Margani, 2014). Thus, the design of visually engaging façades should consider the necessity to enhance both new and existing buildings' energy performance.

Media facades' operational energy use may be reduced potentially by exploiting optics and changing atmospheric conditions. Gielen (2015) argued that in media architecture it is possible to avoid artificial light sources by producing 'contrast' through the control of optical phenomena that can induce variations in the luminance or in the colour of surfaces (Gielen, 2015). The Californian artist Ned Kahn created kinetic building skins like the *Technorama Façade* (see fig. 12.), composed of countless swinging modules that dynamically reflect natural light while being continuously reshaped by the wind (Ned Kahn Studios, 2012). The media screen system SUN_D (see fig. 13.) exploits optics redirecting sunlight or ambient light to display images through a matrix of pixels (SUN_D, n. d.).



Fig. 12. *Technorama Façade* by Ned Kahn (2002)

Figure removed due to copyright restrictions

Fig. 13. *SUN_D Media Screens*

Some researchers proposed solutions for visually communicative architectural skins that try to limit the use of electric power through the integration of shape-changing materials. Decker & Zarzycki (2014) showed that it is possible to complement and even substitute electrically operated components in kinetic façades through the incorporation of smart materials such as shape memory alloys. These, despite being less controllable, can be engineered to naturally deform at specific temperatures and can be seamlessly integrated into architectural screens to produce cycles of movements in a self-sufficient way (Decker & Zarzycki, 2014). Coelho & Zigelbaum (2011) provided a survey of the available shape-changing materials for integration into controllable kinetic surfaces, referring to materials that are capable of deforming in response to 'direct or indirect electrical stimuli'. As the authors showed, shape memory alloys can be activated by heat and can impart movement with significant force to then return to their initial shape without permanent deformation when the stimulus has ceased. They defined as 'soft mechanics' systems that are capable of producing movement through shape-changing materials. Among these, shape memory alloys and Nitinol were indicated as the most 'versatile'. It was suggested that soft mechanics may be applied to create different form changes. Among design examples deploying soft mechanics, *Shutters* represents a permeable system for a kinetic architectural surface (Coelho & Zigelbaum, 2011), characterised by a pixelated configuration (see fig. 14.).



Fig. 14. *'Shutters' by Marcelo Coelho*

More research was directed at investigating the potential for creating environment reactive architectural skins using minimal operational energy. Fiorito et al. (2016) provided a review of possibilities for low-energy solar shading devices based on the use of shape-changing materials such as shape memory alloys which can serve as thermally-triggered actuators in the form of springs and wires (Fiorito et al., 2016). Employing physical prototyping and parametric design techniques, Khoo & Salim (2012) explored the potential for applying soft mechanics to the creation of environment responsive architectural skins capable of also functioning as media screens to display digital content (Khoo & Salim, 2012). In their study on deployable shading systems using shape memory alloy actuators, Pesenti et al. (2015) were inspired by paper folding, and particularly by the Japanese art of Origami, to optimise the movement of kinetic skins (Pesenti et al., 2015). Investigating the possibility of creating reliable and durable kinetic skins, Khoo et al. (2011) presented shape-changing materials and indicated liquid paraffin wax as capable of producing strong actuation without any electrical stimuli (Khoo et al., 2011:404). Leung (2014) developed a system for environment-responsive building skins using paraffin-based thermal actuators that can impart movement to façade elements in a self-sufficient way (Leung, 2014).

Other researchers explored alternative possibilities to produce kinetic effects on architectural skins by exploiting different materials' properties. For instance, the hygroscopic behaviour of wood was addressed by Correa et al. (2013), who applied computational methods to the design of a wooden skin capable of self-regulating its porosity in response to humidity oscillations. This caused apertures to open in dry conditions and to close in wet weather (Correa et al., 2013), as exemplified by *HygroSkin* (see fig. 15.). A self-adjusting skin system was also proposed which exploited the characteristics of thermobimetals instead, combining two layers made of alloys with different expansion coefficients into single components. This caused them to curl in response to thermal stimuli (Sung, 2008), as shown by the project *Bloom* (see fig. 16.).



Fig. 15. '*HygroSkin: Meteorosensitive Pavilion*' (2013)



Fig. 16. '*Bloom*' by DOSU Studio Architects (2011)

Solar technologies also started to be integrated into visually communicative facades. Self-powered examples like the *GreenPix* media wall (see fig. 17.) in Beijing (Simone Giostra & Partners, 2016a), the prototype *SolPix* (see fig. 18.) exhibited in New York (Simone Giostra & Partners, 2016b) and the *Balance Tower* (see fig. 19.) in Barcelona (Leeb, 2010) present photovoltaic modules associated with computer-controlled LED lights. Instead, the *Solar Display* project (see fig. 20.) features rotating photovoltaic pixels that dynamically depict digital content (Sommerer et al., 2009:271-275). In other designs, solar modules compose static shapes and patterns, such as in the facade of the Thyssenkrupp Steel building (see fig. 21.) in Duisburg (Thyssenkrupp Steel, 2002) and in the photovoltaic glass panel (see fig. 22.) inspired by Piet Mondrian's painting *Broadway Boogie-Woogie* (Scognamiglio et al., 2006). *Solar Ivy* (see fig. 23.) features leaf-like photovoltaic elements that mimic the climbing plant (SMIT, 2011). A prototype of *Dancing Screen* (see fig. 24.), designed and constructed by the researcher in 2013, presented thin-film photovoltaic panels associated with photoluminescent film, forming modules that simulated a dance by moving in the wind (Nicoletti, 2017). Thus, solar technologies may offer possibilities for creating architectural skins with visually engaging elements, which can potentially improve the energy performance of buildings.



Fig. 17. *GreenPix Media Wall* (© Simone Giostra & Partners/Arup)



Fig. 18. *SolPix* (© Simone Giostra & Partners)

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Fig. 19. *Balance Tower in Barcelona*

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Fig. 20. *Solar Display*

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Fig. 21. *Thyssenkrupp Steel Building in Duisburg*

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Fig. 22. *'Broadway Boogie-Woogie' Photovoltaic Glass Panel (2006)*

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Fig. 23. *'Solar Ivy' by SMIT*



Fig. 24. '*Dancing Screen*' by Eleonora Nicoletti (2013)

To summarise, various systems may potentially overcome the problem of operational energy use in facades with visually engaging characteristics. This may be achieved by exploiting optics and changes in natural lighting conditions. However, it can be noted that the dynamic systems presented in this section may not overcome drawbacks of kinetic skins such as maintenance or durability issues and poor control capabilities. They respond to limited environmental stimuli or use electronics and therefore electric power as in *Shutters* (see fig. 14.) to allow better control. Such problems are not negligible for building envelopes which have to fulfil multiple functions. On the other hand, it emerged that captivating façade designs can be composed also through the architectural integration of solar technologies and especially of photovoltaics. This hints at the possibility of creating visually engaging architectural skins that, instead of being power-intensive, may even supply buildings with renewable energy generated onsite. However, exploring such potential requires an understanding of how solar technologies can be deployed effectively on buildings.

2.5 Conclusions

This chapter showed, in its second section, that human vision is highly important to how most people experience architectural skins and thus to how these fulfil their

communicative role, which may be facilitated by the display of certain captivating features and improve the quality of public spaces.

As emerged in the third section, the attraction of people's attention and interest, which defines 'visual engagement' in this research and is essential to architectural skins' communicative function, can be understood through the scientific study of visual perception involving physiological and cognitive aspects that have been investigated in psychology and neuroscience. The display of certain features can attract gaze and attention, although the former does not always indicate the latter which is affected by characteristics of the environment as well as by the viewers' subjective influences, such as their personal goals. Architectural skins may potentially stimulate visual engagement through the display of salient qualities of forms in two or three dimensions, colours, patterns, figures, and especially motion. The latter can be conveyed even without any moving parts, for instance, with static three-dimensional configurations which appear dynamic to moving viewers, or with particular illusory patterns that, however, may also induce discomfort in some people.

The fourth section showed that the display through architectural skins of visually engaging features which emerged from the study of visual perception in Section 2.3.2, including motion and patterns or figures, is exemplified by media facades that are characterised by modular or pixelated configurations. Such facades may improve the quality of public spaces, which can be accompanied by economic benefits. They encompass various luminous and kinetic systems and can be designed with diverse levels of visibility to stimulate various reactions or types of engagement. They may be characterised by different control systems and types of dynamic effects produced for communicative or environmental purposes, which may even result from the viewer's movement or from variations in the environment. Nonetheless, media facades present drawbacks in terms of suitability for certain contexts and operational problems including control, cost and maintenance related issues as well as intensive energy use. The latter does not seem to meet requirements for nearly zero-energy buildings but may be reduced with solutions exploiting optics, changing atmospheric conditions, material properties and passive kinetics which, however, can involve operational issues. Solar technologies, and especially photovoltaics, may also be integrated into architectural skins to display visually engaging features which emerged from the study of visual perception in

Section 2.3.2. This suggests the possibility of supplying buildings with renewable energy produced onsite through captivating exteriors.

According to the findings of this chapter (see fig. 25.), media facades can exemplify how architectural skins may be designed to stimulate visual engagement as understood from the study of vision. Operational problems including energy use may be overcome with static designs conveying a sense of motion, as also suggested by the study of visual perception, and integrating solar technologies to improve the energy performance of buildings, which this research intends to explore further.

Architecture as Communication	<ul style="list-style-type: none"> • Importance of human visual perception to architectural skins' communicative role (for most people) • Existence of visual features with higher potential for engaging people and enhancing public spaces
Visual Engagement with Architectural Skins	<ul style="list-style-type: none"> • Visual engagement as the attraction of people's visual attention and interest, key to architectural skins' communicative function and understood through the study of visual perception (physiological and cognitive aspects studied in psychology and neuroscience) • Attraction of visual attention depending on both environmental features and subjective influences on the viewer, including their goals (gaze not always indicating attention) • Potentially visually engaging features including qualities of colours, shapes in two or three dimensions, motion, patterns or figures • Motion: a strong visual attractor; conveyable also without moving elements, e.g., with static three-dimensional configurations appearing dynamic to moving viewers, or with illusory patterns (these may be perceived as disturbing in some cases)
Visually Engaging Features as Media Façades	<ul style="list-style-type: none"> • Media facades: architectural skins displaying visually engaging features (as from the study of visual perception in Section 2.3.2) through a pixelated configuration • Potential benefits of media facades: improving the quality of public spaces (with possible economic advantages) • Media façade technologies: a variety of systems producing luminous and kinetic effects • Media façade design: displaying content through pixelated configurations with varying levels of visibility, interactivity or engagement, as well as diverse movement types and control systems (including passive motion, for communicative or environmental purposes) • Drawbacks of media facades: inappropriateness for certain contexts and multiple operational issues, including intensive energy use • Potential solutions to media facades' energy issue: saving energy by exploiting passive kinetics (with likely operational issues), optics, changing atmospheric conditions, or material properties; generating energy by deploying solar technologies to display visually engaging features (as from the study of visual perception in Section 2.3.2)

Fig. 25. *Key Findings of the Literature Review on Visually Engaging Architectural Skins* (2019)

Chapter 3: Solar Architectural Skins

3.1 Chapter Overview

This chapter expands on the previously identified potential for creating visually engaging architectural skins which deploy solar technologies, providing an overview of the state of the art on the topic.

The second section introduces solar technologies for building integration, including solar thermal and photovoltaic-based systems, to then concentrate on the latter.

The third section reviews the design principles outlined by researchers for building-integrated solar technologies, from the aesthetic aspects that have led to the development of coloured and customised solar modules, to the constraints and the opportunities for higher performance levels.

The fourth section reviews the techniques for improving the performance of solar technologies, including novel concepts that are still in development.

The fifth section draws the conclusions of the chapter, hinting at strategies that may be considered in designing effective solar architectural skins with visually communicative potential.

3.2 Solar Technologies for Architectural Skins

3.2.1 Active Solar Technologies for the Building Envelope

Solar energy has been indicated as a prominent, widely available renewable energy source with the potential to offer sustainable solutions to the environmental problems related to conventional fuels (Singh, 2013:1; Buker & Riffat, 2015:328; Modi et al., 2017:1048). There are various technological systems through which solar energy can be harnessed and integrating them into the building fabric presents some advantages. These include more efficient land use, onsite energy production, and a potential reduction of installation costs (Reijenga & Kaan, 2012:698; Shukla et al., 2016:100) as well as of manufacturing, operation and maintenance costs (Norton et al., 2011:1652). Incorporating solar energy systems into roofs or façades can be a suitable way to provide renewable energy in densely built urban areas (Norton et al., 2011:1632), as well as to improve the energy performance of buildings while potentially adding aesthetic value to them (Biyik et al., 2017:854). Using facades to collect solar energy may be especially beneficial in cities where the cost of land is high and exploiting rooftops is insufficient (Meinardi et al., 2017:1).

An architectural façade, or skin, is the ‘outer envelope’ of a building, which usually has a vertical configuration and serves multiple functions ranging from the aesthetic appearance of a building to its protection from the exterior environment. A solar façade enables the use of solar energy and can provide for the building’s needs, from electricity, heating and lighting to thermal insulation and ventilation (Quesada et al., 2012b:2821).

There are several ways of exploiting solar energy in buildings through their skin. Solar façades can be distinguished between ‘active’ and ‘passive’, which can be ‘transparent’ and ‘translucent’ (Quesada et al., 2012b) or ‘opaque’ (Quesada et al., 2012a), depending on whether they allow the transmission of light or not. Employed for energy-intensive applications such as the heating or the cooling of buildings, passive systems are based on characteristics of the envelope allowing the absorption of solar radiation without electrical or mechanical devices which distinguish active systems instead (Chan et al., 2010:781–782). Solar facades identified as ‘passive’, which exploit solar radiation and natural air convection, include solutions such as naturally ventilated skins (Quesada et al., 2012b:2647), solar chimneys, and thermal storage walls (Quesada et al., 2012a:2826–2829) or Trombe walls (Chan et al., 2010:782). These systems utilise conventional building components such as massive walls and glazing. On the other hand, ‘active’ solar facades embedding photovoltaic and solar thermal installations, which can be fully opaque (Quesada et al., 2012a:2821–2826) or have some degree of transparency (Quesada et al., 2012b:2646–2647) incorporate less traditional components for which a visual language in architecture can be explored further. Therefore, the interest of the present research is in the deployment of active solar technologies on architectural skins, which include solar-thermal and photovoltaic-based systems.

3.2.2 Overview of Solar Thermal Technologies

Solar thermal systems can have an important role in the shift towards an economy based on renewable energy, as it was estimated that between 30% and 40% of heat requirements in the world could be met by solar thermal energy. They were found capable of decreasing the need for fuel for space and water heating by up to 60% and 70% respectively (Buker & Riffat, 2015:344). In active solar thermal systems, a ‘solar collector’ absorbs solar radiation as heat. This is then transferred through a fluid, such as water, air or oil, to provide water or space heating, also by storing the hot fluid in a tank for later use (Tian & Zhao, 2013:539). In active solar thermal facades, solar collectors are embedded in the building skin which serves all the

functions of the envelope as well as that of absorbing solar radiation for heating purposes (Quesada et al., 2012a:2821). Heat transfer fluids move through forced convection activated by a pump. The method can be used for space and air heating, ventilation, cooling or water heating which is the most common application in buildings (COST Office, 2015:6-8), with efficiency up to 70% (Buker & Riffat, 2015:336).

There are different types of solar thermal collectors. These have been distinguished as 'concentrating' and 'non-concentrating' (Tian & Zhao, 2013:539–543), or as 'evacuated tube' and 'flat plate' collectors. The latter are usually composed of a clear cover, an absorber plate, fluid manifold, back insulation and casing (Shukla et al., 2013:177; COST Office, 2015:12). Instead, 'evacuated tube collectors' feature heat-absorbing pipes insulated through the vacuum created within sealed glass tubes (Shukla et al., 2013:179; COST Office, 2015:13). Less efficient air-based solar collectors are mostly applied in commercial environments such as shopping malls, agricultural and industrial buildings, whereas water-based systems can be suitable for a variety of applications in the built environment. Building-integrated solar thermal systems include ceramic solar collectors with dark coating, polymer collectors aiming to reduce costs related to metal-based systems, and solar louvre collectors combining shading with heat generation (Buker & Riffat, 2015:335-340). Solar collectors can be embedded in walls, windows, balconies, shading elements and roofs (Zhang, Shen et al., 2015:35). Flat plate collectors may be glazed or unglazed (Munari Probst & Roecker, 2013:19-35), although glazed collectors were found to be more efficient (Buker & Riffat, 2015:344).

Distinct solar thermal systems perform differently. Shukla et al. (2013) pointed out that common flat plate and evacuated tube collectors only reach low to medium temperatures, comprised between 20°C and 120°C. Higher temperatures can be attained with concentrators or reflectors, such as compound parabolic concentrators and V-troughs, which increase the incident radiation onto the absorber. These systems incur heat losses that may be reduced, for instance, with an asymmetric profile, with clear insulation or with high performing materials (Shukla et al., 2013:180-181). Their appearance needs improving towards the creation of attractive solar facades, which requires consideration of geometries, textures and colours (Zhang, Shen et al., 2015:56). However, it was pointed out that among building-integrated solar technologies, solar thermal systems allow limited flexibility in aesthetic features such as colour, form, size, patterns or textures, compared to

photovoltaic applications (Farkas & Horvat, 2012:33). Hence, these appear to have a higher potential for the design of visually engaging building skins.

3.2.3 Overview of Photovoltaic Technologies

The energy generated through photovoltaic-based systems may be defined as ‘electricity obtained directly from the conversion of solar energy’ thanks to materials referred to as ‘semiconductors’, such as silicon, in which sunlight instigates the flow of electrons. The devices in which this occurs are known as ‘photovoltaic cells’ or ‘solar cells’ (Sampaio & González, 2017:591–592). Semiconductor materials are essential to photovoltaic systems and ongoing research has been directed at their development. The improvement of photovoltaic systems also depends on advances in technologies for components such as batteries and inverters (Obeidat, 2018), which being specific to the electrical design of photovoltaic installations goes beyond the scope of this research.

Photovoltaic (PV) technologies have been classified, according to the types of materials employed, as ‘first’, ‘second’ and ‘third generation’ solar cells. The ‘first generation’ comprises the widely produced solar cells based on crystalline silicon (c-Si), including mono- and poly- or multi-crystalline silicon. Relatively established, ‘second generation’ photovoltaics include thin-film solar cells made of materials which range from amorphous silicon (a-Si) to copper indium gallium diselenide (CIGS) and cadmium telluride (CdTe). ‘Third generation’ photovoltaics represent the aim to further improve thin-film technologies, and include, for instance, organic solar cells and other novel concepts that are still in development (Shukla et al. 2016:101–105; Sampaio & González, 2017:593).

While established first-generation photovoltaics currently dominate the market, thin-film solar cells present some notable advantages in comparison. For instance, the recycling of c-Si PV panels was found to produce economic losses, although it was suggested that recovery centres treating multiple types of waste could offer a potential solution to the problem (D’Adamo et al., 2017). On the other hand, thin-film PVs were found to produce lower greenhouse gas emissions during their life cycle, and to have lower Energy Pay-Back Time periods, compared with c-Si PVs (Kommalapati et al., 2017). Additionally, suitable and flexible for integration into buildings, thin-film photovoltaics can be considered for deployment on facades which provide large surfaces despite having lower solar radiation levels than rooftops (Shukla, Sudhakar & Baredar, 2017).

Thanks to their potential, thin-film photovoltaics have been heavily researched. Amorphous silicon currently prevails due to its reduced need for air and water tightness in comparison to other second and third generation thin films (Shukla et al., 2016:100). CIGS solar cells are flexible, resistant to intense solar radiation and have high power conversion efficiency, of about 20% on glass substrates. Thanks to this they have been employed in space applications and have started to be combined with different flexible substrates (Shukla et al., 2016:102), including metal or polyimide, which makes them appealing for building integration and further innovative uses (Jean et al., 2015:1204). Gallium arsenide (GaAs) has been indicated as a highly efficient material for flexible, thin-film solar modules (Moon et al., 2016). However, the toxicity of cadmium, of tellurium (Alharbi et al., 2011:2754), and of the arsenic used in the production of GaAs solar cells (Sampaio & González, 2017:598), as well as the scarce availability of tellurium and indium (Shukla et al., 2016:102) constitute barriers to the widespread use of second-generation thin films. Therefore, alternative materials characterised by non-toxic and abundant components have been explored (Alharbi et al., 2011).

The development of third generation devices has aimed to increase the accessibility of photovoltaics. Based on a photoelectrochemical system, dye-sensitised solar cells present potential advantages such as ease of manufacture through conventional printing techniques, partial flexibility and transparency, as well as low costs. On the other hand, they contain some expensive materials, they are less efficient than other thin-film photovoltaics, and they are not fully suitable for all weather conditions (Shukla et al., 2016:103). This is due to the fact that they are commonly characterised by 'liquid or gel-like electrolytes', replaced by 'solid-state organic semiconductors' in recent developments of the technology (Anscombe, 2011). Dye-sensitised solar cells are also colourful (Jean et al., 2015:1205), which makes them attractive for architectural applications, with an efficiency that can be around 7-11% (Sampaio & González, 2017:595), thus considerably lower than that of crystalline silicon. With similar characteristics, organic solar cells are made of organic polymers or small molecules (Jean et al., 2015:1205; Shukla et al., 2016:103). While still lacking stability, efficiency and strength or durability, they offer benefits such as flexibility, low costs, easy fabrication (Shukla et al., 2016:104; Sampaio & González, 2017:594–595) through printing techniques, versatile integrability into devices and ecological advantages (Sampaio & González, 2017:595).

Other emerging photovoltaic technologies include quantum dots solar cells, using ‘semiconducting particles’ that can be tuned to absorb light ‘across a wide range of energy levels’, and perovskite solar cells. The latter boast high efficiencies above 20% as well as cheap, easy manufacturing, and are usually based on ‘a hybrid organic-inorganic lead or tin halide-based material’ (Shukla et al., 2016:104-105). An American chart by the National Renewable Energy Laboratory (NREL) illustrates recent improvements in the efficiency of solar cells, showing that perovskite-based cells can reach an efficiency of 28% (see fig. 26.). Perovskite cells appear to have great potential for building-integrated applications due to their high efficiency and their suitability for semi-transparent architectural skins. They may facilitate the creation of building envelopes which produce visual comfort for the users, although this needs to be approached with a ‘holistic’ view (Cannavale et al., 2017). Research has been conducted to replace lead with alternative materials such as tin, copper and less toxic elements with promising qualities (Hoefer et al., 2017). Overall, the development of novel photovoltaic materials appears to be heading towards lighter, cheaper and more versatile solutions while also pursuing high conversion efficiencies.

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Fig. 26. *Best Research-Cell Efficiencies Chart by NREL (2019)*

Photovoltaic products for architectural applications have been classified as ‘Building Integrated Photovoltaics’ (BIPVs) and ‘Building Attached Photovoltaics’ (BAPVs) (Jelle & Breivik, 2012a; Shukla et al., 2016), alternatively called ‘Building Applied Photovoltaics’ (Cerón et al., 2013:127) or ‘Building Adopted Photovoltaics’ (Heinstein et al., 2013:126). The distinction aims to separate products that are used

in place of conventional building materials in rooftops or exterior walls (Heinstein et al., 2013:126; Shukla et al., 2016:100), from those which are merely added onto the existing building skin (Heinstein et al., 2013:126; Shukla et al., 2016:105). A study that used surveys to evaluate people's feelings when they viewed BIPVs and BAPVs showed that BIPVs were preferred although they did not trigger a high level of excitement (Sánchez-Pantoja et al., 2018b). The bespoke design of BIPV façades offers great potential for improving both the efficiency and the aesthetics of photovoltaic arrays, although BIPV technologies are still in development (Attoye et al., 2017). Hence, there is room for exploration on how photovoltaics can be successfully deployed on architectural skins.

3.2.4 Overview of Hybrid Technologies

Photovoltaic and solar thermal technologies can be combined into hybrid photovoltaic-thermal (PV/T) systems that provide both electricity and heat (COST Office, 2015:20; Good et al., 2015), enabling a more successful usage of solar radiation (Buker & Riffat, 2015:328; Good et al., 2015:683). As Buker & Riffat (2015) showed in their review of solar thermal collectors for building integration, there can be various types of PV/T systems associating photovoltaic cells with air collectors, water collectors, refrigerant-based collectors, heat pipe-based collectors, concentrating collectors or transpired collectors. These hybrid PV/T systems were said to be highly advantageous as they increase solar cells' efficiency by reducing their operating temperature, while they also utilise thermal energy for heating applications (Buker & Riffat, 2015:328-334). However, Norton et al. (2011) noted that despite the economic viability, PV/T collectors are less efficient than just optimised flat-plate collectors, and reviewed other possibilities for PV/T technologies involving passive heat exchange systems that exploit natural air convection, such as Trombe walls and thermosyphons (Norton et al., 2011:1650-1651). BIPVTs include a variety of emerging technologies, but despite being promising, very few PVT systems for building integration are commercially available. Further developments of PVT techniques are needed, which should consider aspects related to their overall environmental impact and to their economic feasibility, such as life cycle assessment, carbon emissions and payback time (Sathe & Dhoble, 2017).

3.2.5 Building Integration of Solar Technologies

The possibilities for integrating photovoltaic technologies into buildings have been widely explored. Studies reviewing BIPVs identified four types of photovoltaic cladding components for architectural envelopes. Lightweight and flexible ‘foil’ products are suitable for non-ventilated roofs, while ‘tile’ products simulate conventional tiles and can embed crystalline or amorphous silicon solar cells. There can be also BIPV modules which are similar to BAPV components but are installed to replace conventional cladding materials and to act as weather skin elements. Lastly, photovoltaic glazing products, which are available in various colours and customisable degrees of transparency, comprise a layer of amorphous silicon, polycrystalline silicon or monocrystalline silicon solar cells. They provide shading, daylighting and electricity generation at the same time (Jelle & Breivik, 2012a:71-74; Shukla et al., 2016:105).

Solar technologies deployed on the building envelope can take different forms. For instance, Lai & Hokoi (2015) categorised solar façades as ‘transparent’ or ‘semi-transparent’ and ‘opaque’, also considering solar thermal systems, hybrid photovoltaic/thermal facades and ‘smart windows’ that adapt their transparency in response to external conditions (Lai & Hokoi, 2015). According to Sick & Erge (1995), architectural applications of photovoltaic technology concern facades or external walls and roofs or coverings, as well as shading elements (Sick & Erge, 1995:94-96). Nonetheless, typical mounting methods for solar envelopes are similar to those of conventional facades, such as constructions composed of mullions and transoms, which can be adapted to host electrical cabling (Sick & Erge, 1995:29).

In summary, at present there seems to exist a multitude of solar technologies for architectural applications. Among those which actively use solar energy and entail greater challenges for architectural design, photovoltaics may offer more opportunities than solar thermal systems for the creation of visually engaging building skins. This invites exploration of how such technologies may be deployed successfully on buildings with striking visual effects. Therefore, the following section provides an overview of aspects to be considered in the design of solar architectural skins, with a focus on what can affect their visual characteristics.

3.3 Design of Solar Architectural Skins

3.3.1 Challenges and Potential

It may be argued that deploying solar technologies on architectural skins is not always a viable design option. Sick & Erge (1995) suggested that the integration of photovoltaic systems may be unsuitable for buildings with insufficient exposure to sunlight, or that do not lend themselves to innovative solutions or are not designed to be energy efficient (Sick & Erge, 1995:7). Barriers to the spread of BIPVs for retrofitting include the density of built areas with shading effects that are detrimental to the performance of PVs, as well as 'preservation laws' that impede the integration of solar technologies into certain buildings (Scognamiglio, 2017:192). Vertical facades tend to be characterised by non-optimal insolation, and thus may seem inadequate for incorporating solar arrays. Nonetheless, the advantages of building-integrated solar technologies, such as onsite clean energy production and low maintenance, which were mentioned in Section 3.2.1, have motivated research in this field. Freitas (2018) investigated the energy generation potential of photovoltaic facades and argued that these can be beneficial thanks to ongoing developments of BIPVs and to the possibility of adding the contribution of solar facades to that of roofs (Freitas, 2018). Furthermore, solar technologies, and particularly building-integrated photovoltaic installations, are characterised by a modular configuration (Singh, 2013:2). This is also a distinctive feature of media facades, which emerged in the previous chapter. Such similarity suggests that solar architectural skins may be designed like media facades to stimulate visual engagement, yet by taking into account aspects involved in the deployment of solar technologies.

While PVs have great potential for integration into buildings, considering their characteristics from early design stages can be difficult for architectural designers because it forces them to work from the beginning around technical constraints. These can be seen, however, as guiding design criteria rather than as limitations to creativity, which is not unusual in architectural design that is already an 'act of constrained freedom' (Moser et al., 2018:318). While offering several advantages, incorporating PVs into buildings has to comply with multiple constraints relating to aesthetic, dimensional and functional aspects of the installation. Factors such as temperature, shading and the angle of a BIPV installation affect greatly its performance, but the response to such conditions can be conveniently simulated through computational methods (Biyik et al., 2017).

Several factors were found to have an effect on the performance of photovoltaics, which should be considered when they are deployed on buildings. Environmental conditions such as the lack of solar radiation, high temperature, shading and soiling of the PV panels can lower their energy output. Characteristics of the PV installation such as the overall active area, the material and efficiency of the PV modules used, as well as their angle, have an impact on the energy absorbed and converted. There are also economic costs and other related issues to be considered, including the need for maintenance and cleaning of the PV panels. Some aspects, including characteristics of components such as inverters and batteries, which also influence the overall performance of a PV system (Fouad et al., 2017), concern more its electrical design and therefore go beyond the scope of the present research. The overall size of the active area of a photovoltaic building skin, which is capable of absorbing sunlight, appears to be quite important towards creating a visually engaging image and generating a significant energy output. For instance, the less densely distributed solar cells characterising semi-transparent modules, typical of glazing products that are appealing for architecture, determine lower power outputs (Robinson et al., 2008). Therefore, there are multiple aspects to consider in the deployment of solar technologies, and of photovoltaics in particular, on architectural skins.

3.3.2 Previously Proposed Design Criteria

Several studies examined the 'integrability' of photovoltaic modules into architecture, in an effort to make them comparable with conventional cladding materials. Within Task 7 of the International Energy Agency (IEA) Photovoltaic Power System Program, the criteria for BIPVs were identified as 'naturally integrated', 'architecturally pleasing', 'good composition', 'grid, harmony and composition', 'contextuality', 'well-engineered' and 'innovative design'. It was suggested that PV systems need to be 'eye-catching' and original but also in 'harmony' with the building and its context (Schoen et al., 2001:2). Kaan & Reijenga (2004) discerned multiple ways of incorporating a photovoltaic system into an architectural project: applying it 'invisibly', adding it to the design, embedding it in a way that either enhances or determines the architectural image, and proposing innovative concepts (Kaan & Reijenga, 2004:404-408). Cerón et al. (2013) distinguished 'BIPV-Modules' and 'PV constructive elements', the latter of which identify PV products that are specifically made to replace conventional building components (Cerón et al., 2013). Frontini et al. (2013) summarised the

'technological integrability' and the 'morphological integrability' aspects of photovoltaics for architecture. The former aspects relate to the 'constructive compatibility' of PVs with traditional building components, while the latter refer to variations in 'colour', 'grain' and 'texture' of the surfaces (Frontini et al., 2013:3759).

Criteria for the integration of solar technologies into the building fabric were outlined in reports of the International Energy Agency's project '*IEA SHC Task 41: Solar Energy and Architecture*'. Surveys were utilised to investigate architects' positions towards deploying solar technologies in their projects, as well as the existing barriers to this practice, which were largely attributable to the lack of knowledge on solar energy systems (Farkas & Horvat, 2012). Two reports, edited by Farkas (2013) and Munari Probst & Roecker (2013), provided frameworks for designing building-integrated photovoltaic and solar thermal systems respectively, referring to established technologies which are commercially available. Both documents stressed the necessary multifunctionality of solar building envelopes. By examining the 'integrability' issues of solar energy systems, they distinguished 'functional' and 'constructive' aspects from 'formal' or aesthetic considerations. The functional and constructive aspects relate to the building envelope functions. These include weather protection, thermal and sound insulation, security, and control of the ventilation and of the inhabitants' comfort as well as of the visual relation between the inside and the outside. On the other hand, the 'formal' aspects relate to the characteristics determining the visual impact of building-integrated solar technologies, and include the modules' shape and size, the absorbing material with its colour and surface texture, the type of jointing, and the overall size and position of the array (Farkas, 2013:7-22; Munari Probst & Roecker, 2013:11-14).

The same studies identified three levels of 'integrability' of solar energy systems into buildings. A 'basic' level is characterised by the possibility to adapt the design of the modules according to the building's dimensional constraints. A 'medium' level involves the use of active and non-active elements or 'dummies' to ensure relative compositional freedom. An 'advanced' level of integrability can offer a full solar roof or façade system (Farkas, 2013:9-10; Munari Probst & Roecker, 2013:14-15). Although the frameworks provided by Farkas (2013) and Munari Probst & Roecker (2013) provide useful guidelines for the design of solar architectural skins, they are not directed at facilitating the creation of designs which can stimulate particular responses in the viewers.

In a review on the aesthetic impact of solar energy systems it was suggested that research should be conducted on the reactions triggered by solar installations, which should include observations of people's behaviour in field or lab-based studies. It was pointed out that the visibility of a solar installation, which can vary depending on whether it is part of a roof or of a façade, plays an important role in people's perception of solar energy systems in urban environments, while glare has a negative effect on it (Sánchez-Pantoja et al., 2018a:233–234). Thus, there is room for research on designing solar architectural skins which are capable of stimulating people's perception and responses.

As Buker & Riffat (2015) summarised, there are some notable differences between photovoltaic and solar thermal systems with regard to their building integration. First of all, while photovoltaic technologies offer relative flexibility regarding the shape and size of the modules, solar thermal systems have considerable restrictions due to difficulties and costs involved in the customisation of hydraulic circuits. Secondly, if both flat plate collectors and photovoltaic panels can be said to have a sandwich-like composition, photovoltaic modules can be thin and semi-transparent, while solar collectors are much thicker and necessarily opaque, or have a completely different structure in the case of evacuated tubes. Therefore, it is hard to apply solar collectors to see-through parts of the building envelope, although evacuated tubes may have some potential for integration into shading products. While the size of a photovoltaic array is relatively free, a solar thermal installation has to be adjusted according to a building's energy demand, and thermal energy has to be stored onsite necessarily. Instead, photovoltaic systems can feed electricity into the grid. Moreover, while solar collectors require back insulation to limit heat losses, back ventilation is highly recommended to prevent the overheating of photovoltaic modules which would reduce their efficiency. Lastly, partial shading moderately affects the performance of solar thermal collectors, depending on the shadow size, whereas it always has a negative impact on the efficiency of photovoltaic modules as well as on the safety of the system (Buker & Riffat, 2015:341-342). However, it can be noted that the absorption of solar radiation determines the output of both photovoltaic and solar thermal systems. Thus, maximising it appears to benefit both types of solar technologies which are similar in this sense.

3.3.3 Improving Visual Aspects

In the development of solar architectural products with aesthetic value, colour has been highly emphasised. Farkas (2013) illustrated examples of coloured

multicrystalline silicon wafers (Farkas, 2013:18) and coloured, semi-transparent photovoltaic glass panels (Farkas, 2013:63). Tripanagnostopoulos et al. (2000) presented the possibility of solar thermal collectors with coloured absorbers, and although these were found to be less efficient than conventional black collectors, the authors suggested that a lower performance can be acceptable if justified by improved aesthetics (Tripanagnostopoulos et al., 2000). EPFL and CSEM developed coloured, photovoltaic tiles combining thin-film silicon with glass and a composite backing (Perret-Aebi et al., 2013). Some of the technologies classified as 'third generation' photovoltaics (Shukla et al., 2016:102-105) also offer a range of colours for the solar modules, such as the Solaronix (see fig. 27.) dye-sensitised cells (Solaronix SA, 2016) as well as organic (Wen et al., 2014) and perovskite solar cells (Zhang et al., 2015). The company OPVIUS produces bespoke, printed organic photovoltaic modules (see fig. 28.), an example of which was the photovoltaic membrane of the German Pavilion at Expo 2015 in Milan (OPVIUS GmbH, 2017). Providing coloured, semi-transparent photovoltaic glass panels, the company Onyx Solar offers the option to create customised patterns with the photovoltaic layer (Onyx Solar Group LLC., n. d.), which may also be possible with the photovoltaic textiles developed by Power Textiles Ltd. (Power Textiles Limited, n. d.).

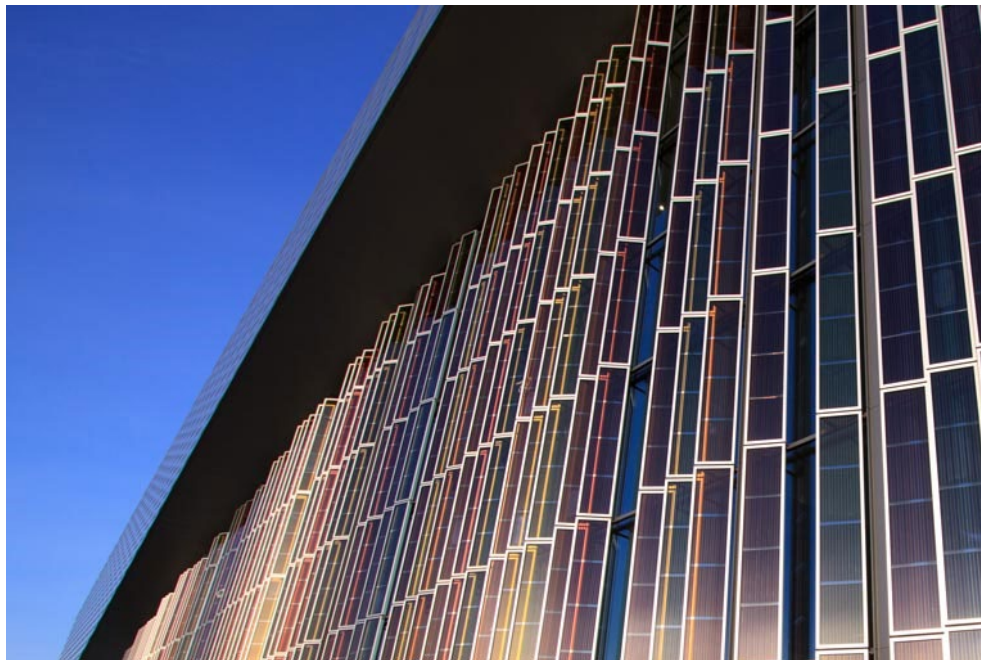


Fig. 27. *Solaronix Solar Cells*

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Fig. 28. *Photovoltaic Skin of the German Pavilion at Expo 2015 in Milan* (2015)

As emerged in the previous chapter, there are more features besides colour which could be displayed potentially through solar architectural skins to stimulate visual engagement. Scognamiglio & Privato (2008) identified potential future developments of solar facades as 'environment responsive surfaces', 'media surfaces', 'pixelated surfaces' and 'fractal surfaces', suggesting ideas for new research in the field, such as the integration of concentrators in responsive facades, new media façade modules combining back-contact solar cells with LEDs and printed circuits, and the adoption of CIGS photovoltaic modules for fractal surfaces (Scognamiglio & Privato, 2008:3225-3232). Thus, there are opportunities for exploration in the design of visually captivating building skins embedding solar technologies.

Examining the design of photovoltaic systems for architecture, Sick & Erge (1995) indicated four 'levels' in the design of solar architectural skins: a 'design' stage concerning matters of orientation, form, scale and colour; a 'mechanical' integration level, referring to the 'multifunctionality' of photovoltaic elements; electrical aspects; and maintenance as well as 'operation control' issues (Sick & Erge, 1995:83). As the focus of the present research is on pursuing visual engagement through solar architectural skins, decisions made at an early design stage about aspects that relate to the external appearance of buildings seem to be the most relevant to this

study. However, such aspects related to solar skins' communicative role are expected to be influenced by issues affecting the energy output of solar technologies, which need to be taken into account.

3.4 Enhancing the Performance of Solar Architectural Skins

3.4.1 Trade-Off between Visual and Energy Performance

The aforementioned examples of solutions for visually improved solar envelopes do not seem to exploit the full potential of solar technologies for building integration, if the need to maximise their energy output is considered. While Scognamiglio & Privato (2008) proposed further developments of media façade systems combining LEDs with photovoltaics (Scognamiglio & Privato, 2008:3231), Heinstein et al. (2013) suggested that generating energy to waste it by powering LED displays may not make much sense (Heinstein et al., 2013:152). On the other hand, it emerged in the previous sections that conventional solar modules characterised by colour or degrees of transparency tend to generate less energy than those without improved visual features. Hence, there is room for exploration on ways of tweaking the appearance of solar architectural skins with a limited impact on their performance. This can be researched with a focus on photovoltaic applications, since it was found earlier in this chapter that they offer greater potential for composing visually engaging designs.

3.4.2 Considerate Architectural Design

There may be several other ways of enhancing the efficiency of photovoltaics deployed on architectural skins. As suggested by Norton et al. (2011), the performance of BIPV systems can be considerably improved without necessarily increasing the PV cells' efficiency (Norton et al., 2011:1652). It was highlighted that optimal orientation and tilt, back ventilation of PV modules particularly made of crystalline silicon, and preventing shading play an essential role in contributing to the efficacy of building-integrated photovoltaic systems (Reijenga & Kaan, 2012:700-701; Shukla et al., 2016:107). Reijenga & Kaan (2012) offered a range of pragmatic criteria for designing well-functioning BIPV installations, which included controlling reflections onto nearby buildings, using easy mounting and dismounting systems, choosing simple and reliable electrical connections, and weatherproofing. They indicated the optimum tilt of PV modules, to achieve irradiance above 90%, as approximatively equivalent to the site latitude minus 10°, whereas the ideal orientation should be comprised between the South-East and the South-West. While horizontal PV installations can be a suitable solution for difficult orientations, vertical

PV surfaces were found to be more sensitive to shading issues (Reijenga & Kaan, 2012:700-701) and less efficient than tilted array by 50%-70% in terms of electrical output (Shukla et al., 2016:107). A south-facing orientation is optimal in the northern hemisphere (Sick & Erge, 1995:160), being the opposite in the southern hemisphere. Some authors suggested that the optimal fixed tilt can be simply equal to the latitude, although changing the tilt twice a year can be beneficial if possible (Jain & Lalwani, 2017). Furthermore, the relative performance of a BIPV system can be higher if the building presents energy-efficient features such as low-energy lighting (Shukla et al., 2016:107).

Various factors can be acted on to improve the efficiency of photovoltaic building skins. Sick & Erge (1995) indicated maximised exposure to solar radiation, depending on the site location as well as on solar modules' tilt and orientation, as the primary factor determining the higher energy output of building-integrated photovoltaic systems. They also pointed at high temperature and at obstructions to sunlight, such as partial shading and the presence of dirt, as major causes of drops in efficiency. Moreover, the same authors highlighted electrical factors which can reduce the power output of photovoltaic systems, such as wire resistance, the need for blocking diodes and mismatches between electrical characteristics of interconnected modules. The latter factor causes poorly performing modules to lower the performance of the entire system (Sick & Erge, 1995:27-28). A consequence for design is that it is preferable to have arrays or sub-arrays of photovoltaic modules with a uniform angle (Cheng, 2009:8-9), rather than setting different angles for each module. This can constitute a considerable constraint for the deployment of photovoltaics on architectural skins that present, for instance, curved geometries and self-shading issues.

3.4.3 High-Efficiency Photovoltaic Modules

One way of increasing the energy output of photovoltaics in architecture may be to use solar cells characterised by higher efficiencies. The NREL chart (see fig. 26.) shows that some solar cells which have been researched, including multijunction cells and single-junction gallium arsenide cells, reach much higher efficiencies than conventional crystalline silicon solar cells. In a review of technological developments that appear to be promising for the future of building-integrated photovoltaics, Jelle & Breivik (2012b) indicated several solutions that intervene at the material scale to increase the efficiency of photovoltaic modules. Stack solar cells combine multiple layers with different spectral absorbance characteristics in order to utilise a larger

portion of the incoming solar radiation. Similarly, so-called ‘antennas’ and ultra-high efficiency PV modules such as quantum dots solar cells and nanostructured devices can absorb a broader light spectrum. Another approach is using high-purity materials with enhanced characteristics on the front and back surfaces to prevent energy losses, such as buried contacts to minimise shading and textured surfaces for light-trapping. ‘Inverted pyramid texturing’ on the surface of silicon solar cells was found capable of trapping light rays in triple bounces, reducing reflection losses and increasing light absorption. Among thin-film photovoltaics, CIGS and CdTe solar cells seem to offer a good compromise between high-efficiency, flexibility and light weight, unlike photovoltaic paints which at present they are still poorly efficient (Jelle & Breivik, 2012b). However, it may be noted that reflection losses persist due to the need of an encapsulant material such as glass, and as previously mentioned, CIGS and CdTe solar cells present issues for large scale deployment. Moreover, although technological developments at the material scale are evidently important, they fall outside the architectural design expertise the present research is centred on.

3.4.4 Improved Geometry

Given the importance of incident solar radiation in increasing the power output, various geometric configurations for building-integrated photovoltaics have been explored to maximise solar modules’ exposure. Sick & Erge (1995) showed possibilities for more efficient photovoltaic facades characterised by inclined or corrugated surfaces presenting, for instance, a ‘sawtooth’ profile (Sick & Erge, 1995:98-102), thanks to which photovoltaic modules can be positioned with optimal orientation or tilt. A corrugated configuration was also explored by Bernardi et al. (2012), who demonstrated that three-dimensional photovoltaic modules (see fig. 29.) can perform better than flat panels (Bernardi et al., 2012). It was also suggested that the use of bifacial solar cells can increase the electrical output of photovoltaics (Singh, 2013:7) as it enables the absorption of more light. Sphelar® photovoltaic technology, particularly suitable for building integration, is characterised by semi-transparent modules comprising regularly arranged, spherical solar cells made of crystalline silicon (see fig. 30.), which are capable of capturing sunlight from multiple directions, performing well in diffuse and low-angle lighting (Nakata & Wac, 2011). Hence, photovoltaic building skins presenting a three-dimensional configuration or bifacial modules may perform better than conventionally flat PV surfaces. This can suggest possibilities for creating solar architectural skins which, thanks to qualities of stereoscopic depth, may be visually engaging, as hinted in the previous chapter.

However, producing light and shadow effects on PV envelopes might cause shading on photovoltaic modules, which as observed earlier, would impair their performance.

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Fig. 29. *Three-Dimensional Photovoltaic Modules*

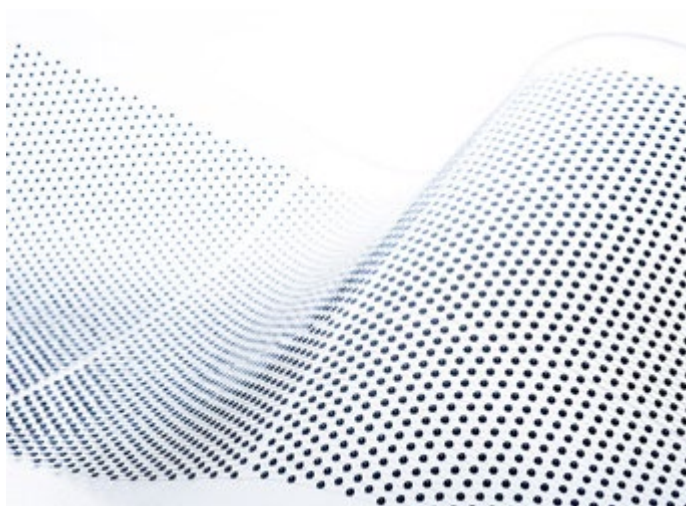


Fig. 30. *Sphelar® BIPV*

There is another issue to consider, which is related to the need for maximising active modules' exposure to sunlight. A photovoltaic skin should be easy to clean and maintain, since the build-up of snow, dust or dirt on PV modules can be detrimental to their performance as well (Norton et al., 2011:1631). This problem can be mitigated with various methods, ranging from manual cleaning to active or passive self-cleaning (Jamil et al., 2017). As it stops sunlight from reaching the absorber, soiling is one of the major causes of decreased efficiency in PV modules. It can be reduced, for instance, by protecting PV modules with hydrophobic or hydrophilic surfaces and through cleaning with water (Shaju & Chacko, 2018). Thus, the angle

of PV modules on an architectural skin should be determined also by considering the need for cleaning and maintenance.

3.4.5 Cooling of Photovoltaic Modules

As previously mentioned, high temperatures can lower the performance of photovoltaics, and therefore methods for the thermal management of solar cells have been proposed. As emerged from a review by Shukla et al. (2017), ways of cooling photovoltaic modules can range from active systems which require electric power and involve maintenance-related issues to passive systems which are freed from such problems (Shukla et al., 2017). Opting for hybrid photovoltaic/thermal systems (PV/T) can improve the performance of solar architectural skins (Shukla et al., 2016:107), as it provides a solution to cool the rear of the PV modules. This increases their efficiency while making the extracted thermal energy available for heating applications (Buker & Riffat, 2015:328). Hybrid photovoltaic/thermal systems can also involve the passive use of natural air convection to lower the temperature of photovoltaic modules (Norton et al., 2011:1650-1651), and well ventilated PV envelopes composed of fins were recommended for their higher performance (Singh, 2013:3).

Among thermal management strategies for PVs, which encompass natural or forced air cooling, water cooling, heat pipe cooling, thermoelectric cooling and the use of phase change materials, the latter was found promising, but economic viability also matters. Despite its low heat transfer rates, natural ventilation is an inexpensive solution (Shukla et al., 2017). While the use of phase change materials can increase the efficiency of PV modules by 5%, this solution is still not cost-effective and more research is required (Chandel & Agarwal, 2017). However, the combination of phase change materials and fins showed some potential for lowering the temperature of PV modules effectively (Thongtha et al., 2017). Besides the use of phase change materials (PCMs) and of paraffin in particular, which were proposed for the thermal regulation of photovoltaic systems (Norton et al., 2011:1649-1650; Ma et al., 2015; Sharma et al., 2016; Sharma, Sellami et al., 2016), micro- and nano-technologies such as carbon nanotubes, highly thermal conductive coating, micro-heat pipes and micro-fins were found to have potential for the passive cooling of photovoltaic-based systems (Micheli et al., 2013). Moreover, spectral beam splitting techniques using dichroic components were suggested as methods to decouple photovoltaic and thermal receivers in concentrating solar systems, thus preventing the overheating of solar cells (Imenes & Mills, 2004; Crisostomo et al., 2014). Several promising

cooling techniques may be considered for future applications, including water immersion of photovoltaic modules, but further research is needed (Siecker et al., 2017).

3.4.6 Solar Concentration Systems

3.4.6.1 Defining Concentrating Solar Technologies

Solar concentration is a further strategy for increasing the energy output of photovoltaics. Among possible future developments for building-integrated photovoltaics with enhanced performance, Jelle & Breivik (2012b) pointed at the use of solar concentrators combined with photovoltaic modules. The latest solar cell efficiency chart (see fig. 26.) published in the United States of America by the National Renewable Energy Laboratory (NREL) showed that the highest efficiencies are reached by photovoltaic modules with concentrators. Concentrating photovoltaic (CPV) systems direct solar radiation onto solar cells by utilising optical devices such as lenses or reflectors (Shukla & Khare, 2014:98). The use of the latter to focus solar radiation onto solar cells was said to reduce the cost of electricity generated through photovoltaics, as it enables the replacement of semiconductors with cheaper reflector materials (Singh, 2013:7). It may be evinced that when combined with concentrators photovoltaic materials become subsequently less visible as they are largely substituted by optical components.

Solar concentration does not only improve the performance of photovoltaics. Devices such as compound parabolic concentrators (CPC) and V-troughs were also indicated as capable of increasing the efficiency of solar thermal systems (Shukla et al., 2013:180-181). It was suggested that when integrated into architectural envelopes, concentrators like Fresnel lenses can also contribute to the control of daylight and solar gain in buildings (Tripanagnostopoulos & Tripanagnostopoulou, 2007:1054). Concentrating systems appear particularly promising for the effectiveness of solar building envelopes in terms of both output energy and cost. These were said to be the main factors affecting the acceptance of photovoltaic technology (Singh, 2013:2). Thus, advances in the development of concentrating solar technologies can be quite relevant to the deployment of both photovoltaic and solar thermal systems in architecture.

There can be various types of concentrating systems for architectural applications. In his review of building-integrated concentrating photovoltaics, Chemisana (2011) introduced concentrating systems by explaining the differences between high,

medium and low concentration devices also in relation to their potential for architectural artefacts. Concentrators are distinguished on the basis of their concentration factor, which is the ratio between the 'aperture area' of the optical device and solar cell area. The advantage of concentrating photovoltaics is the possibility to replace part of the semiconductor materials with the cheaper materials of which the optical devices are made, and a higher concentration factor can imply a higher cost reduction (Chemisana, 2011). As pointed out by Shanks et al. (2016), concentrating photovoltaic systems increase the efficiency of solar cells while lowering costs by using less material made from rare metals, and they also have a reduced impact on the albedo change in an area in comparison to conventional, 'flat plate' solar panels. Nonetheless, CPV technologies are not yet competitive and there seems to be a need for novel systems which are capable of performing well without costly sun-tracking and cooling systems (Shanks et al., 2016:395).

3.4.6.2 High and Medium Concentration Systems with Sun Tracking

High concentration devices seem problematic to integrate into the building envelope. They have a concentration factor greater than 100x and require to be accompanied by high precision, two-axis sun-tracking systems, which makes their incorporation into the building fabric impractical. With a concentration ratio comprised between 10x and 100x, medium concentration systems include parabolic troughs and devices using Fresnel optics as lenses or mirrors and can be less complicated to integrate into buildings. They may be deployed particularly on flat roofs, more easily when they have a relatively low concentration factor, as in the case of parabolic troughs that require single-axis tracking only. Linear Fresnel reflectors can involve two-axis sun tracking achieved through the movement of the entire system, tracking in which the concentrator is static and the receiver is dynamic, and conversely, tracking with a moving concentrator and a static receiver. These types of linear concentrators require active cooling systems with heat transport fluids to prevent overheating and can thus combine photovoltaic cells with solar collectors into hybrid photovoltaic thermal concentrators (CPVT). Linear Fresnel lenses present numerous advantages such as low volume, efficient use of material, low cost, light weight, durability, and the capacity to separate direct and diffuse solar radiation which is useful for glare control in buildings. Among Fresnel lenses, only non-imaging lenses can use one-axis sun tracking, while image forming lenses require high precision, two-axis tracking (Chemisana, 2011). The '*Integrated Concentrating Solar Façade*' (see fig. 31.) developed at Rensselaer Polytechnic

Institute provides an example of CPV system for integration into double skins, using Fresnel lenses and active sun-tracking as well as active cooling (Dyson et al., 2007). Despite their potential benefits, high and medium concentration systems need sun tracking, which can cause some issues.

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Fig. 31. *'Integrated Concentrating Solar Façade'*

While sun tracking was highlighted as a method to enhance the efficiency of photovoltaic systems (Singh, 2013:8), it emerged in the previous chapter that having moving parts in architectural skins may entail operation and maintenance problems. Instead, low maintenance is one of the distinctive benefits of photovoltaic systems (Sick & Erge, 1995:79; Singh, 2013:2). Sun tracking can significantly boost the performance of solar technologies, but it was pointed out that it can also entail some relatively high operational energy losses, particularly when applied to small solar panels (Mousazadeh et al., 2009). Moreover, existing tracking systems can be expensive to build and to maintain (Reif & Alhalabi, 2013:3). Sun-tracking methods used to keep solar panels with an optimal orientation relative to the sun can be distinguished as passive and active trackers. In passive trackers, unequally irradiated actuators which exploit either the thermal expansion of materials or shape memory alloys produce unbalanced forces causing the system to rotate. On the contrary, the movement of active trackers is electronically controlled through a computer or can be induced with a microprocessor and an electro-optical sensor, with an auxiliary bifacial solar panel connected to a permanent magnet DC motor,

or with a combination of systems (Mousazadeh et al., 2009:1806-1815). In the passive solar tracker developed by the company Zomeworks, the rotating movement from East to West is imparted by the vapour pressure of a fluid in a canister heated by solar radiation and by a subsequent shift in weight (Zomeworks Corporation, 2017). Hence, sun tracking systems tend to require electric power to function unless they are passive, which, however, may not remove the control and maintenance related issues associated with kinetic components.

Alternative sun tracking systems were suggested which may need less or no electric power to be operated. For instance, a concept was proposed for a flexible, self-adjusting photovoltaic system inspired by kirigami (see fig. 32.) or 'the art of paper cutting' (Lamoureux et al., 2015). With a micro-tracking approach, Tremblay et al. (2012) described an idea for an adaptive, planar lightguide concentrator combining passive motion with spectral beam splitting, in which a phase change material, locally heated by sunlight focused through a lens, imparted movement to a transparent elastomer and a dichroic facet array (Tremblay et al., 2012). Thus, exploring new techniques may make sun tracking and the concentration systems which require it more viable solutions for building integration in the future.

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Fig. 32. *Sun Tracking Photovoltaic System Inspired by Kirigami* (2015)

3.4.6.3 Low Concentration Systems

Low concentration systems, with concentration factor smaller than 10x, were indicated as the most suitable for integration into building envelopes. This category of concentrators includes, for instance, V-trough reflectors and compound parabolic

concentrators which can be more efficient if filled with dielectric material that can even be oil or water (Chemisana, 2011). Low concentration devices have a high acceptance angle, which means they can work in both direct and diffuse lighting conditions, without the need for solar tracking. Therefore, low concentration photovoltaic systems can be static or quasi-static. For instance, V-troughs perform well as fixed devices with a concentration factor smaller than 2x, while several tilt adjustments can improve their efficiency when the concentration factor is greater than that. Similarly, it was shown that a 3x compound parabolic concentrator needs no tracking, whereas a 6x one was found to require five adjustments a day (Shanks et al., 2016:399). Systems approaching a 10x concentration ratio were suggested to be 'the most desirable' (Chemisana, 2011:604). These may offer a good compromise between architectural integrability, high efficiency and low cost.

3.4.6.4 Design Opportunities for Concentrating Systems

Several different designs and materials have been explored for low concentration systems. Concentration methods were distinguished as 'reflective', 'refractive', 'luminescent', and 'total internal reflection', the latter of which also belongs to the refractive and luminescent categories. The compound parabolic concentrator was found to be an effective device which can be proposed in different shapes (see fig. 33.). 'Light funnels' and 'homogenisers' in various forms are capable of improving both the acceptance angle and the irradiance distribution of a CPV system, increasing its efficiency. Among optical devices with such potential there are dome and ball lenses, although the latter can be difficult to support. Those made of dielectric material exploit total internal reflection, reducing reflection losses. Promising materials for novel concentrating devices include polymer mirror films, silvered glass, aluminised plastics and anodised aluminium for reflectors, while polymethylmethacrylate seems particularly indicated for refractive devices besides being used already in other industries, for instance in lighting. There is no absolutely optimal solar concentrator, as the best solution in each situation depends on factors such as the location characteristics and the incident light conditions. Novel concepts for solar concentrators were proposed as well, which can involve the use of special coatings, nanocrystals, graphene and other materials, including filling with water. Further research is needed in order to overcome problems of CPV systems such as sensitivity to high temperature and ultraviolet radiation, and to improve concentrators' optical tolerance. New designs, materials and surface structures could be developed and even be influenced by biomimicry (Shanks et al., 2016).

Hence, there is room for exploration in the field of low-concentration photovoltaic systems for building integration, although what is to be studied, particularly at the material scale, may fall outside the architectural expertise.

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Fig. 33. *Variations of the Compound Parabolic Concentrator* (2016)

New concepts for low-concentration devices may lead to envisioning their possible applications in architecture. For instance, the development of a dielectric based device shows promise for the building integration of solar concentrators (Baig et al., 2014) which could be part of semi-transparent architectural skins (see fig. 34.). Research was conducted on highly reflective butterfly wings in relation to V-trough concentrators (Shanks et al., 2015), demonstrating how new ideas can be inspired by biomimicry. Optical devices can also be 3D-printed for external light trapping applications with thin-film solar cells (Van Dijk et al., 2015), which allows the creation of very small concentrators (see fig. 35.) that may compose textured, reflective architectural surfaces. Overall, the variety of design possibilities for low concentration devices seems to suggest it is worth exploring the potential for their deployment on building envelopes which by interacting with sunlight may produce visually engaging effects.

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Fig. 34. *Dielectric Based Three-Dimensional Cross Compound Parabolic Concentrator* (2014)

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Fig. 35. *3D-Printed Concentrators for External Light Trapping* (2015)

Low concentration systems which seem to be promising for building integration include devices that are either still in development or uncommon, such as luminescent concentrators, quantum dot concentrators and holographic concentrators. Luminescent concentrators (see fig. 36.) contain dye molecules which absorb solar radiation and emit light of a longer wavelength, mostly directed through total internal reflection towards the edges of the optical device where the photovoltaic cells are placed. Quantum dot concentrators present crystalline semiconductors, which can be tuned to absorb light of specific wavelengths, in place of the luminescent dye. Holographic concentrators (see fig. 37.) are static, planar devices with integrated holograms that direct sunlight onto solar cells, which can be suitable for integration into glazed parts of the building envelope (Chemisana, 2011:608-609).

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Fig. 36. *Luminescent Solar Concentrators*

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Fig. 37. *Holographic Solar Concentrator*

3.4.7 Spectral Conversion

Like luminescent concentrators, some light filters use photoluminescence to improve the efficiency of PV modules, in a method indicated as ‘spectral conversion’ which consists in adding a coloured photoluminescent film to PV surfaces. The filter absorbs photons which the PV material cannot utilise effectively and re-emits them in a useful wavelength. This enables the PV material to absorb the portion of the solar spectrum it performs best with. For instance, the preferred ‘spectral window’ for silicon is in the visible or near infrared region, while for third generation devices including perovskite-based solar cells it can be adjusted to some degree through the choice of the photoluminescent dye. The method may be used to increase the efficiency of PV module in densely built areas with reduced insolation (McKenna & Evans, 2017:1–2).

Besides increasing solar cell’s efficiency, the luminescent filter could serve as an encapsulant while transforming the appearance of PV modules, for instance by

giving them a red colour (Hardy et al., 2013). By improving solar cells' absorption of solar radiation in useful wavelengths, the coloured filter may reflect other portions of the spectrum. This way radiation in the infrared range, which would cause the PV modules to overheat, may be avoided. Thus, spectral conversion can be considered as a potential strategy to improve both the energy output and the visual design of photovoltaic building skins.

3.5 Conclusions

This chapter showed, in its second section, that the energy performance of buildings can be improved thanks to different active solar technologies, including photovoltaic and solar thermal systems. Among them, photovoltaics (PVs), especially as thin films, can offer greater potential for deployment in architectural skin designs displaying visually engaging qualities of motion, form, colour, patterns or figures according to findings on visual perception from the previous chapter. With possible variations, for instance, in colour and transparency, PV products are becoming more versatile thanks to promising emerging technologies, such as perovskite solar cells.

As emerged from the third section, designing solar architectural skins involves challenges posed by the design context, including characteristics of the building, its surroundings and regulations, and by constraints of solar technologies, which complicate the early creative stages. Yet, solar envelopes can improve buildings' energy performance, and being characterised by modular configurations like media facades, they may be designed similarly to display visually engaging features as emerged in Chapter 2. Previous studies proposed design criteria which examined integrability and aesthetic issues of deploying solar technologies on building envelopes, distinguishing aspects related to form and function. While considering certain visual design features, such studies did not encompass emerging technologies or address the design of solar building skins specifically for visual engagement as understood through Section 2.3 and Section 2.4. They did not contemplate possibilities for producing the impression of motion through solar building skins without moving parts. Visual aspects of solar architectural products were addressed with an emphasis on colour, and with some degree of shape and pattern customisation. Suggestions of possible developments for more interesting solar skin designs, including media facades, left room for further exploration.

The fourth section showed there is a trade-off between increasing the energy output of solar envelopes and improving their appearance, for instance, with modules characterised by coloured absorbers, semi-transparency or electrically operated

lighting. Performance losses can be reduced through considerate architectural design which minimises energy use and maximises solar energy capture and conversion with optimised geometries to avoid shading and soiling on photovoltaic components, as well as their overheating. There are strategies for increasing the energy output of solar envelopes which may also enable the display of visually engaging features, as understood from the study of visual perception, and involve technologies that are still in development. They include using high-efficiency PVs, although unsuitable for large-scale deployment, and three-dimensional or bifacial configurations. They encompass active or passive cooling methods, such as hybrid PV/T systems, natural ventilation, spectral beam splitting with dichroic components and other emerging techniques. Solar concentration technologies may enhance the performance of solar skins by increasing energy capture and reducing costs, while also displaying visually dynamic effects, similarly to what was suggested in Section 2.4.4.2, thanks to optical devices. These can present different shapes and visual properties, including reflectivity, refractivity or luminescence, and currently appear more suitable for building integration when they are static and characterised by low-concentration factors. Photoluminescent films for spectral conversion, associated with PV modules, may also improve their performance while adding colour to them and potentially serving as encapsulants.

The above findings, summarised in the table below (see fig. 38.), suggest the need for research on how to facilitate the design of solar building envelopes for visual engagement, in relation to the study of visual perception and media facades. This is particularly relevant to early design stages and can involve deploying enhanced PV technologies on building skins to convey a sense of motion through static configurations, which this research intends to explore further.

Solar Technologies for Architectural Skins	<ul style="list-style-type: none"> • Among active solar technologies (photovoltaic and solar thermal systems), greater potential of photovoltaics, particularly thin films, for architectural skin designs displaying visually engaging features (as from the study of visual perception in Section 2.3.2) • Existing variety of solar products for the building envelopes with possible visual variations, e.g., in colour and transparency
Design of Solar Architectural Skins	<ul style="list-style-type: none"> • Complexity of early architectural design due to design context and technology constraints, such as factors impacting energy generation • Potential for improving buildings' energy performance and for displaying visually engaging features (as from the study of visual perception in Section 2.3.2) through modular configurations (similarly to media facades, as from Section 2.4) • Previously proposed design criteria addressing integrability and aesthetic issues with aspects of form and function, but not addressing specifically design for visual engagement (as understood from the study of visual perception in Section 2.3 and of media facades in Section 2.4), producing motion impressions through static configurations or emerging technologies • Visual aspects addressed with an emphasis on colour and possibilities for customised shapes and patterns • Potential for developments towards more visually articulate solar skins
Enhancing the Performance of Solar Architectural Skins	<ul style="list-style-type: none"> • Necessary trade-off between optimising appearance and energy output of solar skins • Energy loss reduction through considerate architectural design (e.g., for energy efficiency, optimising geometry and preventing the overheating of PV modules) • Potential PV performance enhancement and visually engaging effects (as from the study of visual perception in Section 2.3.2) with: <ul style="list-style-type: none"> - high-efficiency PV absorbers (not for large-scale deployment) - three-dimensional or bifacial configurations - active or passive cooling, e.g., PV/T systems, natural ventilation, spectral beam splitting and emerging techniques - concentrating technologies for building integration (more suitably of low concentration factor, without sun-tracking) with visual effects, e.g., with reflections, refractions or luminescence (similarly to suggestions from Section 2.4.4.2) - coloured photoluminescent films serving as spectral converters and encapsulants

Fig. 38. *Key Findings of the Literature Review on Solar Architectural Skins* (2019)

Chapter 4: Research Methodology

4.1 Chapter Overview

This chapter presents the methodology adopted in the present research and how it was formulated.

In the second section, it first introduces the topic of research in the inherently multidisciplinary field of architecture, starting from the relationship between research and design practice. It illustrates briefly the different paradigms and the types of investigation at a strategic level, as well as the corresponding tactics, that characterise architectural research.

The third section presents the exploratory nature of the present research with its specific aims, target audience, expected impact and research questions. It describes how the idea first originated and how it matured throughout the literature review phase of the project, informing the choice of a combined strategy.

The fourth section illustrates and justifies the chosen methodology integrating secondary research of qualitative type with primary, practice-based research. It also explains the rejection of alternative research designs.

Lastly, the fifth section draws the conclusions of the chapter, summarising the choices of specific research strategies and methods.

4.2 The Context of Architectural Research

4.2.1 Understanding Research in the Field of Architectural Design

Research in architecture, beyond the applicability to specific building projects, started to be conducted relatively recently, leading back to the second half of the twentieth century only (Groat & Wang, 2013:7), whereas in Britain the nature of research related to design disciplines began to be questioned in the early 1990s (Biggs & Büchler, 2008:84). A generally accepted definition indicates that research is a 'systematic inquiry directed toward the creation of knowledge' (Snyder 1984, cited in Groat & Wang, 2013:8). What appears to distinguish research is therefore the 'systematic' and 'methodical' character of the investigation, as well as the contribution to the increase of knowledge (Amaratunga et al., 2002:18).

Groat & Wang (2013) summarised the debate on what constitutes research in design, highlighting that while research is 'conceptually systematic' and produces 'generalizable' knowledge, design proposes artefacts making 'episodic uses of

research' (Groat & Wang, 2013:26-57). Forsyth & Crewe (2006) also recapped the distinctive features of research. They stressed its ability to answer questions with relatively general interest by systematically collecting, analysing and reporting evidence through methods that are transparently described and assessed for the process to be replicable, whilst building on previous work (Forsyth & Crewe, 2006:164). With reference to 'practice-based' projects, it was argued that even this type of investigation should follow 'conventional research criteria' (Biggs & Büchler, 2008:86). Nonetheless, according to Friedman (2008) sometimes designers erroneously present practice as research instead of constructing theory from it by making 'tacit knowledge' explicit (Friedman, 2008:154). A distinction was proposed between 'basic' and 'applied' research, the former of which aims at developing broad theories about design, while the latter investigates less general design problems which are still less specific than those examined as individual cases through 'clinical research' (Frankel & Racine, 2010).

Frayling (1993) proposed a classification of design-related research into three categories that he named research 'into', 'through' and 'for' design respectively. In his view, research 'into' design represents 'straightforward' types of investigations on subjects that encompass particularly the humanities and the social sciences, focusing, for instance, on historical and aesthetic aspects. In research 'through' design the creative process itself is seen capable of generating new knowledge, such as exploration involving the manipulation of materials. Research 'for' design represents the thinking that ends up 'embodied' in an artefact, such as investigations on technologies and materials that foster the design process (Frayling, 1993). Nonetheless, Friedman (2008) criticised Frayling's model, pointing at the confusion generated around the role of practice in design-related research (Friedman, 2008:155-156), and by contrast he encouraged the creation of theory-based knowledge in support to designers (Friedman, 2008:158).

4.2.2 Research Paradigms

Some major distinctions in research are made at the level of paradigms. Guba & Lincoln (1994) briefly defined a research paradigm as a 'basic belief system' or 'worldview' guiding the researcher (Guba & Lincoln, 1994:105). Paradigms framing research differ from each other in the perspective on the 'nature of reality' and the way it is possible to learn about it (Groat & Wang, 2013:63). Thus, they diverge in an ontological and an epistemological way, given that, according to *The Cambridge Dictionary of Philosophy*, 'ontology', as a synonym of 'metaphysics', is 'the

philosophical investigation of the nature, constitution, and structure of reality' (Audi, 1995b) and 'epistemology' is 'the study of the nature of knowledge and justification' (Audi, 1995a). The intrinsic multidisciplinary of architecture and design in general suggests the insufficiency of a single paradigm to address research in these fields (Groat & Wang, 2013:27). Such multidisciplinary characterising architecture was already recognised by Vitruvius, who wrote: 'The architect should be equipped with knowledge of many branches of study and varied kinds of learning, for it is by his judgement that all work done by other arts is put to test' (Pollio et al., 1914:5). Chynoweth (2009) proposed the use of the term 'interdisciplinary' rather than 'multidisciplinary' regarding the study of the built environment, emphasising the necessity to integrate different disciplines (Chynoweth, 2009).

Groat & Wang (2013) reviewed several of the research methodology frameworks developed by scholars from different disciplines, considering the various branches of knowledge characterising architecture. Besides the distinction between 'quantitative' research seeking causal links through deductive reasoning and 'qualitative' research exploring phenomena holistically through induction, and the corresponding contraposition of *hard* and *soft* sciences, Groat & Wang (2013) presented other theoretical models. They condensed them into a paradigmatic framework conceived as a three-part continuum gravitating between the two poles of 'positivism/postpositivism' and 'constructivism', with a middle ground paradigm identified as 'intersubjective' (Groat & Wang, 2013:76-79).

The positivist/postpositivist approach aims at investigating reality objectively, although in the postpositivist view it is accepted that perfect objectivity may not be achieved and that adaptations may be necessary in studies involving people. This paradigm is thus characterised by the ontological assumption of reality as objective and by the epistemological perspective of a researcher distanced from the phenomena investigated, for which it is believed causal factors can be identified (Guba & Lincoln, 1994:109-110). According to Groat & Wang (2013), the positivist/postpositivist paradigm is typical of technical research in architecture, such as explorations regarding energy or structural issues, based on objectively measurable characteristics, although research on these topics can also assume a non-positivist perspective (Groat & Wang, 2013:76-78).

The constructivist approach is characterised by the ontological assumption that there are multiple or even infinite realities which are socially constructed, while the epistemological position is that knowledge is created by researchers and

participants as the investigation is carried out (Guba & Lincoln, 1994:110-111). Alternatively identified as 'naturalistic', this paradigm is suitable, for instance, for research on the subjective, human experience of environments (Groat & Wang, 2013:78-79). Mediating the two extremes of positivism/postpositivism and constructivism, the 'intersubjective' paradigm ontologically assumes the existence of multiple realities and yet presumes epistemologically the possibility of achieving a collective understanding of such realities. It was suggested that this paradigm can characterise, for instance, investigations regarding the interpretation of meanings within specific social and historical contexts (Groat & Wang, 2013:78).

The diverging perspectives distinguishing the positivist/postpositivist and naturalistic approaches determine differences in the way the quality of research is achieved and assessed. The trustworthiness of studies in the positivist/postpositivist paradigm is attained by demonstrating the correctness of the information used, the generalisability of the conclusions, the stability of the results produced, and the transparency and replicability of the impartially applied procedures, which means meeting the 'internal validity', 'external validity', 'reliability' and 'objectivity' criteria respectively. Studies in the constructivist or naturalistic paradigm are instead expected to prove 'credibility' by using interviewees' feedback and triangulation of data from multiple sources, as well as 'transferability' by providing thorough contextual descriptions. They need to show 'dependability' by clarifying in detail the methodology employed, and 'confirmability' by practicing triangulation and openly declaring the perspective adopted (Guba 1981, cited in Groat and Wang, 2013:80-86).

4.2.3 Research Strategies

Research is often identified as either qualitative or quantitative. The former uses words and observations to describe phenomena related to people in their natural settings, whereas the latter greatly relies on numbers and thus focuses on quantifiable entities (Amaratunga et al., 2002:19). While such distinction was used to indicate different strategic approaches to research (Creswell, 2009:12), it was pointed out that given the multiplicity of disciplines involved in architectural research, the distinction between quantitative and qualitative approaches is oversimplified and more appropriate to describe research at the level of 'tactics' rather than broader strategies (Groat & Wang, 2013:23). This view seems supported also by Guba & Lincoln (1994) who highlighted that both quantitative and qualitative methods may be used with different research paradigms (Guba & Lincoln, 1994:105).

Groat & Wang (2013) tried to overcome the reductive dichotomy of quantitative and qualitative research that focuses on the 'tactics' (Groat & Wang, 2013:71). Their methodological framework for architectural research has been influential, as authors of studies on architecture-related research have widely referred to their model. Building on work by Groat and Wang, Forsyth & Crewe (2006) proposed a classification of environmental research into five 'major forms': 'standard empirical studies', based on data collection and analysis; 'logical argumentation', using theoretical reasoning; 'critical analysis', combining the previous two; 'synthesis', developing conceptual systems by summarising, analysing and categorising findings; and 'creative work', producing artefacts while conforming to the criteria of research (Forsyth & Crewe, 2006:161-169). In their study reviewing and comparing research strategies for the evaluation of architectural designs, Han & Moon (2010) also referred to the model by Groat and Wang (Han & Moon, 2010). In *Architectural Research Methods*, Groat and Wang summarised the literature contributing to the development of architectural research approaches, identifying seven research 'strategies' (Groat & Wang, 2013). The framework they provided served as guidance for the design of the research methodology in the present project.

Among the research designs or strategies proposed by Groat & Wang (2013), 'historical research' involves examining evidence of past events. 'Qualitative research' explores phenomena with a naturalistic approach in their real settings, focusing on meanings attributed by people, through inductive reasoning and multiple tactics appropriate to the context under study as well as to the research question. 'Correlational research' employs statistics to investigate patterns of relationships between variables in real-world situations, using a variety of methods which include survey questionnaires and observations among others, whilst in 'experimental' and 'quasi-experimental research', characterised by random and non-random assignment respectively, causal links are examined by controlling and manipulating variables through a 'treatment' producing measurable outcomes. Frequently used in support of or in combination with other strategies, 'simulation research' employs representation techniques that can be computer-based or not, including photographs and full-scale mock-ups. Instead, 'logical argumentation' builds theories or 'logical frameworks' from fundamental assumptions, proposing conceptual systems based on categories through various tactics such as 'naming', 'analogy' or 'association' and 'dissociation' among others. 'Case studies' are empirical inquiries that examine phenomena or settings using multiple sources of

information to explain causal relationships and develop theories. Combined strategies are recognised by the authors to have great potential in architectural research given the multiplicity of the disciplines involved (Groat & Wang, 2013).

A combined strategy or 'mixed-methods' approach is believed to reduce the weaknesses and to increase the benefits of individual tactics (Amaratunga et al., 2002; Abowitz & Toole, 2010; Groat & Wang, 2013:441), and constitutes a form of 'triangulation' (Abowitz & Toole, 2010), using different types of sources to corroborate information (Yin, 2011:81). As highlighted by Groat & Wang (2013), the selection of appropriate strategies and methods depends on the nature of the research questions (Groat & Wang, 2013:168) which emerge from the review of the literature in the area of interest (Groat & Wang, 2013:145). The next section therefore describes the rise of the research questions in the present project and the subsequent choice of a suitable research approach.

4.3 Research Methodology

4.3.1 Identifying the Subject Under Study

The previous section of this chapter introduced the approaches of architectural research to be selected depending on the research questions asked. In other words, the choice of a research design is determined by the problem raised, and the correspondence between the research questions, purposes and methods affects the coherence of a study (Creswell, 2007:42). The purposes of an investigation include the 'motivation', the 'audience' and the expected 'impact' of the research, as well as the aim to create or expand theory, or to apply it to design (Groat & Wang, 2013:138). Thus, this section illustrates the emergence of the research problem central to the current study, presenting the choice of an appropriate research design.

The idea for this project originated from previous academic work conducted by the author as well as from her professional experience in the field of media art and architecture. Her interest in both the potential of media architecture for improving the quality of urban spaces and in renewable energy technologies developed while she was working on her Master's Thesis. This investigated the available technologies for media facades operated without electric power or alternatively using or supplying energy produced from renewable resources (Nicoletti, 2011). In her professional practice, the researcher created *Dancing Screen* (see fig. 24.) a kinetic art installation representing a prototype of an architectural screen activated by the wind, featuring integrated thin-film solar panels (Nicoletti, 2017). That

experience helped her understand the problems involved in the design of architectural skins embedding solar technologies. It showed the complexity of composing efficient solar arrays capable of captivating the interest of passers-by like media facades do using dynamic visual effects, as presented in Chapter 2. This motivated the researcher to explore the issue further through professional training in solar technologies. It led to the research proposal for this project, propelled by the author's aspiration to investigate possible ways of combining high efficiency in energy collection and usage with the pursuit of visual engagement in the design of solar architectural skins.

As emerged from the literature review, the efficiency of energy generation in building-integrated solar technologies is challenged by other desired features of architectural skins, such as compactness and ease of maintenance, for which sacrificing the output efficiency of solar installations to a certain extent seems reasonable. The literature review also revealed an abundance of relatively efficient solar technologies that are partly still in development, for application within the building envelope, which manifest potential for deployment in novel concepts for solar facades. Therefore, the subject under study was refined as the design of solar architectural skins that can produce visual engagement by deploying solar technologies in effective ways.

4.3.2 Identifying the Research Questions

Given the interdisciplinarity of the subject, finding its foundations in the seemingly distant fields of vision science, media architecture and solar energy technologies, the primary aim of the present project was identified as the development of a framework connecting different disciplines to facilitate the design of effective solar architectural skins that are capable of triggering visual engagement. Architecture practitioners and researchers, as well as students, are expected to be the main audience of the present study, since they may find in the constructed framework a guide to the design of novel concepts for solar architectural skins and directions for further exploration. The impact of this project is therefore foreseen as an influence on future architectural research and designs, through the creation of theory that builds on existing knowledge in different fields.

The research questions that emerged for this project from the literature review, which determined the choice of research strategies and methods, are the following.

1. How can architectural skins produce visual engagement with minimal energy use?
2. How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?
3. How can novel concepts of effective solar architectural skins be designed to produce visual engagement?

It can be noticed that the three research questions ask *how* certain effects *can* be obtained through the design of architectural skins: *how* to produce visual engagement with minimal energy use (unlike power-intensive media facades), *how* solar technologies deployed effectively on building skins can trigger visual engagement, and *how* novel concepts for effective and visually engaging solar architectural skins *can* be designed. Aiming to explain *how* solar technologies *can* be applied to architectural skins successfully to produce visual engagement and *how* this *can* be pursued through design, the present study seems to ascribe to Frayling's category of research 'for' design (Frayling, 1993:5). However, rather than embedding theory into an artefact, this research aimed to make explicit a conceptual framework with potential for application to multiple future designs, through the exploration of technologies and compositional principles for solar architectural skins.

The three '*how can*' questions reveal that the research sought possibilities more than mere explanations to the investigated phenomena, therefore the aim of the research was eminently exploratory. Rather than a conclusive, explanatory theory, the outcome of the research was thus expected to be open-ended, suggesting directions for future research and ideas for design work.

4.3.3 The Choice of a Combined Research Strategy

Since the overall research design is informed by the ultimate purpose of an investigation (Groat & Wang, 2013:138), adopting in this project the strategy of logical argumentation aimed at framing theories could appear a reasonable choice. Nonetheless, theories can also be created through qualitative research (Merriam, 2002:5), and logical argumentation is often implicit in other research designs. Moreover, logical argumentation, which demands verification of the created conceptual model, builds theory from 'first principles' or 'fundamental assumptions' (Groat & Wang, 2013:379-410), requiring a theoretical knowledge base to start with (Han & Moon, 2010:47). Along with the multiplicity of the disciplines involved, the aim of the present research to create a valid theoretical model suggested the need to adopt a combined strategy with diverse methods.

The 'mixed methods' approach has been interpreted in different ways. Creswell (2009) defined it as a combination of qualitative and quantitative research (Creswell, 2009:203), while Greene (2008) proposed that the mixed methods approach constitutes a standalone methodology referring to multiple research paradigms (Greene, 2008), and other authors recognised it as a paradigm itself (Johnson & Onwuegbuzie, 2004). In line with Groat and Wang's framework, created specifically for architectural research, the mixed methods approach was interpreted in this project as a strategy or research design (Groat & Wang, 2013:443) and it was adopted to integrate different strategies, enhancing their strengths.

The interdisciplinary field in which this research is rooted and the exploratory aim to translate a broad knowledge base into a valid design framework implied the study needed to be undertaken with a holistic approach. Therefore, the present study adopted a combined strategy with a predominantly naturalistic paradigmatic stance which, as previously mentioned, ontologically accepts multiple realities and epistemologically presumes the researcher's active role in knowledge creation. The combined strategy integrated secondary and primary, practice-based research, as explained in detail in the next section.

4.4 Selection of Research Strategies and Methods

4.4.1 Overview of the Chosen Research Methodology

The aims of the investigation and the research questions have been presented, and the reasons for the choice of a mixed-methods approach have been explained, whereas the selection of research strategies among those introduced previously has yet to be clarified and justified. It was highlighted in the previous section that this research is exploratory and interdisciplinary, and that it aims to propose a framework directed at design. It focuses on the design of solar architectural skins for visual engagement, thus while considering energy aspects that are integral to the study of solar technologies, it has an emphasis on qualitative aspects. In light of the above considerations, the researcher found that the most suitable combination of strategies to conduct this investigation involved exploratory secondary research of qualitative type, complemented by primary, practice-based research. A broad knowledge base was created through a qualitative review of literature underpinned with case studies, or empirical examples, based on secondary sources. This allowed potential links between concepts to emerge so that an initial conceptual framework could be outlined for the design of effective solar architectural skins capable of producing visual engagement. The suggested model was tested through its

application to early design, which integrated primary simulation and experimental research and could contribute to the refinement of the design framework itself. The strategies involved in the adopted mixed-methods approach are explained in detail in the following subsections.

4.4.2 Secondary Research: Literature Review and Case Studies

As previously mentioned, the ambition of the present exploratory research is to propose a framework for the design of effective solar architectural skins that are capable of triggering visual engagement. This was defined as the attraction of people's attention and interest in Section 2.3 where it also emerged that visual engagement may be stimulated by salient qualities of motion, colour and form, including patterns and figures. While energy aspects that are inherent in the study of solar building envelopes were considered, the focus on visual engagement as well as the interdisciplinarity of the present research suggested the possibility of undertaking it with a qualitative type of strategy.

The subject explored, the active role played by the researcher and the need for a broad knowledge base suggested that the study could use qualitative research. This is characterised by an interpretative, naturalistic approach, emphasises qualitative aspects and employs a variety of methods for retrieving empirical data, which can be field-based and include the analysis of texts as well as case studies (Denzin & Lincoln, 2008). Typically used in social sciences, qualitative research is rooted in the belief that 'meaning is socially constructed by individuals in interaction with their world' (Merriam, 2002:3). Distinctive traits of qualitative research are its focus on meanings, the explanatory contribution of its outcomes, the importance of people's perspectives, the relevance of real settings or contexts, and the use of multiple data sources. These often translate into adopting a 'flexible' methodology, employing 'field-based' research methods, examining non-quantitative data or interpreting findings from other qualitative research in potentially new ways (Yin, 2011:7-10). Four 'basic types' of data can be identified, namely 'interviews, observations, documents, and audio-visual materials', and the thorough retrieval of information from varied sources constitutes the 'backbone' of qualitative research (Creswell, 2007:43). The qualitative research process can be seen as cyclic and composed of five phases: 'compiling' notes, 'disassembling' and then 'reassembling' contents into different groups and series, 'interpreting' the reassembled data and 'concluding' (Yin, 2011:177-179). Resulting from inductive reasoning and 'intuitive understandings', the outcome of qualitative research is 'richly descriptive', uses

written as well as visual materials, and may present the findings in conceptualised forms that can include, for instance, categories, hypotheses and theories (Merriam, 2002:5). Qualitative research can also take different specific forms which include 'grounded theory', case studies and several others. For instance, the 'grounded theory' approach constructs a theory which emerges from the data, while the 'case study' approach examines a particular phenomenon (Merriam, 2002:6-10; Yin, 2011:17).

Case study research 'stands apart' and lends itself to integration with other types of inquiry (Merriam, 2002:8), as it is distinguished by the 'interest in an individual case' rather than by the methods employed (Stake, 2005:443). The definition provided by Yin (2009) was adapted to the context of architectural research by describing a case study as 'an empirical inquiry that investigates a phenomenon or setting' (Groat & Wang, 2013:418). Aiming to understand particular phenomena in real-world conditions, unlike experiments that isolate them from their context, case study research is suitable for investigating intricate situations involving many variables. It uses triangulation relying on multiple data sources and is facilitated by previously created theory guiding the collection and analysis of information. Moreover, it can focus on a single or on multiple case studies, and it has the ability to 'explain' causal relationships, as well as to 'describe', to 'illustrate' or to 'enlighten' situations involving some level of complexity, producing generalisations (Yin, 2009:18-20). It was highlighted that case studies are particularly relevant in the 'practice-oriented' field of architectural research (Johansson, 2003:4). Literature reviewed in this project showed that case study research, as a way of learning from precedents within the practice of design, was used in other studies on the design of architectural skins. For instance, cases of environment-responsive and media facades were examined so that their 'common ground' could be identified in the design of kinetics (Moloney, 2006), while the integration of shape-changing materials into building skins was studied through a discussion of adaptive façade precedents (Decker & Zarzycki, 2014).

While qualitative research often relies on field-based methods and therefore on primary sources of information, in this project the researcher used qualitative research of secondary type. First of all, the context for the research needed to be understood, thus the starting point for the creation of the necessary knowledge base was undertaking a literature review. This revealed the wealth of knowledge already available in the seemingly disparate fields investigated, from the study of vision to

media architecture and solar technologies for architectural integration. Concepts which emerged from the literature review, such as building skin features which have potential for stimulating visual engagement and for improving the performance of solar technologies, suggested the need to research empirical examples of architectural skins with those characteristics. Therefore, the literature review was underpinned by case studies based on secondary sources. As further explained in Section 4.4.4, the choice of examining case studies as secondary research was largely determined by the challenges of conducting qualitative research in real urban settings and by the time and resource constraints of this PhD project. The combined findings of the literature review and case study research led to outlining an initial framework for designing effective solar architectural skins with potential for stimulating visual engagement.

Reviewing the existing literature on a topic is essential for the researcher to gain an understanding of the subject investigated, from the main issues involved to the research carried out already and the approaches used before. To be high-quality, a literature review must be accurate, rigorous, consistent and analytical but also concise (Hart, 1998:1). It has to be conducted critically (Hart, 1998:9) and allow for the research subject to be gradually narrowed (Hart, 1998:13). The literature review 'should be *concise, clear, critical, convincing and contributive*' (Callahan, 2014:272), although it is inevitably influenced by the researcher's particular point of view (Hart, 1998:25). It was suggested that the grounded theory approach may offer a suitable method for undertaking a literature review which relies on selected academic publications as sources of information (Wolfswinkel et al., 2011). Hence, a qualitative research strategy based on secondary sources appeared appropriate for creating the knowledge base needed in the early stages of this project.

In the present study, the literature review was carried out by selecting and examining the relevant academic articles, books and online publications in seemingly disconnected research fields of vision, media architecture, kinetic facades and solar energy technologies particularly for building integration. The contents which emerged from academic publications were complemented and illustrated with references to other relevant sources. These included European Directives addressing energy issues in buildings, and web sources exemplifying some of the technologies and applications identified, such as webpages about solar products or architectural projects. Prioritising the search for publications which provided broader explanations, such as up-to-date reviews on state-of-the-art solar technologies,

revealed the abundance of knowledge already created in the different research areas investigated. The literature review also helped the researcher exclude approaches that were applied in previous research and could produce redundant work. For instance, the research carried out within the International Energy Agency's project '*IEA SHC Task 41: Solar Energy and Architecture*' utilised surveys to investigate architects' positions towards the integration of solar technologies in their designs and the existing barriers to this practice (Farkas & Horvat, 2012). Moreover, as presented in Chapter 3, the architectural integration of solar technologies has been investigated from an aesthetics point of view, leading to the creation of frameworks identifying 'formal' aspects as opposed to 'functional' and 'constructive' aspects (Farkas, 2013; Munari Probst & Roecker, 2013). The literature review conducted in this study revealed there may be potential for a different approach applying principles of media architecture and vision research to designing static solar architectural skins which can stimulate visual engagement by conveying a sense of motion.

The literature review was followed by the selection and analysis of fifteen case studies based on secondary sources. The cases were chosen among designs of static architectural skins for their unique characteristics with which they produce the impression of motion and show potential for the integration of solar technologies, according to the findings of the literature review. The information on the case studies, analysed in a descriptive and exploratory way from a compositional and technology perspective, also with reference to reviewed literature, was obtained from multiple sources. These included textual descriptions and images found in designers' and artists' websites as well as in online magazines and books, so that the researcher could corroborate data as much as possible.

The quality of the secondary research in the present study was ensured in multiple ways. To establish the trustworthiness of qualitative research, scholars established a number of strategies. These include, among others, retrieving abundant data, considering antagonist explanations and using 'triangulation' to corroborate data (Maxwell 2009, cited in Yin, 2011:79). Among similar strategies in case study research, there are using correct, unbiased, transparent and replicable procedures as well as clarifying the study's limits of generalisability (Yin, 2009:40-45). A strategy for ensuring the validity of qualitative research is triangulating information (Yin, 2011:81), which also applies to case study research (Baxter & Jack, 2008:556; Yin, 2009:18). Therefore, in the present study abundant information was collected largely

from reliable scholarly sources such as academic journals, conference proceedings, reports by reputable institutions and European directives. Throughout the study, the researcher tried to maintain an open attitude and an unbiased perspective considering contrasting views expressed in previous works. She also acknowledged limits of generalisability of the design framework proposed thanks to qualitative research, considering that it may not be applicable, for instance, to buildings in areas of historical interest. Moreover, the research relied on multiple data sources in a triangulating manner, referring to academic publications, online magazines and websites of artists and architects, including both texts and visual evidence. It also used a mixed-methods approach, since the framework resulting from the secondary research, including literature review and case studies, was tested through primary, practice-based research, as explained in the next section. Hence, this study began with strong secondary research of qualitative type, which supported the project throughout its different stages, including the definition of its methodology and the practice-based design phase.

4.4.3 Primary, Practice-Based Research: Simulation and Experimental Strategies

Since this project aimed to propose a framework for designing effective solar architectural skins that are capable of stimulating visual engagement, the most obvious way of testing the approach outlined as a result of the secondary research was its application to design. Hence, the findings of the secondary research served as the starting point for the primary, practice-based research carried out in this project in the form of a design example which is presented in detail through Chapter 7 and Chapter 8. The researcher tested the framework in the earliest stage only of designing a solar architectural skin. This choice was determined by the time and resource constraints of the PhD project. It was also motivated by the study's main focus on visual aspects, which are central to early design, and by the challenges for this creative stage that integrating photovoltaics into buildings involves, as emerged in Section 3.3. Testing the framework through design was directed at confirming or refuting the existence of a causal link between a visual composition created in line with the proposed approach and people's responses indicating visual engagement.

Exploring the causal relationship between a design based on the outlined framework and people's reactions suggested it was appropriate to adopt an experimental strategy. Experiments offer a highly suitable approach to investigating causal links, since they allow control over the causes so that subsequent changes in the effects

can be observed and alternative possible reasons can be excluded or considered (Shadish et al., 2002:6-7). Whether in the form of a lab or field study about aspects that can range from physical to behavioural characteristics, experimental research selectively manipulates variables in a controlled environment without the complexity of their real context (Groat & Wang, 2013:316-329). On the other hand, simulation research tries to reproduce the investigated conditions holistically and can be used for developing and testing theories, although sometimes the complexity of the real settings may not be adequately imitated (Groat & Wang, 2013:360-363). It is frequently used with other research strategies, including experiments and studies of people's responses to certain environments, and employs representation techniques that often involve computer programs but may also include other media (Groat & Wang, 2013:349-350). Allowing researchers to evaluate design proposals and to test theories by examining causal links in a controlled and replicable manner, simulation can improve the generalisability of experiments while reducing the risks and the expenses of assessments conducted in real-world settings (Han & Moon, 2010:48-49). Thus, in this PhD project, the researcher chose to combine simulation and experimental research to test in a controlled way the capacity of a newly conceived solar skin design for stimulating visual engagement within a reproduction of its real context.

As explained in detail in Chapter 7, the primary, practice-based research process started from the generation of a concept for a photovoltaic façade for an existing site. Following an understanding of the starting conditions for the design based on the review of secondary written sources as well as photographs and drawings of the context, a design for a solar architectural skin was conceived with the guidance of the framework outlined in Chapter 6 and through the iterative use of computer simulation techniques. These involved the interactive generation and modification of solar skin configurations, with climate-based tests and visualisations. They considered multiple factors affecting the appearance and the performance of solar envelopes, which emerged from the secondary research. The researcher used the parametric computer-aided design platform Grasshopper (Davidson, 2018) which is a visual programming language that allows the creation of custom algorithms, including various types of analysis and design optimisation, and it is operated in Rhinoceros (Sharaidin, 2014:X-XI). This is a 3D modelling software developed by Robert McNeel & Associates, that enables designers to generate mathematically accurate representations of complex objects (Robert McNeel & Associates, 2017).

To carry out climate-based simulations relevant to the performance of a solar skin, the researcher used the parametric tool Ladybug (Sadeghipour Roudsari & Pak, 2013; Ladybug Tools LLC, 2018) within Grasshopper. Furthermore, she employed the computer visualisation tool V-Ray for Rhino by Chaos Group (Chaos Software, 2018) to simulate through image and video rendering qualitative aspects of the design such as chromatic and lighting effects. Further information on the choice of methods is summarised in the table below (see fig. 39.).

PRIMARY RESEARCH, PART 1: GENERATION OF A SOLAR SKIN CONCEPT		
CHOSEN METHODS	CHOSEN TOOLS	REASONS FOR THE CHOICE
Parametric 3D Modelling	Grasshopper within Rhino	<ul style="list-style-type: none"> • The researcher was familiar with the methods and tools. • There was a need for an interactive modelling tool allowing the creation of geometries in response to various input variables, which Grasshopper is capable of (Sharaidin, 2014:108). • The use of Grasshopper was exemplified by several of the studies reviewed within the secondary research, such as Khoo & Salim (2012), Pesenti, Masera & Fiorito (2015), Pesenti et al. (2015) and Sharaidin (2014). • In the development of an adaptive, photovoltaic façade system, Nagy et al. (2016) also employed Rhino and Grasshopper to simulate shading on solar modules depending on the direction of sunlight rays (Nagy et al., 2016).
Climate-Based Simulations	Ladybug within Grasshopper	<ul style="list-style-type: none"> • There was a need to consider climate-based aspects affecting the energy output generated by solar architectural skins.
Visualisations	V-Ray for Rhino	<ul style="list-style-type: none"> • The researcher was familiar with the methods and tools. • There was a need to test through rendering qualitative visual aspects of the design. • V-Ray enables the creation of photorealistic visualisations and can be operated within Rhinoceros (Chaos Software, 2018)

Fig. 39. *Choice of Simulation Methods for the Generation of a Solar Skin Concept* (2019)

As presented thoroughly in Chapter 8, the capacity of the generated solar skin concept for stimulating visual engagement was then evaluated through a participatory experiment using virtual reality (VR), which was conducted at the Epsom Campus of the University for the Creative Arts over the course of two days. For this purpose, the researcher produced a non-interactive virtual experience through visualisation work for VR using V-Ray for Rhino. The simulation imitated the

experience of the real urban setting chosen for the design and showed the newly conceived solar skin as well as the surrounding conventional-looking building fronts, in a controlled way which facilitated the analysis of participants' responses. After an informal trial was run with three volunteers to test the research methods of the experiment (see fig. 40.), this was conducted with a larger sample of participants (see fig. 41.). Following a briefing phase, participants experienced the simulation individually by wearing a headset, while their reactions were observed and recorded. Immediately after the simulation, each participant's feedback was collected in written form, which answered a single question on the virtual experience (see fig. 42.).

TESTING THE EXPERIMENT METHODS	
PARTICIPANTS	<p>Three volunteers recruited among friends</p> <ul style="list-style-type: none"> • Gender: two women; one man • Ages: 30, 36 and 45 • One with architectural design expertise; two without • All sighted, but one volunteer found out during the simulation they did not see well
METHODS	<p>The researcher repeated the experiment procedure with each volunteer separately at their home, by:</p> <ol style="list-style-type: none"> 1. briefing them; 2. letting them experience the virtual environment for one minute with the headset, while taking notes of the volunteer's head movements and of other reactions, e.g., exclamations; 3. immediately after the simulation, asking them a single question: 'Was there a building façade that you found more interesting than others, and if so, what did it look like?'
RESULTS	<p>Observations during the simulation</p> <ul style="list-style-type: none"> • Two volunteers turned their heads to the left, with exclamations of surprise. This potentially suggested they looked at the newly designed façade design. • One volunteer only looked all around, saying they could not see well. <p>Interviews</p> <ul style="list-style-type: none"> • The same volunteers who had turned their heads to the left said they noticed a façade with a decorative pattern. • The volunteer with architectural expertise showed a special interest in the new solar façade design. • The volunteer who did not see well responded they did not notice a façade in particular.
IMPLICATIONS	<p>From the trial, the researcher could learn the following.</p> <ul style="list-style-type: none"> • It was preferable to collect data in written form. • Notes on the observed reactions needed to be taken concisely, preferably using symbols. • Architectural expertise could cause bias to be avoided. • The experiment participants needed to be fully sighted.

Fig. 40. *Testing before the Experiment* (2019)

SAMPLE OF PARTICIPANTS	
SIZE	<p>15 participants</p> <p>This size was chosen with reference to the average sample sizes in lab studies for the evaluation of public displays (Alt et al., 2012:5).</p>
DEMOGRAPHICS	<p>Gender:</p> <ul style="list-style-type: none"> • 11 female participants • 4 male participants <p>Age:</p> <ul style="list-style-type: none"> • 7 participants in the age range 18-30 • 8 participants in the age range 31-65 <p>Occupation:</p> <ul style="list-style-type: none"> • 8 professionals • 7 students
RECRUITMENT	<p>Random recruitment, yet:</p> <ul style="list-style-type: none"> • on a voluntary basis; • within UCA Epsom Campus, to prevent bias due to architectural expertise (no courses in architectural design are taught in that campus); • restricted to sighted people without health issues that could make them susceptible to potential side effects of the simulation. <p>Recruitment methods:</p> <ul style="list-style-type: none"> • email invite sent in advance to students and staff at UCA Epsom Campus, with information about the study; • by approaching people directly in and near different locations within UCA Epsom Campus where the experiment was carried out (in a spare room, in the canteen and in the library). <p>Prevention of ethical issues</p> <ul style="list-style-type: none"> • Each participant was thoroughly briefed in advance about the characteristics of the experiment, about which they were provided a written document, yet without details of the location shown in the simulation or of the question to be asked at the end, which could have caused biased responses. A consent form was signed by participants before the start of the experiment, which also ensured the protection of participants' personal data. • Participants that were more susceptible to the potential side effects of the simulation were prevented from taking part in the experiment. • Participants were asked to notify the researcher immediately if they had felt any form of discomfort during the simulation, so that this could be stopped. • The simulation was designed to prevent side effects (e.g., thanks to its short duration and its predominantly static nature).

Fig. 41. *Sample of Participants* (2019)

PRIMARY RESEARCH, PART 2: EVALUATION OF VISUAL ENGAGEMENT		
METHODS	DETAILS	REASONS FOR THE CHOICES
Non-Interactive, Immersive VR Simulation	<p>Production of a one-minute long 360° video mimicking the static and dynamic visual experience of the urban site, using:</p> <ul style="list-style-type: none"> • Rhino and V-Ray for Rhino for modelling and visualising the virtual environment; • Adobe Premiere Pro for editing the video; • VRTV VR Video Player for displaying the video with a smartphone and a headset that was compatible with Google Cardboard 	<ul style="list-style-type: none"> • VR may aid the early stages of the architectural design process (Groat & Wang, 2013:351) serving as an innovative research tool. • Immersive VR imitates the experience of being inside the simulated environment (Groat & Wang, 2013:355). • Types of virtual reality simulation were previously employed in studies for the evaluation of architectural designs with people's involvement, such as Dijkstra et al. (2003) and Westerdahl et al. (2006). • The situations depicted in VR are plausible and can trigger realistic responses in people even though the simulation can be fully controlled for experimental purposes. Thus, VR integrates the validity and generalisability strengths of experimental research and of fieldwork (Rovira et al., 2009). • VR may be used in studies related to perception. Complex environments may be presented in a controlled way, triggering potentially close-to-realistic responses, although VR also has drawbacks. It may induce side effects such as motion sickness or psychological issues depending on the study (Wilson & Soranzo, 2015). • Limiting the duration of the VR experience and its dynamic content may prevent side effects. • Using non-interactive VR can be sufficient for studying the visual experience only and requires limited resources.
Observations	<ul style="list-style-type: none"> • After careful briefing with the signing of a consent form, observation of how each of the 15 participants reacted while they individually viewed the 360° video by wearing a headset • Concise notetaking of the observed responses during the VR simulation, including head movements and other reactions 	<ul style="list-style-type: none"> • Research on urban media, particularly on public displays, showed that their evaluation benefits from a combination of methods, particularly observations and subsequent interviews (Alt et al., 2012; Memarovic et al., 2012). • Qualitative and quantitative observations of head movements could give a potential indication of whether participants looked at the newly designed façade in the virtual environment. • Conducting observations during the simulation and before interviews could facilitate the naturalness of participants' responses. • Concise notetaking using symbols was needed to make the data collection process more efficient, which emerged from the informal trial run prior to the experiment.
Interviews	<p>Collection of each participant's feedback on the VR experience immediately after the simulation:</p> <ul style="list-style-type: none"> • in written form; • by asking each participant the same single, open-ended question: 'Was there a building façade that you found more interesting than others, and if so, what did it look like?' 	<ul style="list-style-type: none"> • Observing head movements gave an indication of their gaze direction, but as emerged in Section 2.3.2.1, gaze does not always reveal attention. Complementing observations with interviews could enable a better understanding of whether attention was paid to the newly designed façade. • Structured interviews in written form made data collection more efficient, as understood from the trial run before the experiment. • A single question was sufficient to obtain data on whether the newly designed solar façade had attracted attention or interest. • Unlike a closed-ended questionnaire, an open-ended question could prevent biased responses.

Fig. 42. *Choice of Methods for the Evaluation of Visual Engagement* (2019)

The validity of the primary research presented in this section was ensured through multiple strategies. The VR experience was designed to imitate the real urban setting in a controlled way and to facilitate the observation of participants' reactions. Data collection was conducted very carefully, and steps of the process were repeated when the outcome was invalid. The researcher maintained an unbiased view and prevented participants' bias through their recruitment (see fig. 41) as well as through choices concerning the data collection methods (see fig. 42.). She selected participants randomly, although some restrictions had to be applied (see fig. 41.). Using both observations and interviews for data collection could improve the reliability of the findings. Random sampling facilitates the generalisability of experimental research (Shadish et al., 2002:22). On the other hand, triangulating methods improves the validity of a study's outcome towards interpreting causal links (Abowitz & Toole, 2010). However, the validity of a study must be assessed in relation to the aims of the specific inquiry (Brewer, 2000:3). This research is open-ended and exploratory in nature, aiming to point at potential directions for future research and design work rather than to draw definitive or fully generalisable conclusions. Therefore, the above strategies were considered adequate for the purpose of the study and the primary research could contribute thanks to the inductive generalisation of its findings to the proposed framework for designing solar architectural skins.

4.4.4 Rejected Research Strategies and Methods

In choosing a research methodology for this project, the researcher rejected certain research strategies and methods which were found inappropriate in relation to the aims of the study. As this research explored the design of solar architectural skins deploying technologies that are still in development, it appeared clear that 'historical research', based on the interpretation of facts that occurred in the past (Groat & Wang, 2013:207), was not a suitable strategy for this project. 'Correlational research' which examines spontaneous relational patterns using statistical methods (Groat & Wang, 2013:269) was also rejected in this project. This decision was determined by the exploratory aim of this study which by seeking possibilities for the design of solar architectural skins valued empirical instances, such as the precedents of visually stimulating facades examined as part of the secondary research, for their uniqueness rather than for their contribution to relational patterns. For the same reason, the primary research could involve a relatively small sample of participants, because it explored just the possible causal link between a newly

conceived solar skin design and people's visual engagement, without investigating more complex patterns of correlations.

The relationship between architectural skins and people's visual engagement could have been explored potentially through primary qualitative research conducted in real urban settings. Studies in the field of media architecture showed that the evaluation of how people respond to certain interactive installations in the public realm is conducted especially through observations of passers-by's reactions to physical prototypes located in real settings, and through field interviews (Memarovic et al., 2012; Lin et al., 2015:331). Studying the capacity of public displays for engaging passers-by can involve methods such as observations and interviews or questionnaires in field- or lab-based studies (Alt et al., 2012). Either by directly investigating people's responses to existing architectural skins in their real environment or by installing a prototype in a physical urban setting, the researcher would have encountered multiple obstacles. These included high costs, such as expenses to cover travel and equipment, as well as potential ethical issues. As emerged from literature reviewed in Section 2.3, there are visual features that can be noticed by humans instantly. Thus, observations are a highly suitable primary tactic for investigating people's responses of attention to an architectural skin. Nonetheless, conducting them in a natural setting such as an outdoor public space in an urban environment would have required permissions as well as resources beyond what was achievable within the budget and timeframe of the PhD project, including potentially the costs of building and installing a prototype. Moreover, the complexity of a real urban context with its multiple distracting stimuli, such as moving people or vehicles and the noises they emit, would have interfered with the evaluation of a direct causal link between people's visual engagement and the proposed design. Considering the above and the wealth of information already available thanks to secondary sources, the researcher decided to start from a secondary research phase to build a knowledge base for generating a design. This was then evaluated with observations associated with the controlled, virtual simulation of a real urban setting, which were completed by subsequent interviews. On the other hand, asking people questions in advance appeared inappropriate because it would have affected the spontaneity of participants' reactions by forcing them to pay attention to the proposed design.

As evinced from the second research question, this research intends to identify possible ways of deploying solar technologies successfully in the composition of

visually engaging architectural skins, rather than to develop new technological systems. Research aimed at technology development would have required further testing beyond what the present study could cover, such as assessing the performance of physical prototypes through technical procedures involving expertise in the fields of physics and engineering. It would have demanded the availability of time and resources beyond what characterised this PhD project. Given also the importance of visual aspects in the project and their particular relevance in the earliest stages of designing solar building skins, the researcher chose to focus on the early design process and rejected research methods for design or technology development.

4.5 Conclusions

This chapter described the subject under study in the present project, situated within the context of architectural research, and the mixed-methods approach tailored to solve the posed problem. It clarified that the exploratory aim of this research is to propose a conceptual framework, building on existing knowledge, to both facilitate the design of novel, visually engaging architectural skins by deploying solar technologies effectively, and to show potential directions for further research on the topic. The target audience of the study was thus identified in architecture practitioners and researchers, as well as students, and its impact was predicted as an influence on future architectural design and research.

The nature of the investigation, illuminated by three research questions refined throughout the literature review, determined the choice of adopting a combined research strategy within an eminently naturalistic perspective, which integrated secondary qualitative research and case studies based on secondary sources with primary, practice-based research using simulation and experimental strategies. The conceptual framework constructed through qualitative and case study research was applied to the early design of a solar architectural skin using parametric 3D modelling techniques. These included quantitative climate-based simulations and were complemented by photorealistic rendering to confer visual qualities to the solar skin model inserted into the virtual urban environment that participants experienced as part of a VR experiment. The capacity of the proposed design for triggering visual engagement could be evaluated thanks to data from observations and subsequent participants' feedback. The results could provide useful insights, contributing to the refinement of the design framework. The trustworthiness of the study was largely

achieved by relying on multiple methods and data sources in a triangulating manner to retrieve information.

The following table (see fig. 43.) summarises the formulated research methodology for the present project according to the aims and research questions.

Aims	Research Questions	Research Type	Research Strategy	Methods
To develop a design framework for architectural skins deploying solar technologies effectively and producing visual engagement	1. How can architectural skins produce visual engagement with minimal energy use? 2. How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?	Secondary	Qualitative Research	<ul style="list-style-type: none"> Literature review based on archival sources
			Case studies	<ul style="list-style-type: none"> Descriptive analysis of information from multiple secondary sources and media, from a compositional and technological perspective
To test and refine the design framework	3. How can novel concepts of effective solar architectural skins be designed to produce visual engagement?	Primary, practice-based	Simulation Research	<ul style="list-style-type: none"> Parametric 3D modelling and environmental design Photorealistic Rendering Virtual Reality
			Experimental Research	<ul style="list-style-type: none"> Qualitative and quantitative observations of participants' reactions Interviews following the observations

Fig. 43. *Summary of Research Methodology* (2019)

Chapter 5: Selected Case Studies of Visually Engaging Architectural Skins

5.1 Chapter Overview

This chapter illustrates precedents of visually captivating building exteriors, selected for their capacity for producing motion impressions in ways that could potentially be applied to the design of effective solar architectural skins.

Throughout the second section of this chapter, fifteen case studies based on secondary sources are analysed in a descriptive and explorative manner from a compositional and technology perspective. This reveals factors informing each design, features affecting perception by producing a sense of motion, and potential for the application of solar technologies to the configurations examined.

The influences on design identified in the analysed case studies are then discussed in the third section of the chapter, along with characteristics of the artefacts that respond to those aspects, followed by considerations on the potential for the deployment of solar technologies in the reviewed configurations.

The chapter concludes with a summary of the aspects that emerged from the examined case studies, which are relevant to the design of effective solar architectural skins capable of stimulating visual engagement.

5.2 Selection and Analysis of Case Studies

5.2.1 Selection Criteria According to Findings on Visual Perception

As emerged from the literature reviewed in Section 2.3, architectural skins are more likely to produce visual engagement when they embed salient features of form, colour and motion, as well as more complex, recognisable elements such as patterns and figures. Motion was found to have a strong capacity for attracting people's gaze and attention, but as presented in Section 2.4, integrating actual movement into architectural facades, also in the form of dynamic night lighting, entails drawbacks including intensive energy use, control and maintenance issues, as well as high costs. However, it emerged that a sense of motion can be conveyed without actual movement, and that the design of static architectural skins which can attract attention by producing motion impressions is still relatively unexplored, particularly in relation to building-integrated solar technologies.

The reviewed literature revealed possibilities for conveying a sense of movement through visual illusions induced by patterns featuring asymmetric luminance gradients and by three-dimensional compositions observed from varying perspectives by moving viewers. However, certain striped patterns that may appear dynamic can cause forms of discomfort in some people, which is to be considered in design. The above findings suggested the need to search for empirical cases of architectural artefacts exemplifying ways of producing motion impressions in forms that exclude the integration of kinetic or electrically operated components.

Relevant examples of architectural skins could have been analysed potentially in their urban contexts through primary case study research. The researcher could have attempted to examine existing building skins or physical prototypes as well as passers-by's reactions to viewing them in real, outdoor urban environments. Doing this could have provided useful insights into the effectiveness of certain architectural skin designs towards stimulating visual engagement in actual urban spaces with their countless variables. The results could have been highly reliable, deriving from real-life situations. Conducting non-intrusive observations would have been necessary for obtaining data without influencing people's behaviour. However, observing and recording information in environments characterised by numerous competing stimuli, such as moving vehicles and people as well as noises and even smells, would have been extremely complex. The abundance of distractors would have been a major obstacle to data collection. Analysing multiple case studies in different locations through primary research would have involved a lengthy process with expensive travels and equipment as well as possible ethical issues, related, for instance, to rights for the use of spaces and to the privacy of passers-by. To overcome such obstacles, considering the time and resource constraints of the PhD project, the researcher decided to examine selected case studies of artefacts through secondary research. Therefore, she relied on secondary sources to analyse examples of architectural skin designs with potential for stimulating visual engagement and deferred the primary study of people's reactions to a later stage of the project.

5.2.2 Selection Criteria According to Findings on Media Facades

As emerged in Section 2.4, despite their operational drawbacks, media facades may provide a model for the integration of visually engaging features into building envelopes, thanks to their modular or pixelated configuration enabling the dynamic display of discretised visual content such as images and patterns. On the other

hand, controlling optical phenomena may create dynamic visual effects on static architectural skins in ways that eliminate the use of electrically operated components and mechanisms. Therefore, identifying and analysing precedents of artefacts characterised by static, modular configurations and by visual properties allowing the display of salient features, including motion, could point at directions for the design of effective, visually engaging building envelopes without the operational issues of luminous and kinetic media facades.

5.2.3 Selection Criteria According to Findings on Solar Architectural Skins

The literature reviewed in Chapter 3 showed that among active solar technologies for building integration, which are either established or still in development, photovoltaics can have higher potential for the creation of visually captivating architectural skins that are modular similarly to media facades. Even in hybrid photovoltaic-thermal systems which are capable of utilising solar radiation more effectively, the photovoltaic layer is more relevant to the visual impact of solar installations as it is directly visible to people. It emerged that, as the efficiency of solar technologies largely depends on incident radiation, bifacial or three-dimensional configurations can increase the effectiveness of photovoltaic architectural skins. For instance, their performance may be improved by corrugated or textured surfaces, spherical cells, or static low-concentration optical devices reflecting solar radiation onto the absorber. It was noted that systems which can enhance the performance of photovoltaics and are partly still in development may have some potential for triggering visual engagement when integrated into building skins. They may be used to display salient features like dynamic reflections or luminance contrast, thanks to optical properties such as the capacity to reflect, refract or emit light, or to cast shadows. Other developing technologies identified as promising in terms of both efficiency and aesthetics include colourful perovskite solar cells and spectrum selection with filters that can enable a more effective use of solar radiation. By considering the potential for deploying solar technologies on architectural skins with visually engaging effects, examples of precedents may be selected for their modular configurations and visual qualities such as colour, three-dimensionality, and optical properties including the capacity to transmit, reflect, refract or emit light.

5.2.4 Summary of Selection Criteria

In light of the above findings on what can characterise visually captivating facades and enhanced photovoltaic-based technologies for building integration, it can be

evinced that the sought-after features for visually engaging, solar architectural skins are the following:

- the display of motion;
- the display of forms, colours, patterns and recognisable or evocative elements;
- three-dimensionality;
- modularity or pixel configuration;
- physically static and non-electrically operated components;
- optical properties such as the capacity to reflect, refract, emit or transmit light.

To investigate possibilities for the effective deployment of solar technologies on architectural skins aimed at triggering visual engagement, the researcher selected fifteen illustrative case studies of artefacts presenting the above characteristics, among architectural facades and artworks. The case studies were chosen for the visually stimulating features they embed, but also because they manifest some potential for the integration of solar technologies which emerged from the literature reviewed in Chapter 3.

5.2.5 Analysis Method

For each case, information on the visual composition and technologies used, gathered from multiple secondary sources, including texts and images from designers' and artists' websites as well as online magazines and books, was summarised in a brief description. This also comprised suggestions for the adaptation of the analysed configurations to solar skin designs, which referred to solutions reviewed in Chapter 3.

As shown in the next section, each case is situated in space and time, with data on the location and on the year of completion, where applicable. As it emerged from the literature review that motion impressions can be produced by certain static, three-dimensional compositions in combination with viewers' movement, characteristics of a location determining the way an artefact is perceived appear particularly relevant. Moreover, it was found in Chapter 3 that some features of a site can also influence the performance and thus the design of building-integrated solar energy systems. They can affect, for instance, the orientation and tilt of a solar array as well as its efficiency which also depends on the presence of shading elements. Therefore, the description of each case study includes some information on aspects of the location, where applicable, and on how they impact the way the artefact is perceived.

5.2.6 Case Studies

5.2.6.1 *May/September* at the Eskenazi Hospital Parking Structure

Created by Rob Ley and completed in 2014 (Rob Ley, n. d.; ArchDaily, 2014; Ward, 2015), *May/September* is situated in Indianapolis, Indiana, and is part of the Sidney & Lois Eskenazi Hospital (ArchDaily, 2014b; Ward, 2015). The façade design (see fig. 44.) was inspired by the idea of ‘camouflage’ (ArchDaily, 2014b; Ward, 2015) to mask a car park building that requires considerable ventilation (ArchDaily, 2014b), and it was developed to appear dynamic and ‘interactive’ (Rob Ley, n. d.; ArchDaily, 2014b; Caula, 2014).



Fig. 44. '*May/September*' by Rob Ley (2014)

The façade is perceived by viewers moving through the site at different speeds, as the street close to the building serves both pedestrians and vehicles. Therefore, the designers decided to exploit passers-by's motion to convey a sense of movement through apparent changes in colour and transparency (Rob Ley, n. d.; ArchDaily, 2014; Caula, 2014; Ward, 2015), instead of employing actively moving components that would have caused durability and maintenance issues typical of kinetic facades (ArchDaily, 2014b; Ward, 2015).

The installation is composed of about 7,000 variably angled metal panels (see fig. 45.), displaying two different colours depending on whether they are seen from the East or from the West, which produces a sensation of motion in viewers passing by

the façade, varying with their pace and viewpoints (Rob Ley, n. d.; ArchDaily, 2014b; Caula, 2014; Ward, 2015). The design is based on the study of ‘digital image manipulation and reproduction techniques, such as error diffusion, dithering, half-toning, and lossy-compression quantization’, which was aimed at the development of a methodology for creating façade configurations with complex patterns (ArchDaily, 2014b).

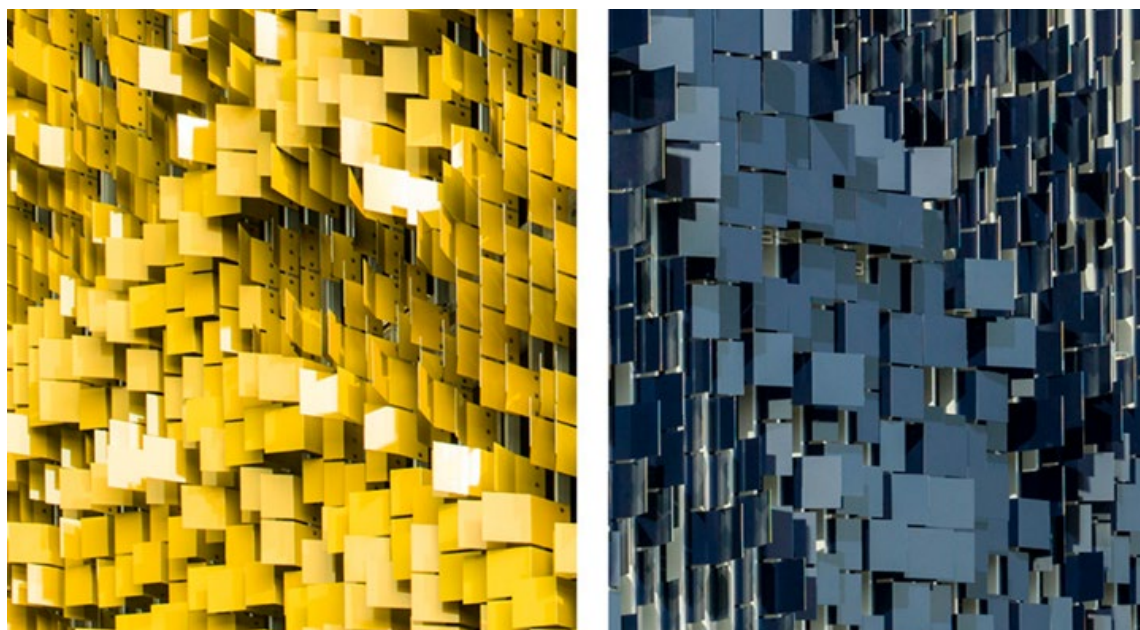


Fig. 45. ‘May/September’ by Rob Ley: *Detail* (2014)

The design process involved the construction of physical prototypes, but an eminent role was played by computer programs, and the designers even developed some custom software (ArchDaily, 2014b), using the Rhino 3D modelling platform with a Grasshopper plug-in (Ward, 2015).

This façade configuration could potentially be adapted to host efficient thin-film photovoltaic modules with improved orientation, using the metal panels as substrate and exploiting their angle variations as well as natural ventilation for cooling to increase the energy output. Shading simulation techniques in early design stages may be used to prevent the active photovoltaic modules from being incorrectly distributed and their light absorption from being compromised. However, to improve the system performance despite the different modules’ angles, a distributed system optimisation based on micro inverters and power optimisers may be used instead of a more conventional central inverter. Maximising the energy output of each individual photovoltaic panel, micro inverters were found to be particularly advantageous in building-integrated photovoltaic arrays that tend to be relatively small and prone to shading, and were indicated as a potential solution to reduce the

overall cost of the installation (Scholten et al., 2013; Ikkurti & Saha, 2015). The same benefits were attributed to ‘micro’ maximum power point tracking converters or ‘power optimisers’ that act at the panel level to optimise the energy output of a photovoltaic array (Koirala et al., 2009; Orduz et al., 2013).

5.2.6.2 Dichroic Light Field

Created by James Carpenter Design Associates and completed in 1995 (James Carpenter Design Associates Inc., n. d.; Marpillero, 2006:36; Schielke, 2013; Carpenter | Lowings, 2017), *Dichroic Light Field* (see fig. 46.) was installed on the side of the Millennium Tower facing Columbus Avenue in New York. The artwork was conceived to animate an opaque brick façade with the illusion of depth and with the display of kinetic effects from the surrounding. These are produced by reflected variations in light conditions (James Carpenter Design Associates Inc., n. d.; Marpillero, 2006:36; Schielke, 2013) as well as by the passers-by’s changing viewpoints, while the illumination of the street is also improved (Marpillero, 2006:36). This visually dynamic installation faces a road with vehicular traffic, and it is positioned at a certain height.



Fig. 46. ‘Dichroic Light Field’ (© David Sundberg, Courtesy of JCDA)

The skin is composed of planar, laminated glass panels secured onto a steel substructure attached to the facade, and of dichroic glass fins perpendicular to the vertical screen (see fig. 47.). The planar, reflective surface displays the changing

light conditions of the sky as well as patterns in different colours produced by the mirrored dichroic fins (Marpillero, 2006:36–45; Schielke, 2013; Carpenter | Lowings, 2017). While the glass screen is characterised by textured, semi-reflective panels, the fins contain a dichroic coating that was vacuum deposited and laminated within the elements, to split and reflect complementary colours of the incident light spectrum (Marpillero, 2006:40).

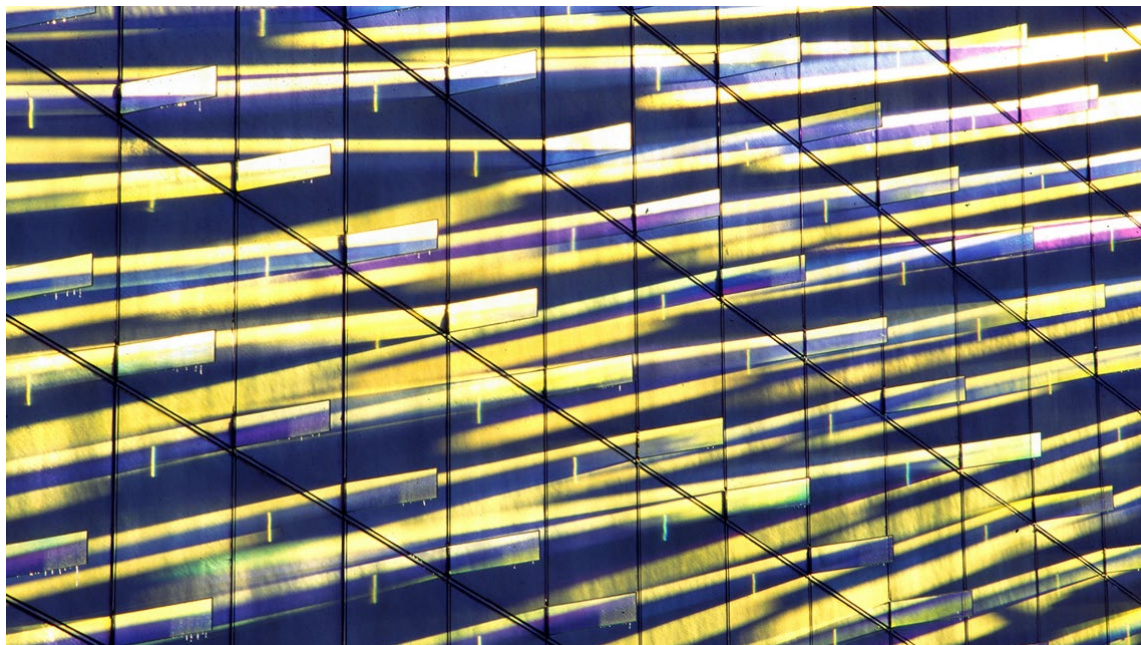


Fig. 47. *'Dichroic Light Field': Detail* (© David Sundberg, Courtesy of JCDA)

It may be noted that this façade configuration could be adjusted for the integration of photovoltaic modules with optimal tilt and orientation, potentially using dichroic filters which were presented among strategies for spectral selection or splitting (Imenes & Mills, 2004). As the glass fins are installed perpendicularly to the façade, and they are exposed to natural light from multiple directions, they could embed spherical solar cells for enhanced performance, preferably with an arrangement of the active modules that prevents shading.

5.2.6.3 *Piksol*

Created by Drzach & Suchy in Switzerland (Chin, 2010; Scholtus, 2010; Schwartz, 2010) *Piksol* (see fig. 48.) is a concept for a solar skin system consisting of photovoltaic modules placed orthogonally to a building façade with a particular arrangement, so that the shadows cast on the façade surface constitute pixels forming images that vary with sunlight's angle and intensity (Chin, 2010; Scholtus, 2010; Schwartz, 2010; Drzach & Suchy, 2017).

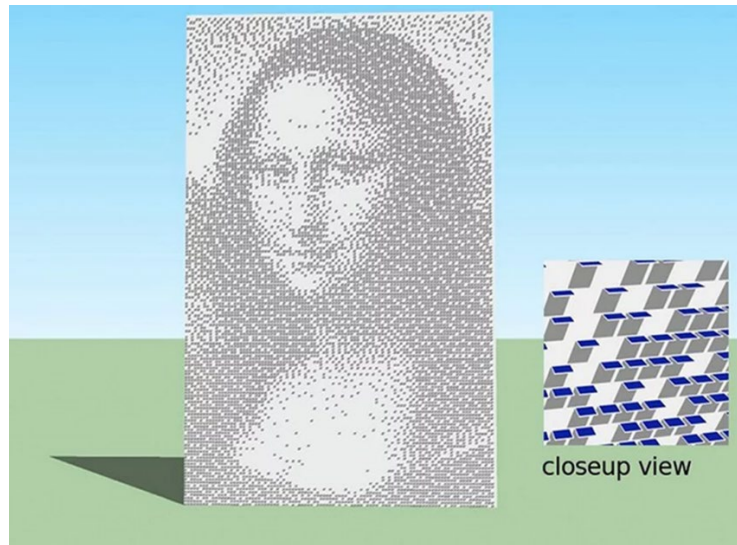


Fig. 48. '*Piksol*' by Drzach & Suchy

This type of configuration may be utilised to integrate photovoltaic modules into visually engaging facades displaying specific, predetermined visual content. The system applies digital images to facade designs with a pixel configuration in which shadows constitute pixels composing pictures that are distinguishable thanks to luminance contrast. The displayed images are also dynamic as they vary with natural lighting conditions throughout the day. However, it may be noted that the installation can be inefficient in terms of energy output unless photovoltaic modules are placed with angles close to optimal and their arrangement does not cause shading on active components. Yet, the effect of differences in incident radiation might be partly reduced or mitigated by placing non-active modules where preferable or by using micro inverters and power optimisers as mentioned in the case of the *May/September* design by Rob Ley.

Given the high number of small photovoltaic modules to interconnect, there seems to be a possibility to also incur additional energy losses due to resistance of cabling and other components within the electrical system (Norton et al., 2011:1636).

It appears that to preserve a limited thickness of the small fins casting shadows as pixels, thin-film photovoltaic modules would be more suitable for this application. The façade geometry would clearly allow the natural back-ventilation of solar cells, preventing them from overheating, with a positive impact on their performance. Potentially the configuration could be adapted for the panels to be optimally angled and sunlight absorption to be maximised.

5.2.6.4 *Complex Vision*

Authored by Yaacov Agam, the artwork *Complex Vision* (see fig. 49.) was completed in 1976 and then restored between 2014 and 2015. It is situated in Birmingham, Alabama, and is part of the Callahan Eye Hospital at the University of Alabama (Almond, 2015; Park West Gallery, 2015; Shepard, 2015). The sculpture is integrated into a façade of the hospital, and is intended to be appreciated also by people left with a mild form of visual impairment after eye surgery (Almond, 2015; Park West Gallery, 2015).

Figure removed due to copyright restrictions

Fig. 49. '*Complex Vision*' by Yaacov Agam

The artwork is composed of 69 aluminium panels that are about 3 meters long, 33 centimetres wide and that weigh nearly 23 kilograms each, painted to display different patterns depending on the angle from which the sculpture is viewed, producing the impression of movement (UAB Health System, 2017; Park West Gallery, 2015; Almond, 2015). The panels are two-sided (Almond, 2015; Park West Gallery, 2015), forming a corrugated surface configuration with vertical folds, suitable to be perceived by viewers moving in a direction parallel to the façade.

As emerged from the reviewed literature on building-integrated photovoltaics, corrugated surfaces presenting, for instance, a 'sawtooth' profile can improve photovoltaic modules' absorption of sunlight (Sick & Erge, 1995:98-102). Therefore, it seems the configuration of *Complex Vision* by Agam could be suitable for the integration of photovoltaic modules into facades with non-optimal orientation, to orient PV modules towards the South or towards the North, depending on whether the building is in the Northern or in the Southern hemisphere. However, the panels of the corrugated configuration might need to be scaled appropriately to avoid the façade's self-shading. Thin-film photovoltaic modules could be applied on the metal

substrate and complemented by coloured, non-active elements simply painted as in Agam's work.

Being impenetrable and opaque, the configuration of *Complex Vision* may be suitable for application to insulated walls, thus a hybrid photovoltaic-thermal system with solar water collectors may be deployed in this case, to enhance the performance of photovoltaic modules through active cooling while also utilising thermal energy from the sun for heating purposes inside the building.

5.2.6.5 Leong Leong Façade

Designed by Leong Leong for the City View Garage in the Miami Design District (Leong Leong, n. d.; Ouimet-Vives, 2015; A. Zahner Company, 2017), the *Leong Leong Façade* (see fig. 50.) was completed in 2015 (Leong Leong, n. d.). It masks the Western side of a parking structure in a prominent location at the periphery of the Design District and adjacent to a main road in Miami. Inspired by the shimmering effect of a water surface hit by sunlight, the iconic design's pattern also evokes forms of the nearby palms (Leong Leong, n. d.; Ouimet-Vives, 2015; A. Zahner Company, 2017).

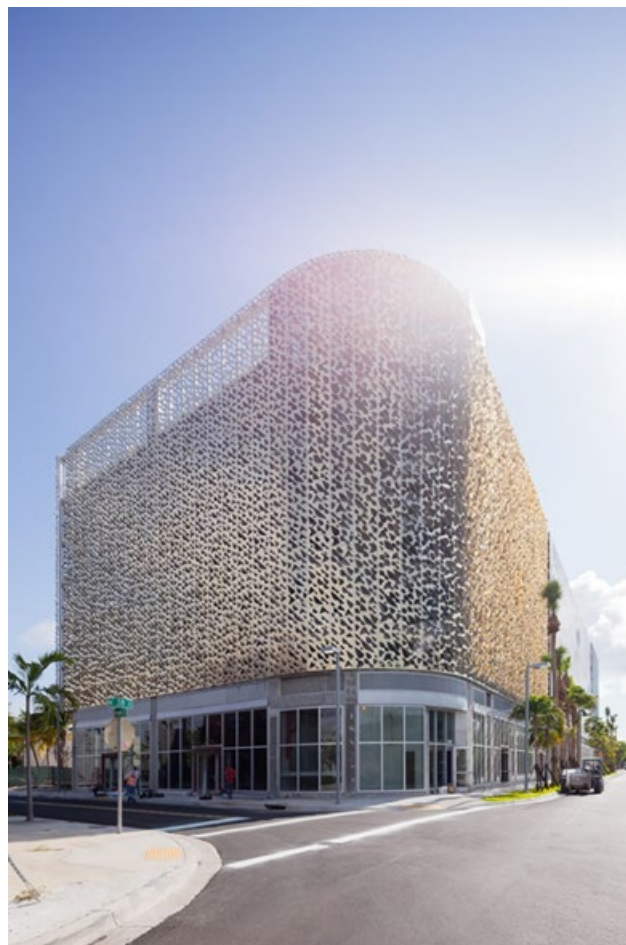


Fig. 50. *Leong Leong Façade* (Photo by Tex Jernigan, Courtesy of Zahner)

As the building typology of the parking structure demands both natural light and ventilation, the façade was designed with a multitude of openings to meet those requirements (Leong Leong, n. d.; A. Zahner Company, 2017). The façade is made of titanium-coated stainless steel and features fins (see fig. 51.) that were punched as curvilinear shapes and folded out to enable the natural ventilation of the building (Leong Leong, n. d.; Ouimet-Vives, 2015; A. Zahner Company, 2017). Characterised by a golden colour, the façade surface reflects qualities of the surrounding environment (Leong Leong, n. d.; A. Zahner Company, 2017).



Fig. 51. *Leong Leong Façade: Detail* (Photo by Tex Jernigan, Courtesy of Zahner)

This type of configuration may be adapted for the integration of efficient thin-film photovoltaic modules supported by folded metal fins with optimal tilt and orientation. It can be observed that the overall dynamic pattern is created by both reflections and shadows. This may hint at possibilities for the effective integration of photovoltaics into facades, which could potentially exploit the reflectivity of materials also to increase the incident solar radiation on active modules, whereas shadows should be preferably prevented on the same components. Therefore, the fins should be appropriately positioned from early design stages. For a seamless application of photovoltaic panels onto fins of curvilinear shape, either customised thin-film modules or standardised components complemented by non-active elements may be utilised.

It can be noted that the perforated configuration of the Leong Leong façade, featuring angled fins that could potentially support photovoltaic modules, would enable the natural back-ventilation of solar modules, which is a key strategy for enhancing the performance of building-integrated photovoltaics, as emerged from literature reviewed in Section 3.4.

5.2.6.6 Anamorphic Façade

Authored by Carpenter | Lowings in 2006, the *Anamorphic Façade* (see fig. 52.) was designed for Merchant Square in London (Carpenter | Lowings, 2017a). Developed only as a design proposal, it was conceived to be perceived from the public space of Merchant Square in the Paddington Basin development. As the façade faces a piazza, the designers exploited passers-by's possibility of appreciating the artefact from different perspectives and generated a three-dimensional skin configuration presenting a pattern that varies (see fig. 53.) with changing viewpoints (Carpenter | Lowings, 2017).



Fig. 52. *Anamorphic Façade by Carpenter | Lowings*

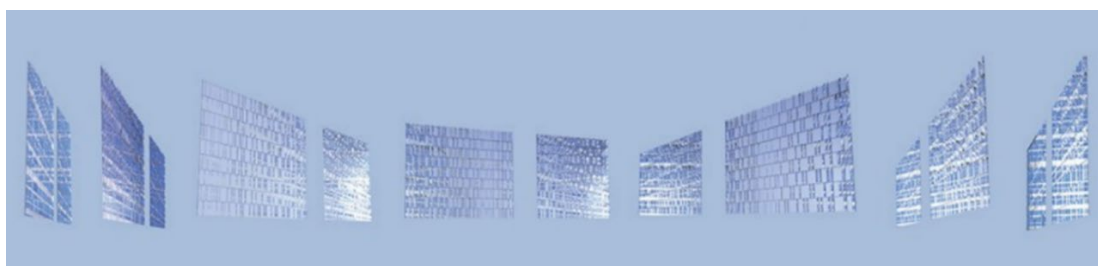


Fig. 53. *Anamorphic Façade by Carpenter | Lowings: Patterns*

Composed of semi-transparent, coloured glass fins that act as shading devices (see fig. 54.), the façade displays an abstract two-dimensional pattern created with colours and reflections, that is overlaid on three-dimensional perspectives of the buildings, for it to be distinguishable from specific viewpoints within the public space of the square (Carpenter | Lowings, 2017).

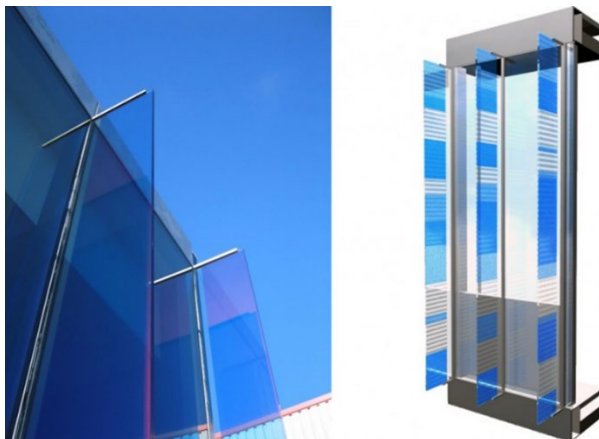


Fig. 54. *Anamorphic Façade* by Carpenter | Lowings: Detail (with Photo by Luke Lowings)

Although the *Anamorphic Façade* was not built, another two completed projects by the same designers employ a very similar visual strategy, proving the feasibility of the examined design. One of those projects is the *Fin Façade* in Oxford Street, London, featuring vertical glass fins with segments of blue colour composing a pattern on the three-dimensional building skin (Carpenter | Lowings, 2017c). The other is the *Translucent Hands* project which uses glass fins in a similar fashion to display medical imagery of hands, printed onto the interlayer of the laminated glass elements, through the façade of the Royal National Orthopaedic Hospital in London (Carpenter | Lowings, 2017d).

The configuration of the *Anamorphic Façade* suggests possibilities for the integration of a range of photovoltaic technologies into vertical glass fins, particularly in climatic zones of higher latitudes where the optimal tilt of solar panels is close to vertical. Colour could be conferred to glass fins by means of embedded arrays of bifacial or spherical solar cells as in Sphelar® photovoltaic modules (see fig. 30.), or through the incorporation of semi-transparent thin-film solar modules available in different colours, such as dye sensitised solar cells or perovskite cells. Coloured filters might also be used as spectral converters to improve the efficiency of solar cells, as emerged in Chapter 3. The integration of Sphelar® modules into glass fins perpendicular to a building façade might be especially beneficial, thanks to the

capacity of these modules to absorb sunlight from multiple directions (Nakata & Wac, 2011). However, the spacing of the fins might be critical not just for the composition of patterns, but also to prevent shading on photovoltaic modules.

5.2.6.7 Façade of the Brisbane Girls Grammar School

Designed by M3architecture and situated in Brisbane, Australia (Kaji-O'Grady, 2007; Brisbin, 2011:145), the examined façade of the Brisbane Girls Grammar School was completed in 2006 (Brisbin, 2011:145). The selected design characterises the Western façade of the school, which was created to be visible from the highway at some distance from the site (Kaji-O'Grady, 2007), and thus to be noticed by passing motorists who perceive it as vibrating as an Op Art work, reminiscent of Bridget Riley's style (Brisbin, 2011:151).

Composed as a battened screen characterised by the repetition of vertical elements (see fig. 55.), the permeable skin attempts to veil a wall with a small number of openings and a fire escape path (Brisbin, 2011:149). The facade produces a 'moiré effect' (Kaji-O'Grady, 2007; Brisbin, 2011), giving the impression of motion thanks to the visual interference patterns created by overlaid grids (Brisbin, 2011:151), so that passing viewers perceive circular waves. This was achieved by combining an outer screen composed of slats made of bronze anodised aluminium with the inner wall surface featuring white and black vertical stripes (Kaji-O'Grady, 2007). According to Brisbin (2011), the perception of the optical illusion depends on the distance from which the screen is seen, being more effective when it is viewed from far away. The same author also associated the façade with the tradition of screened buildings typical of the same region in Australia, which was influenced by materials availability as well as by climatic and cultural conditions determining the need for a transitional zone between public and private spaces (Brisbin, 2011).

Figure removed due to copyright restrictions

Fig. 55. *Façade of the Brisbane Girls Grammar School*

As also emerged from the literature review, certain striped patterns like those in Op Art works were found to cause discomfort in susceptible people, which includes nausea and strong headaches (Lee, 2001:26). Recent research on discomfort caused by visual stimuli specifically investigated the effect on the brain of modern urban scenes characterised by spatial frequencies far from those of comforting natural images (Le et al., 2017). Despite its potential for inducing discomfort, which could be investigated further, a façade configuration based on moiré patterns could potentially be adapted to host elongated, thin-film photovoltaic modules characterised by optimal tilt and orientation, also using back-ventilation for improved efficiency.

5.2.6.8 Façade of the Delancey and Essex Municipal Parking Garage

Designed by Michielli + Wyetzner Architects and built in New York City (Minner, 2011; Welch, 2014; Michielli + Wyetzner Architects, 2016) in 2016 (Michielli + Wyetzner Architects, 2016), the skin of the Delancey and Essex Municipal Parking Garage (see fig. 56.) was designed to subtly evoke the history of the area, formerly occupied by the garment industry, and to be perceived as kinetic by viewers driving and walking along the street. It also had to meet requirements for natural ventilation (Minner, 2011; Welch, 2014; Michielli + Wyetzner Architects, 2016) typical of parking buildings. Masking a concrete structure, the skin was created as part of a renovation project which entailed the replacement of the pre-existing concrete covering that had started to decay (Minner, 2011; Welch, 2014).

Figure removed due to copyright restrictions

Fig. 56. *Façade of the Delancey and Essex Garage*

Like the previously examined Western façade of the Brisbane Girls Grammar School (see Section 5.2.6.7), the three-dimensional, porous screen of the Delancey and Essex Municipal Parking Garage presents two overlaid gratings (see fig. 57.), composing a pattern that is reminiscent of woven threads on a loom and produces a moiré effect with illusory motion perceived by viewers in movement (Minner, 2011; Welch, 2014; Michielli + Wyetzner Architects, 2016). The pattern design was inspired by Optical Art works like drawings by Francois Morellet (Welch, 2014; Michielli + Wyetzner Architects, 2016), and was intended to recall the ‘aerodynamic flow of moving cars’ (Minner, 2011; Welch, 2014). The façade is composed of two layers of 1.25” diameter cables made of a composite fibre core covered by a woven

stainless steel jacket, with the outer layer of cables folding in and out from the planar grating behind, being held in place by comb-like supports (Minner, 2011; Welch, 2014).

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Fig. 57. *Façade of the Delancey and Essex Garage: Detail*

The potential for the integration of solar technologies into this skin configuration is similar to that identified for the Brisbane Girls Grammar School's façade. Regarding the possibility of embedding solar cells into steel-covered cables, it appears that several challenges, like those which emerged from research on photovoltaic textiles, could be encountered, particularly the series resistance of long, thin cells. While fabricating photovoltaic textiles seems feasible with different strategies ranging from attaching solar cells to fabric or weaving photovoltaic threads to directly depositing photovoltaic thin-film material onto textiles, various issues related to mechanical stress, sealing, durability, shading and energy output efficiency of solar textiles need to be overcome (Mather & Wilson, 2017).

5.2.6.9 Façade of the Leitão_653 Studios

Authored by Triptyque and located in São Paulo, Brazil (Triptyque, n. d.; ARQA, 2013; Buscador de Arquitectura, 2015; Howarth, 2017) the Leitão_653 building was completed in 2012 (Triptyque, n. d.; ARQA, 2013). Designed as a 4-metre wide and 25-metre high office block rising on a narrow site in the heart of the Pinheiros district, the building is surrounded by both small constructions and towers (see fig. 58.). The

architects intended to communicate the idea of connection between the activities carried out inside the building and the city, which determined the design of a patterned façade composed of glass blocks (see fig. 59.) characterised by three degrees of transparency (Triptyque, n. d.; Howarth, 2017). The façade presents a grid structure that can be associated with a ‘moucharaby’ (Triptyque, n. d.), with ‘latticework’ (ARQA, 2013) and with a ‘chequerboard’ (Howarth, 2017). The façade displays scenes from the interior, filtering light from the outside during the day and radiating it from the inside at night (Triptyque, n. d.; ARQA, 2013).

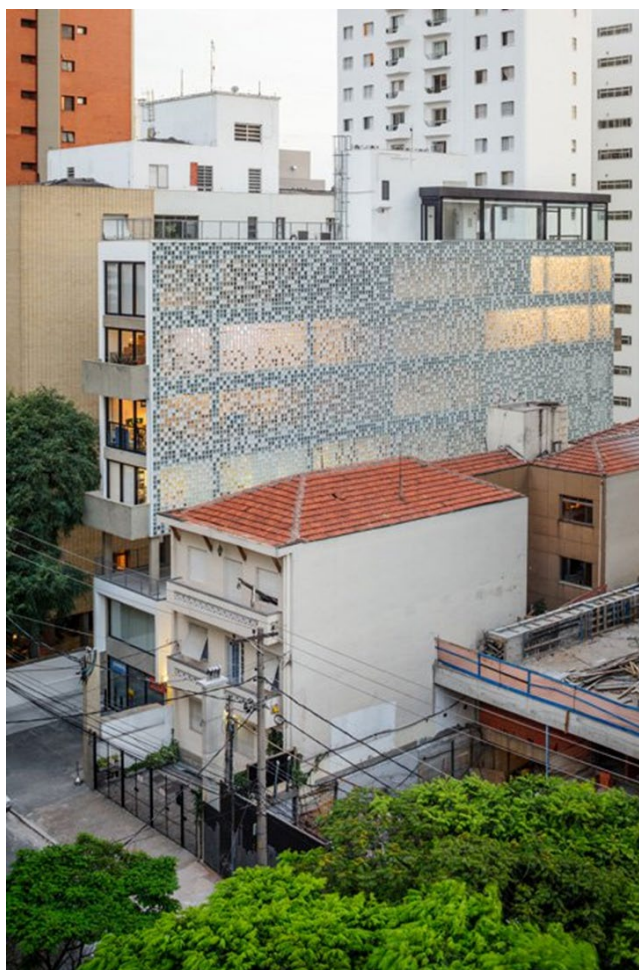


Fig. 58. *Façade of the Leitão_653 Studios by Triptyque*

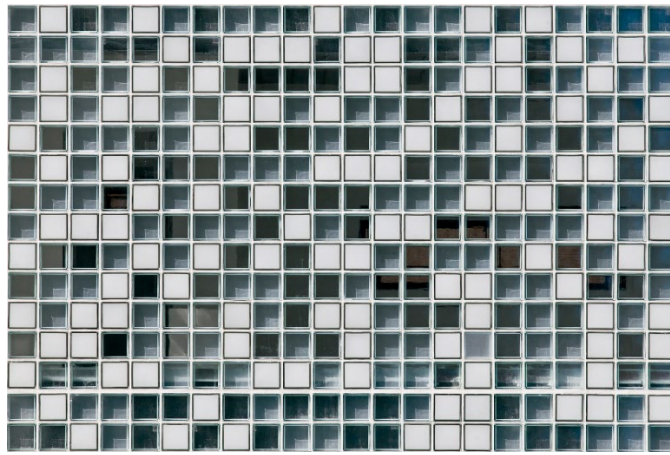


Fig. 59. *Façade of the Leitão_653 Studios by Triptyque: Detail*

The 'pixel' configuration of the skin designed by Triptyque for Leitão_653 Studios, featuring glass bricks of different opacities, could be adapted to embed modular, low concentration devices filled with dielectric material (see fig. 34.) such as the dielectric based 'Three-Dimensional Cross Compound Parabolic Concentrator' (Baig et al., 2014). Such optical devices could be arranged in combination with less transparent, non-active modules to compose patterns across the screen, while displaying blurred motion from activities carried out inside the building.

5.2.6.10 Façade of the Harpa, Reykjavik Concert Hall and Conference Centre

Completed in 2011 (Henning Larsen Architects, n. d.; ArchDaily, 2011a) and situated close to the water in Reykjavik's harbour area, the Harpa Concert Hall and Conference Centre features a façade that was created through a collaboration between the artist Olafur Eliasson and Henning Larsen Architects (Henning Larsen Architects, n. d.; ArchDaily, 2011a; Reinartz, 2011). Inspired by Iceland's geology, the glass façade (see fig. 60.) presents a crystalline configuration and shimmers with colourful reflections that change with people's viewpoints (Henning Larsen Architects, n. d.; Moore, 2011). Facing the South, the glass and steel façade is composed of more than 1000 'quasi-bricks' (see fig. 61.), which are twelve-sided stereoscopic modules (Olafur Eliasson, n. d.; Henning Larsen Architects, n. d.) with hexagonal and rhomboidal faces (Olafur Eliasson, n. d.) made of dichroic glass (Reinartz, 2011).

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Fig. 60. *Façade of the Harpa Centre*

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Fig. 61. *Façade of the Harpa Centre: Detail*

The three-dimensional façade configuration of the Harpa Centre, inspired by a crystalline structure, could potentially be adapted for the integration of a variety of solar technologies among those revealed by the reviewed literature in the third chapter. For instance, Sphelar® semi-transparent modules (see fig. 30.), coloured perovskite cells, and luminescent concentrators could replace conventional glass panels, whereas dichroic elements could be utilised for light spectrum selection to improve the performance of photovoltaic materials.

5.2.6.11 Façade of the SAIT Polytechnic Parkade

Designed by Bing Thom Architects, the SAIT Polytechnic Parkade was completed in 2009 in Calgary, in the Canadian region of Alberta. Like previously examined cases, its façade (see fig. 62.) was conceived to act as a screen for a parking structure requiring natural ventilation, but also to revitalise a university campus with a dynamic appearance. The skin is composed of metal screens with thousands of holes punched into them (see fig. 63.) to create a pixelated configuration that allows natural ventilation of the building while interacting with sunlight and displaying the changing patterns of the sky (Bing Thom Architects, n. d.; ArchDaily, 2011b; Architizer, 2017).



Fig. 62. *Façade of the SAIT Parkade* (© Nic Lehoux)

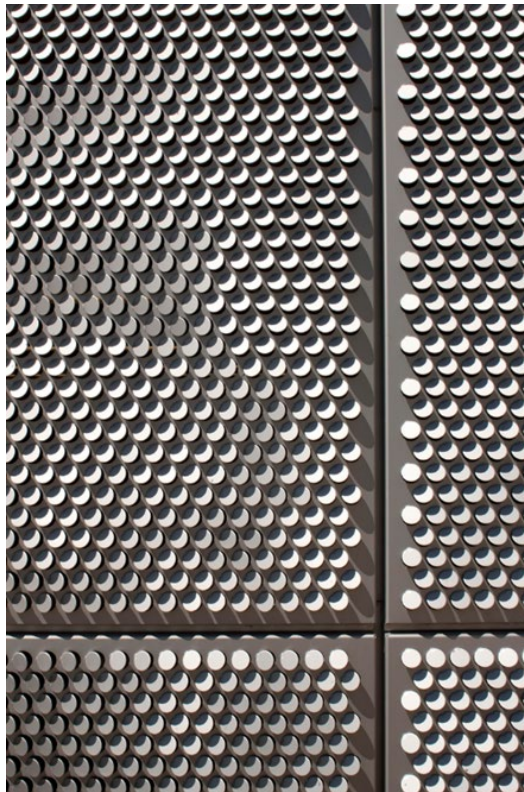


Fig. 63. *Façade of the SALT Parkade: Detail* (© Nic Lehoux)

A skin with a similar patterned configuration, with pixels punched into metal screens and folded out with different angles, could be suitable for the integration of thin-film photovoltaic modules, ideally with optimal tilt and orientation, and would exploit natural ventilation for cooling the back of solar cells, enhancing their performance. As noted for previous cases, a design characterised by elements with different angles entails problems related to shading or inhomogeneous irradiance on photovoltaic cells that could potentially be overcome to some extent with micro inverters and power optimisers.

5.2.6.12 Façade of the Šiauliai Arena

Designed by E. Miliuno Studija and Dvieju Grupe, the Šiauliai Arena is situated in the city of the same name in Lithuania (ArchDaily, 2009; Mimeo, 2017) and was completed in 2007 (Mimeo, 2017). Hosting a variety of functions, such as sports and arts events (Rėklaitė, n. d.; ArchDaily, 2009), the Šiauliai Arena is located in a park surrounded by poor blocks of flats from the Soviet period (ArchDaily, 2009). The architects intended to convey the impression of sunlight, as the name Šiauliai was said to derive from a word meaning ‘the sun’ (ArchDaily, 2009). Thus, they developed a façade design displaying the multiple colours of sunlight (see fig. 64.) like a chameleon’s skin (kamane.lt, 2007; ArchDaily, 2009; Mimeo, 2017), for which they used visualisation techniques from early stages of the project (ArchDaily,

2009). Covering a cylindrical building with a diameter of 100 metres and a height of about 19 metres, the skin of the Šiauliai Arena is made of holographic glass (see fig. 65.), which changes its appearance with varying lighting conditions, from a uniform colour to rainbow effects in bright sunlight (Rėklaitė, n. d.; ArchDaily, 2009; Mimoa, 2017).

Figure removed due to copyright restrictions

Fig. 64. *Façade of the Šiauliai Arena*

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Fig. 65. *Façade of the Šiauliai Arena: Detail*

It may be suggested that a visual effect similar to that of the Šiauliai Arena's skin could be achieved by replacing holographic glass panels with holographic concentrators (see fig. 36.) which, as emerged from reviewed literature, can reduce

the use of silicon in building-integrated photovoltaic installations (Chemisana, 2011:609). Previous considerations on the impact of angle discrepancies on the energy output efficiency of a photovoltaic installation, and on the possibility of mitigating the negative effect with micro inverters and power optimisers, also apply to a curved façade configuration such as the Šiauliai Arena's envelope.

5.2.6.13 Façade of the Dalarna Media Library

Collaboratively created by the artist Jeppe Hein and ADEPT Architects, the Dalarna Media Library was completed in Falun, Sweden (ADEPT, n. d.; ArchDaily, 2014a) in 2014 (ArchDaily, 2014a). The building is part of the Dalarna university campus and is surrounded by a space that was converted from parking lot to urban plaza (ADEPT, n. d.; ArchDaily, 2014a). It was designed to unite library and multi-media functions, but also to be enjoyed as a space for study and meetings (ADEPT, n. d.; ArchDaily, 2014a), thus to attract people (ADEPT, n. d.; ArchDaily, 2014a; Tebutt, 2014).

The façade (see fig. 66.) consists of a double skin comprising an inner wooden cladding made of Siberian larch, and an outer screen made of polished steel elements (see fig. 67.), which displays fragmented reflections of the exterior spaces (ADEPT, n. d.; ArchDaily, 2014a; Tebutt, 2014). While the inner cladding relates the facade to the local tradition of employing wood as building material (ADEPT, n. d.), the highly polished, horizontal lamellae mirror the surrounding environment with the people in it (ADEPT, n. d.; ArchDaily, 2014a), thus displaying dynamic visual content on a discontinuous, permeable surface.



Fig. 66. *Façade of the Dalarna Media Library* (© Bara Bild)



Fig. 67. *Façade of the Dalarna Media Library: Detail* (© Bara Bild)

The configuration of the Dalarna Media Library façade could be adapted to host, in place of reflective lamellae, linear, low concentration devices such as compound parabolic concentrators and V-troughs. These could perform better as part of a hybrid photovoltaic-thermal system that would prevent the solar cells from overheating (Chemisana, 2011:608).

5.2.6.14 Façade of the Michael Kors Flagship Store in Shanghai

Created by Kohn Pedersen Fox with Tillotson Design Associates (Tillotson Design Associates, n. d.; Donoff, 2015), the examined façade of the Michael Kors flagship store is part of the Jing An Kerry Centre in Shanghai, China (Michael Kors, 2014; Donoff, 2015) and was completed in 2014 (Michael Kors, 2014). The concept for the façade was informed by the intent to make the store distinctive and attractive within a shopping environment and to convey the Michael Kors brand identity with a bright, dynamic screen (Donoff, 2015; Kohn Pedersen Fox Associates PC, 2017), evoking shimmering fabric (Michael Kors, 2014; Donoff, 2015) and capable of shining day and night (Donoff, 2015; Kohn Pedersen Fox Associates PC, 2017).

The sparkly screen is composed of angled, textured aluminium reflectors (see fig. 68.) forming a pattern when lit by daylight or by integrated night lighting (Donoff, 2015; Kohn Pedersen Fox Associates PC, 2017). The designers simulated the skin with models at multiple scales to achieve the desired effect while avoiding glare,

developing a configuration that uses hundreds of thousands of aluminium reflectors characterised by a textured surface (see fig. 69.) with mirror finish (Donoff, 2015). According to the architects, the complex pattern created by the angled shingles appears to vary as viewers move towards the store (Kohn Pedersen Fox Associates PC, 2017).

Figure removed due to copyright restrictions

Fig. 68. *Façade of the Michael Kors Flagship Store in Shanghai*

Figure removed due to copyright restrictions

Fig. 69. *Façade of the Michael Kors Flagship Store in Shanghai: Detail*

Featuring multiple levels of complexity, from the overall façade composition to the material texture, the configuration of the store's luminous skin could be adapted for

the integration of reflective devices for external light trapping (see fig. 35.) such as small 3D-printed concentrators (Van Dijk et al., 2015). These could be arranged with optimal tilt, in combination with photovoltaic cells that would appear invisible from a distance and with similarly reflective non-active elements.

5.2.6.15 Façade of the SPG Headquarters

Designed by Giovanni Vaccarini's studio and situated in Geneva, Switzerland (Giovanni Vaccarini Architetti, n. d.; Ingalls, 2016; AD Editorial Team, 2017; Architizer, 2017b), the headquarters of the Swiss Société Privée de Gérance (SPG) was completed in 2016 (Giovanni Vaccarini Architetti, n. d.; Architizer, 2017b). It is located on Route de Chêne, the road giving access Geneva's historical centre (AD Editorial Team, 2017).

The skin of the SPG Headquarters was created as part of an extension and conversion project, which included the recladding of an existing structure (AD Editorial Team, 2017; Architizer, 2017b) consisting of a framework with pillars and slabs made of reinforced concrete (Giovanni Vaccarini Architetti, n. d.). Inspired by Kandinsky's ideas (AD Editorial Team, 2017), the façade was composed through the reiteration of glass elements (see fig. 70.) producing a blurred, kinetic effect (Ingalls, 2016; AD Editorial Team, 2017; Architizer, 2017b). The façade design was informed by the need to provide high quality office spaces (Architizer, 2017b), protecting them from solar radiation while maximising visibility (Giovanni Vaccarini Architetti, n. d.; AD Editorial Team, 2017; Architizer, 2017b) and using natural ventilation at the perimeter (Giovanni Vaccarini Architetti, n. d.; AD Editorial Team, 2017).



Fig. 70. *Façade of the SPG Headquarters by Giovanni Vaccarini Architetti*

The façade consists of a double skin, the outer layer of which is composed of glass fins characterised by a dotted print (Giovanni Vaccarini Architetti, n. d.; AD Editorial Team, 2017; Architizer, 2017b). According to the architect, the double skin was constructed from prefabricated glass and aluminium cells that are 1.5 metres wide and 4 metres high and were attached to the building structure and to each other with dry construction methods. While the inner skin presents a traditional configuration, the outer layer comprises panels made of screen-printed, single tempered glass (see fig. 71.) attached to the frames with structural silicone (Giovanni Vaccarini Architetti, n. d.). The double skin has an overall thickness of up to 80 cm (Architizer, 2017b), with variations in the size of the glass panels (AD Editorial Team, 2017; Architizer, 2017b) and in their surface design (AD Editorial Team, 2017). The angle of the glass fins also varies (Giovanni Vaccarini Architetti, n. d.; Architizer, 2017b) because they are partly electronically controlled to rotate vertically (Giovanni Vaccarini Architetti, n. d.).

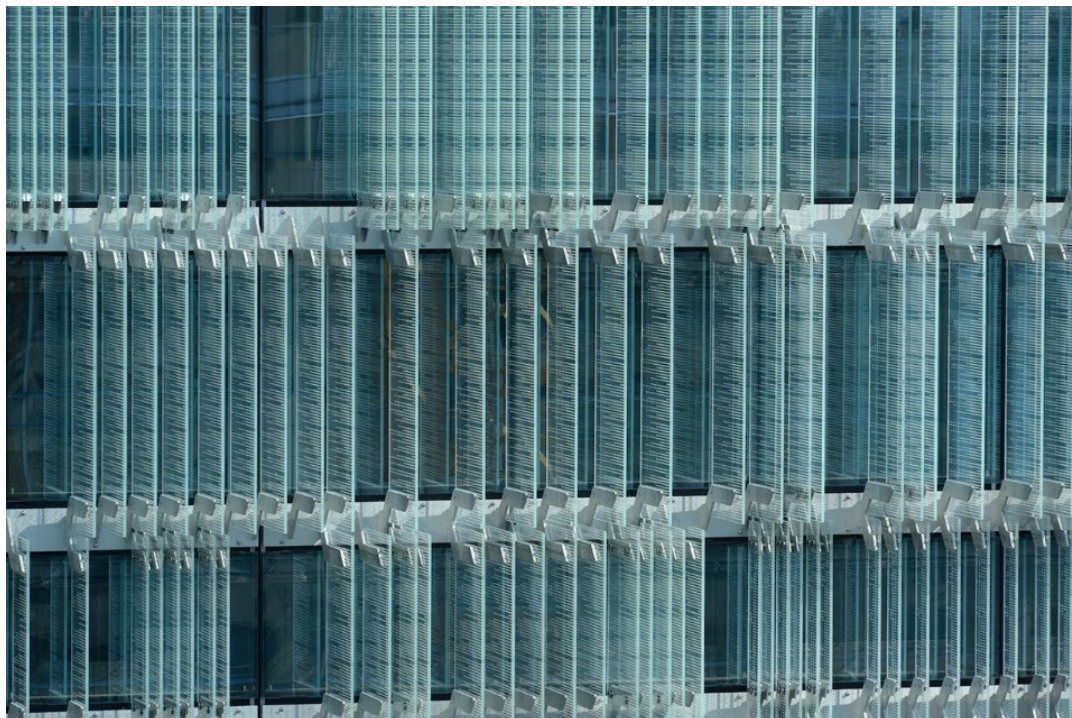


Fig. 71. *Façade of the SPG Headquarters by Giovanni Vaccarini Architetti: Detail*

Although the façade system employs active kinetics in some measure, motion impressions seem to be rather produced by multiple transparencies and reflections (Architizer, 2017b), by the limited spacing of the glass fins (Ingalls, 2016), by the dotted print and by reiteration creating rhythm (AD Editorial Team, 2017), as well as by varying light conditions from daylight to LED night lighting (AD Editorial Team, 2017; Architizer, 2017b). The motion impression can be better perceived when the façade is viewed from a distance (Ingalls, 2016).

The visually permeable configuration characterising the outer skin of the SPG Headquarters could potentially be adapted for the integration of Sphelar® photovoltaic modules (see fig. 30.), in place of the dotted prints, into static glass fins, as the spherical shape of the small Sphelar® cells could compose similar patterns. Additionally, Sphelar® cells would allow the absorption of sunlight from multiple directions (Nakata & Wac, 2011), with a potentially higher energy output efficiency, for which preventing shading on photovoltaic cells by optimising module spacing and positions could be crucial. Natural ventilation of the glass fins might also have a positive impact on the performance of solar cells.

5.3 Discussion

5.3.1 Multiple Influences of the Location on Design

A first observation that can be made is that in cases of architectural facades and of artworks installed on building exteriors, such as Yaacov Agam's *Complex Vision*

(see Section 5.2.6.4) and *Dichroic Light Field* by James Carpenter Design Associates (see Section 5.2.6.2), some characteristics of the location greatly influenced design choices. Several of the examined cases were designed to face roads or streets and to be perceived by viewers moving in directions approximately parallel to the considered building front. Such cases include the façade *May/September* at the Eskenazi Hospital Parking Structure (see Section 5.2.6.1), featuring a multitude of variously angled metal panels with sides of two different colours, and the envelope of the Delancey and Essex Municipal Parking Garage (see Section 5.2.6.8), characterised by two distinct, overlaid layers of cables producing a moiré effect perceived as dynamic by pedestrians and drivers. Some architectural skins were conceived to be appreciated from a distance, which affected the displayed pattern scale. For instance, The Western façade of the Brisbane Girls Grammar School (see Section 5.2.6.7) was designed to be perceived as moving by motorists on a highway, while facades of buildings belonging to university complexes, namely of the SAIT Polytechnic Parkade (see Section 5.2.6.11) and of the Dalarna Media Library (see Section 5.2.6.13), were conceived to be seen from the open spaces of the campuses and to visually blend with their landscapes. The design of the *Anamorphic Façade* by Carpenter | Lowings (see Section 5.2.6.6) was informed by considerations on the various viewing perspectives characterising the public space of Merchant Square in Paddington Basin, where the skin was expected to be built. Other facades were conceived to stand out in environments rich in stimuli such as the densely built neighbourhood in São Paulo where the Leitão_653 Studios (see Section 5.2.6.9) rise, or the high-end shopping district in Shanghai where the Michael Kors store is situated. The configuration of *Complex Vision* by Yaacov Agam (see Section 5.2.6.4) was designed not only considering the site shape and the direction of viewers' movement, but also taking into account the 'audience' including visually impaired people. Therefore, it can be evinced that characteristics of the location such as the type of surrounding landscape, the shape of the public space in front of a façade, the subsequent type of viewers' movement and the expected 'audience' to engage visually can determine the choice of certain architectural skin configurations or features over others.

5.3.2 Influence of the Site on Design

The morphology of the site, affecting the distance of people's viewpoints from a given façade, appears to determine the scale of modular skin configurations in terms of both size and spacing of modular components. These variables appear especially

critical in pixelated skins such as that of the Eskenazi Hospital Parking Structure (see Section 5.2.6.1), or *Piksol* (see Section 5.2.6.3), in which the size of a 'pixel' relatively to the whole façade, comparable to the resolution of digital images, is what makes visual content distinguishable from a certain distance. Scale is crucial also for the perception of façades displaying moiré patterns, not just for the appreciation of kinetic effects from a given distance, but also for the possible impact that viewing those patterns may have on some people's health. As emerged from the literature review in Section 2.3, striped patterns typical of Op Art works can induce forms of discomfort such as headaches, nausea and even seizures in sensitive individuals, which is associated with a pattern's spatial frequency. Some researchers therefore suggested that spatial frequency should be considered in the design of urban environments, and that it may be possible to predict the potential negative impact of scenes characterised by mid-range spatial frequencies (Le et al., 2017) following a proposed algorithm (Penacchio & Wilkins, 2015). However, the complexity of dynamic urban settings suggests the need for further research on the topic, which goes beyond the scope of the current exploration.

5.3.3 Influence of the Building on Its Skin Design

In analysed cases of architectural façades, sometimes built to retrofit existing constructions, the building type was found to influence the preference of certain skin features over others. Several of the architectural skins examined were designed to mask car park buildings, responding to natural lighting and ventilation requirements with porous screen configurations. These are the facades of the Eskenazi Hospital Parking Structure (see Section 5.2.6.1), of the City View Garage in Miami (see Section 5.2.6.5), of the Delancey and Essex Municipal Parking Garage (see Section 5.2.6.8) and of the SAIT Polytechnic Parkade (see Section 5.2.6.11). These architectural skins are characterised by porosity and by the predominant use of metal components, such as angled metal panels, fins punched and folded out of metal screens, or composite cables covered in stainless steel. In other cases with no demands for natural ventilation, the buildings present impenetrable skins, like in the artworks *Dichroic Light Field* by James Carpenter Design Associates (see Section 5.2.6.2) and *Complex Vision* by Yaacov Agam (see Section 5.2.6.4), or in the concept *Piksol* by Drzach & Suchy (see Section 5.2.6.3), which seems conceived to display on blank, opaque facades patterns or images composed by means of shadows as pixels. In these cases, the freedom granted by the limited skin functions allows the creation of visual content with components such as painted

metal screens, laminated glass panels and dichroic glass fins. It can be observed that in cases of building types demanding a fine-tuned control of lighting conditions, such as office buildings, designers opted for solutions playing with degrees of transparency to provide shading while maximising the use of natural lighting in the interior and visual permeability. This is illustrated by the pixelated façade of the Leitão_653 Studios (see Section 5.2.6.9), made of glass bricks, and by the outer skin of the SPG Headquarters (see Section 5.2.6.15), featuring closely spaced glass fins characterised by a dotted print. It is also demonstrated by the *Anamorphic Façade* (see Section 5.2.6.6), presenting semi-transparent, coloured glass fins, and by the façade of the Harpa Concert Hall and Conference Centre (see Section 5.2.6.10), composed of twelve-sided, crystal-like modules featuring dichroic glass.

5.3.4 Influence of the Communicative Purpose on Design

It can be noted that all the examined artefacts were informed to some extent by the designers' intent to convey or evoke a certain concept or semantic content, or to make viewers undergo a particular experience. While the *Piksol* system (see Section 5.2.6.3) attempts to directly translate digital images into solar façade installations, the façade of the Eskenazi Hospital Parking Structure (see Section 5.2.6.1) was inspired by the idea of 'camouflage' and conceived to convey movement and interactivity. Various case studies incorporated the display of variable environmental conditions into reflective façade configurations, sometimes enhanced by colour and contrast effects. This is illustrated by the artwork *Dichroic Light Field* (see Section 5.2.6.2), by the patterned facade of the SAIT Polytechnic Parkade (see Section 5.2.6.11), and by the outer skin of the Dalarna Media Library (see Section 5.2.6.13) mirroring its surrounding in fragmented reflections. It is also exemplified by the holographic skin of the Šiauliai Arena (see Section 5.2.6.12) evoking the idea of sunlight that was said to represent the origin of the city's name. In some of the examined cases, the designers attempted to relate a building with the history or traditions of its location by means of its skin's appearance. Examples are the screen of the Brisbane Girls Grammar School (see Section 5.2.6.7), recalling verandas characterising the regional architecture of Queensland in Australia, or the envelope of the Delancey and Essex Municipal Parking Garage (see Section 5.2.6.8), evoking the former presence of the garment industry in the area. Alternatively, other projects establish a connection with physical features of the site. This is visible in the Leong Leong façade in Miami (see Section 5.2.6.5), hinting at shapes of palms and at a shimmering water surface that are both present in the city,

or in the façade of the Harpa Concert Hall and Conference Centre in Reykjavik (see Section 5.2.6.10), evoking the crystalline structure typical of Iceland's geology. Conversely, other analysed building skins were designed to convey identities, as evident in the façade of the Leitão_653 Studios (see Section 5.2.6.9), communicating the idea of connection between the studios' activities and the city, and in the front of the Michael Kors Store in Shanghai (see Section 5.2.6.14), representing distinctive characters of the fashion brand identity through a visual effect reminiscent of shimmering fabric. Lastly, the envelope of the SPG Headquarters in Geneva (see Section 5.2.6.15) evokes motion with a seemingly blurred effect.

5.3.5 Design Strategies and Methods for Visually Engaging Architectural Skins

It can be observed that combined factors related to characteristics of the site, to the building type and to the content to be communicated translated into a variety of visual strategies in terms of skin configurations and uses of materials for the display of motion impressions. These strategies include mirroring dynamic environmental conditions with reflective materials, comprising dichroic and holographic glass, and using three-dimensional, vertically segmented configurations with patterns to be perceived as changing by viewers moving in a direction parallel to the skin's plane. They can also involve exploiting variations in transparency to create blurred dynamic effects and utilising illusions which may be produced, for instance, by overlaying distinct line gratings or with shadow patterns generated by angled elements.

The analysed case studies also revealed design methods utilised in the development of architectural skin configurations directed at engaging passers-by visually. The seemingly dynamic façade of the Eskenazi Hospital Parking Structure (see Section 5.2.6.1) was designed through the extensive use of digital simulations, employing multiple computer programs ranging from the Rhino 3D modelling platform to an algorithmic design plug-in in Grasshopper and custom software. The development of the design for the Michael Kors Store front in Shanghai (see Section 5.2.6.14) entailed simulations with models at multiple scales in the pursuit of the desired shimmering effect. The design of the holographic envelope for the Šiauliai Arena (see Section 5.2.6.12) involved the use of visualisation techniques from early stages of the project. These examples suggest that simulations of three-dimensional objects and lighting play an important role in the design of visually engaging architectural skins.

5.3.6 Potential for Deploying Solar Technologies

Some potential can be recognised for the translation of the examined designs into solar architectural skin configurations. Three-dimensional facades characterised by porous metal screens could be adapted for the application of optimally angled thin-film photovoltaic modules, the efficiency of which could be further enhanced by natural ventilation. Alternatively, an impenetrable metal screen with vertical folds like in *Complex Vision* by Yaacov Agam (see Section 5.2.6.4) could host thin-film panels with improved orientation and concealed active cooling as part of a hybrid photovoltaic-thermal system. Façade configurations presenting glass modules such as fins or stereoscopic elements like the ‘quasi-bricks’ of the Harpa Concert Hall and Conference Centre (see Section 5.2.6.10) could be adapted for the integration of semi-transparent photovoltaic technologies such as Sphelar® panels and coloured perovskite cells, as well as for the use of dichroic filters for spectrum selection or of luminescent concentrators. A visual effect close to that of holographic glass as in the façade of the Šiauliai Arena (see Section 5.2.6.12) could be obtained with holographic solar concentrators. Other modular façade configurations may offer possibilities for the integration of low-concentration devices. For instance, the pixelated configuration as in the skin of the Leitão_653 Studios (see Section 5.2.6.9) could host devices such as the ‘Dielectric Based Three-Dimensional Cross Compound Parabolic Concentrator’ (Baig et al., 2014). Instead, the façade design of the Dalarna Media Library (see Section 5.2.6.13) could be envisioned with integrated compound parabolic concentrators or V-troughs. On the other hand, the patterned front of the Michael Kors Store in Shanghai (see Section 5.2.6.14) could be adapted for the integration of optimally tilted, small 3D-printed concentrators for external light trapping (Van Dijk et al., 2015). However, the suggested solutions may present issues related to shading or inhomogeneous irradiance on solar cells due to the three-dimensional arrangement of elements. The negative effects of this might be mitigated with micro inverters or power optimisers, although this requires in-depth investigation beyond the aims of the present research.

5.4 Conclusions

This chapter presented fifteen case studies of architectural skins, based on secondary sources, which were selected for their characteristics that, according to the outcome of the literature review, were found to have potential for stimulating visual engagement and for facilitating effective energy generation through photovoltaic-based technologies. Such features included the display of motion, two-

and three-dimensional forms, colours and patterns or figures, which emerged from the review on visual perception in Section 2.3.2, considering physiological and cognitive aspects of its psychology and neuroscience. They also comprised a modular or pixelated configuration, and the use of static, non-electrically operated components interacting with sunlight thanks to their optical properties enabling them, for instance, to reflect, refract, transmit or emit light. The relevance of these qualities emerged from the review on media facades in Section 2.4 and on solar architectural skins in Chapter 3 which also presented benefits of three-dimensional forms. The fifteen examples of architectural skins, including facades and artworks, were analysed by describing visual design and technology aspects for each case, which was based on data gathered from secondary sources. The analysis considered information on the time of completion and on the location of each project, suggesting possibilities for the integration of solar technologies based on findings from Chapter 3. The overall discussion of the cases revealed aspects that can influence the design of visually engaging architectural skins producing motion impressions without kinetic or electrically operated components, along with strategies with which designers may respond to such factors, potentially deploying solar technologies.

It was found that characteristics of the location, including its landscape and the type of public space it offers, can determine how and by whom an architectural skin is perceived. Features of the particular site, such as its form and size affecting the viewpoints from which people can experience a façade, can impact, for instance, the scale of its modular elements. The building type and hence the activities carried out in the interior spaces influence the choice of porous or impenetrable and transparent or opaque screens, while the intent to communicate certain semantic content or to facilitate a particular experience determines the choice of the visual effects to be displayed on an architectural skin.

Several strategies were identified for producing motion impressions through static architectural skins in order to stimulate visual engagement. Predominantly three-dimensional, the examined designs showed reflections of environmental conditions, as well as blurred effects created with varying transparency levels. They also revealed compositions that are perceived as changing by moving viewers, and illusory effects generated, for instance, with moiré patterns. Simulation and visualisation techniques employed from early design stages seem to play an

important role in the development of static architectural skin configurations that can produce motion impressions.

Opportunities and constraints for the effective deployment of solar technologies on visually engaging architectural skins also started to be identified. Potential solutions for the integration of photovoltaics into seemingly dynamic facades may include the use of thin-film solar cells on angled metal elements, of spherical and perovskite cells embedded into glass fins or stereoscopic modules, or of filters for spectrum selection. They may also involve utilising low-concentration devices such as holographic, luminescent and dielectric filled concentrators, small 3D-printed devices for external light trapping, and reflectors such as V-troughs or compound parabolic concentrators.

The following chapter expands on the above aspects, which are summarised in the table below (see fig. 72.), towards outlining an approach for designing effective solar architectural skins that are capable of stimulating visual engagement.

Selection and Analysis of Case Studies	<p>Selection Criteria</p> <ul style="list-style-type: none"> • <u>Display of motion</u> (according to findings on visual perception from Section 2.3.2) • <u>Display of forms, colours, patterns or figures</u> (according to findings on visual perception from Section 2.3.2) • <u>Three-dimensionality</u> (according to findings on visual perception from Section 2.3.2 and on solar architectural skins from Section 3.4) • <u>Modular or pixelated configuration</u> (according to findings on media facades from Section 2.4 and on the design of solar architectural skins from Section 3.3) • <u>Physically static and non-electrically operated components</u> (according to findings on media facades from Section 2.4.4 and on solar architectural skins from Section 3.4) • <u>Optical properties</u>, e.g., the capacity to reflect, refract, emit or transmit light (according to findings on media facades from Section 2.4.4 and on solar architectural skins from Section 3.4) <p>Selected Case Studies</p> <ul style="list-style-type: none"> • 15 examples of architectural skins (facades and artworks) • Based on secondary sources <p>Analysis Method</p> <ul style="list-style-type: none"> • For each case, collection of data from secondary sources • For each case, description of the visual design and technologies used, including information on the location and year of completion as well as suggestions for the integration of solar technologies (based on findings from Chapter 3) • Overall discussion of the cases
Key Findings	<p>Influences on the design of static architectural skins with potential for stimulating visual engagement (as understood from the study of visual perception in Section 2.3.2) and for deploying solar technologies effectively (according to findings on solar architectural skins from Section 3.4)</p> <ul style="list-style-type: none"> • Characteristics of the location (e.g., landscape, public space, audience, etc.) • Characteristics of the site (e.g., form, size and viewpoints) • Characteristics of the building (e.g., form and function) • Particular communicative purpose (e.g., conveying a particular message or stimulating an experience) <p>Design possibilities for static architectural skins capable of stimulating visual engagement with solar technologies</p> <ul style="list-style-type: none"> • Multiple visual strategies (e.g., mirroring the surroundings, three-dimensional configurations appearing dynamic to moving viewers, blurred effects and illusory patterns), tested through simulations and visualisations, to display visual motion (according to findings on visual perception from Section 2.3.2) • Possible deployment of PVs on different types of façade elements (e.g., fins and angled or stereoscopic modules), semi-transparent or opaque, with light filters or low-concentration devices

Fig. 72. *Summary of the Analysis of Case Studies with Its Key Findings* (2019)

Chapter 6: Towards a Design Framework

6.1 Chapter Overview

This chapter brings together the information gathered throughout the literature review and the analysis of case studies, outlining an approach for designing new concepts of effective solar architectural skins that are capable of stimulating visual engagement.

The second section discusses, through five subsections, the concepts which emerged in earlier chapters regarding the factors that can determine decisions at early stages of designing solar architectural skins for visual engagement.

The third section presents, through four subsections, four main types of possible design variations for solar architectural skins aimed at producing visual engagement, with which designers can respond to the constraints of a project.

The last section draws the chapter's conclusions, delineating a multi-criteria approach to conceiving solar architectural skins for visual engagement, as a framework of aspects to consider in early design.

6.2 Influences on Design

Earlier chapters revealed various factors which can influence the design of architectural skins that are capable of producing visual engagement and of generating energy effectively, particularly through photovoltaic-based technologies. Such aspects emerged from the examination of publications in multiple research fields which ranged from vision science to media architecture in Chapter 2, and from established to emerging solar technologies for building integration in Chapter 3. Design criteria also came to light in Chapter 5 through the analysis of selected case studies of architectural skins displaying visually engaging effects that could be similarly achieved by deploying photovoltaic-based technologies for generating useful energy, as found in Chapter 3. Thus, findings from the interdisciplinary literature review and the analysis of case studies can be discussed and combined into a set of aspects to consider in designing concepts of solar architectural skins for visual engagement while pursuing efficient energy generation. The intent is mainly to identify aspects that are relevant to the visual design of solar envelopes at an early stage, by taking into account what is likely to affect visual perception as well as the performance of photovoltaic-based technologies. This excludes an in-

depth investigation of technical issues concerning design and technology development, which goes beyond the scope of this research. Instead, it reveals some main factors which can influence the early design of solar architectural skins and are presented below.

6.2.1 Location

Intended here as the position of a building on the planet, the *location* was found to be a highly important factor affecting the design of architectural skins which are capable of stimulating visual engagement and of generating energy effectively through photovoltaic-based technologies.

In Section 3.3 and in Section 3.4 it was found that the performance of photovoltaic technologies depends on environmental conditions including insolation levels, temperature, shading, and soiling, which vary with the location's climate and with the latitude. This also affects the optimal tilt and orientation of PV components, as the former should be close to the latitude angle (Sick & Erge, 1995:92), while the latter should be between $+20^{\circ}$ and -20° of due south so that about 95% of the available solar energy can be absorbed (Thomas, 2003:18), at least in the Northern hemisphere (Sick & Erge, 1995:160).

Depending on the location's climate, environmental conditions lowering the performance of photovoltaics may vary, and thus the design of a solar architectural skin should respond accordingly. For instance, in locations where the climate is often characterised by diffuse lighting conditions, solar technologies such as Sphelar® modules (see fig. 30.) and low-concentration systems, which were presented in Section 3.4, may be more appropriate. On the other hand, where temperatures are higher using strategies to prevent the overheating of PV modules, as found in Section 3.4.5, may be particularly important. In relation to this, the topography and wind regime of a location may also have an impact (Thomas, 2003:18), by affecting natural ventilation.

The location of the building also affects the cost of an architecturally integrated solar installation because, as appears obvious, it can determine the ease of material supply, but also because of the different cost-reducing incentives offered by local and central governments in regions around the world. The 'utility interconnection' available in a certain area may also influence the choice of a grid-connected or stand-alone photovoltaic system, which is also subject to constraints imposed by local regulations concerning construction and safety (Sick & Erge, 1995:160-163).

Cultural elements of the building's location may also impact the design of a solar architectural skin for visual engagement. As emerged throughout Chapter 5 and discussed in Section 5.3, a communicative façade design may be inspired by traditional forms of the local architecture or by local history. As highlighted by Carr et al. (1992) climate and topography may determine the presence of an outdoor public life, which can be facilitated in warm areas, but there are also 'cultural forces' affecting it in urban spaces, including 'social', 'functional' and 'symbolic' aspects associated with physical settings (Carr et al., 1992:26–27).

In summary, the building's location can have multiple influences on the design of captivating solar envelopes. It affects the effectiveness of architecturally integrated solar installations, depending on climatic conditions as well as on economic factors, and the visual composition of a façade, which may derive from local cultural influences.

6.2.2 Outdoor Environment

The *outdoor environment* facing a solar architectural skin can impact its design in various ways. The literature reviewed in Section 3.4 revealed that it is important to avoid shading on photovoltaic surfaces, and therefore the form of urban spaces adjacent to a building determines whether there are elements casting shadows on photovoltaic modules, lowering their performance. It can be added that the 'height-to-width ratio' of streets and other urban voids can significantly affect daylighting and energy use in buildings (Sattrup & Strømman-Andersen, 2013:58), which influences buildings' energy demand and thus the sizing of photovoltaic arrays, besides their correct positioning to avoid shading.

As emerged throughout the analysis of case studies in Chapter 5 and discussed in Section 5.3, the urban form of the environment surrounding a façade determines how viewers move in its proximity and thus how they can perceive it. The shape of the outdoor space was found to impact the perspective from which an expressive architectural skin is viewed, affecting its visibility, its form and the scale of its modules or 'pixels'. It was observed that facades were designed differently to be viewed, for instance, from a street or road, or within in a plaza, while moving or not. As proposed by the 'configurational' or 'space syntax' approach, urban spaces can be examined in terms of relations between 'space' or 'physical form', 'use' or 'occupation' and 'movement', and 'perception' (Kropf, 2009:110–111), thus the urban configuration is what mainly determines movement patterns (Oliveira, 2016:121).

Different types of outdoor environments may be found, which impact the design of visually engaging architectural skins. Their influence on design may derive from their form but also from their function or uses. Moudon (1997), distinguished the essential physical elements of urban form as buildings with their open spaces, 'plots' or 'lots' and 'streets' (Moudon, 1997:7). Urban outdoor spaces are not necessarily public, thus Stanley et al. (2012) defined 'open space as *any urban ground space, regardless of public accessibility, that is not roofed by an architectural structure*' (Stanley et al., 2012:1089). They considered various types of open spaces identified as 'green', 'vegetated', 'grey', or 'hard-surfaced'. They also distinguished 'food production areas', 'recreational space', 'transport facilities', 'streets', 'plazas', 'parks and gardens', and 'incidental space'. The latter refers to open spaces which tend to be neglected and underused (Stanley et al., 2012). Pederson (2013) suggested a differentiation between 'street' and 'square' types based on their planar proportions, according to which a street can be thought of as a square elongated beyond a certain limit. Instead, a plaza is a larger type of square, and as such, it is characterised by some sense of 'enclosure', whereas parks are even larger (Pederson, 2013:99-100).

The form and uses of the area in which the building is situated may also influence the design of a visually engaging solar skin in other ways. Literature reviewed in Section 2.4 suggested that urban environments where visual stimuli are already abundant may present too many distractions for a form of public display to have a relevant impact (Memarovic et al., 2014). On the other hand, it should be considered that visually captivating solar installations may not be appropriate for any outdoor environment. It was noted with regard to media facades that these can be unsuitable for placement by roads, where they could cause traffic accidents, or in areas with historical value (Zielinska-Dabkowska, 2014:106). Similarly, covering original materials with visible photovoltaic modules in areas of historical interest might not be an acceptable option. Therefore, the outdoor environment may determine the suitability of a visually engaging solar skin for a particular setting, as well as the choice of appropriate materials, depending on the desired or allowed level of contrast with the surroundings.

To sum up, several forms or types of outdoor environment can be distinguished which can influence in various ways the design of a solar building skin facing the open space. Some appear particularly relevant to the uses of space, to the

movement of people and to the perception of architectural skins. They can be recognised, for instance, as *street, square, plaza, garden* or *park*.

6.2.3 Building Form and Function

As for urban spaces, the form and function of a building are also important factors determining choices in the design of a visually engaging solar envelope. As mentioned in Section 6.2.1 in relation to the building's location, the sunlight absorption of BIPV installations can be improved with their optimal orientation and tilt angles. Furthermore, as reminded in Section 6.2.2, shading should be avoided on a photovoltaic building skin. Therefore, features of the architectural form may affect the suitability of a solar skin solution for a certain building, depending on whether the building's geometry casts shadow on itself.

It can be added that the building form is an important 'parameter' in the design of energy efficient buildings, as it can facilitate daylighting and effective heating, especially depending on the area and distribution of glazing (Catalina, et al., 2011). For instance, south-facing glazing tends to cause overheating much more than north-facing glazing (Pessenlehner & Mahdavi, 2003:1029), at least in the Northern hemisphere. This may suggest the possibility of integrating solar technologies into shading screens in the form of porous skins facilitating natural ventilation to prevent overheating problems.

The building type associated with the activities carried out inside is also an essential factor in determining the size of a photovoltaic array on an architectural skin, responding to the building's energy demand. For instance, PV installations were indicated as particularly desirable for office buildings, as these regularly demand substantial electrical energy especially in the daytime (Thomas, 2003:18). On the other hand, the historical character of a building might impede the installation of a visually impactful solar skin on it. Oliveira (2016) pointed out that in cities two main types of buildings can be found: 'ordinary' buildings, such as those dedicated to residential or commercial uses and services, and 'exceptional' buildings that due to their form and function become iconic or 'clearly distinguishable' in the urban environment (Oliveira, 2016:26). It may be suggested that visually engaging solar skins are more suitable for buildings that are intended to be iconic or clearly visible in the urban panorama.

As emerged from the case studies analysed throughout Chapter 5 and discussed in Section 5.3, which also included examples of architectural skins built to retrofit

existing constructions, the building type determines the choice of certain envelope characteristics over others. Having to comply with natural lighting and ventilation requirements, architectural skins designed to mask car park buildings were found to have porous screen configurations, especially composed of metal elements. Instead, facades of office buildings requiring controlled lighting conditions were found to use degrees of transparency to maximise daylighting, provide shading and allow views on the outside. Instead, displaying patterns or images on blank, opaque facades may grant greater design freedom. Therefore, the building type appears to have an important impact on the choice of envelope characteristics such as transparency and porosity.

In summary, characteristics of the building related to its uses and to its form can affect decisions in the design of solar architectural skins. They can determine, for instance, the position and scale of a PV array as well as some of its visual features. Solar architectural skins that are capable of stimulating visual engagement may be particularly suitable for constructions that are intended to stand out, such as buildings with cultural, commercial or even industrial character.

6.2.4 Content to Be Conveyed

As emerged in Section 2.2, architecture has a communicative role and therefore has a semantic element to it. The aspect of *meaning* or *content* can be related to the ‘cultural forces’ shaping public life in urban spaces (Carr et al., 1992:26–27). From literature reviewed in Section 2.4, it emerged that a distinction can be made between ‘content’ and ‘interface’ in media facades (Halskov & Ebsen, 2013:664-665), which suggests that the former is a visual message and the latter is the medium. The importance of conveying a message was also implicitly highlighted in relation to designing solar architecture. The intent to make ‘a statement about innovative architectural and engineering design’ or to display photovoltaics with demonstration and educational purposes was mentioned among the motivating factors behind the choice of BIPV solutions (Thomas, 2003:17).

Visual content can be displayed on solar architectural skins in different forms. As commented in Section 5.3, the case studies analysed in Chapter 5 revealed the designers’ intent to communicate or evoke an idea or to prompt a certain experience, which often took shape as an image or pattern and informed the façade configuration. Similarly, elements of text could be displayed as well. The literature reviewed in Section 2.3 suggested that showing visual content which conveys a sense of motion is likely to attract attention. This may be achieved through static

building skins to avoid the operational issues associated with dynamic facades, which emerged in Section 2.4. As found in Section 2.3, some types of visual content, such as high-contrast striped patterns, may cause discomfort in some people. Despite that, cases of architectural skins displaying such patterns were identified and presented in Section 5.2.6.7 and Section 5.2.6.8. The negative effect of those patterns might be weaker in dynamic urban settings than in other contexts, but this should be explored through further research.

As noted in Section 5.3, the *content to be conveyed* influences choices regarding the visible qualities of materials, from semi-transparent to reflective, dichroic and holographic, as well as the shape and size of modular components relative to the whole composition. It can also be observed that while the content to be displayed through a solar architectural skin, such as an image or pattern, informs the design of the medium itself, it is ultimately an integral part of the design's result.

6.2.5 Economic Factors

Various economic factors may influence the design of effective solar architectural skins aimed at stimulating visual engagement. As noted in Section 2.4, visually engaging architectural skins broadly indicated as media facades which display dynamic effects tend to be expensive as well as energy intensive. For instance, kinetic façade systems require high initial investments, constant maintenance (Alotaibi, 2015:2), and an energy source to power their operation (Decker & Zarzycki, 2014:180). For these reasons, static façade systems capable of producing motion impressions, as exemplified by the case studies analysed in Chapter 5, may be a more viable option to contain costs.

As highlighted in Section 3.2, there are multiple economic advantages associated with integrating solar technologies into buildings, such as on-site energy production with more efficient land use, and potentially lower installation costs (Reijenga & Kaan, 2012:698; Shukla et al., 2016:100), as well as reduced manufacturing, operation and maintenance costs (Norton et al., 2011:1652). Additionally, the cost of a photovoltaic system can be lowered by incentives, such as tax credits or exemptions, loans and subsidies, made available by governmental and local administrations as a way of encouraging consumers to opt for renewable energy solutions (Sick & Erge, 1995:162). These economic factors may contribute to the decision of integrating solar technologies into the building envelope as part of an architectural project.

Influences on the design of solar architectural skins are also linked to the costs of solar technologies. Some of the photovoltaic technologies mentioned in Chapter 3 can be more cost-effective, although this may vary from case to case in architectural designs. Second-generation photovoltaics, including various types of thin-film solar cells, are manufactured at lower temperatures through deposition on low-cost substrates, which can reduce the cost of solar panels. Dye-sensitised solar cells seem to offer similar economic advantages, although they are less efficient and reliable than other thin-film photovoltaics. This also seems to be a problem of organic solar cells, despite the many benefits they may offer from light weight and flexibility to easy manufacturing through printing as well as disposability (Shukla et al., 2016:102–105). On the other hand, using concentrators to increase the incident radiation on solar cells, and thus their energy output, can reduce the cost of photovoltaic installations by partly replacing semiconductors with the cheaper materials from which optical devices are made (Chemisana, 2011; Singh, 2013:7; Shanks et al., 2016:395). However, further research is needed to make concentrating photovoltaic technologies more competitive (Shanks et al., 2016:395), and low-concentration systems appear to be promising for the future of Building Integrated Photovoltaics (Baig & Mallick, 2011). Systems approaching a 10x concentration ratio may be the most advantageous (Chemisana, 2011:604) as they may offer a good compromise between low cost, architectural integrability and energy output efficiency. Future research on novel approaches to solar concentration, sun tracking and cooling might also offer new opportunities for cost-effective solar building skins.

There are multiple economic aspects involved in architectural projects, an overview of which was provided by a study on building retrofit strategies, which indicated a variety of ‘economic parameters’ related to technological and installation aspects of retrofit projects. The identified economic factors included the costs of design and production, construction, operation and dismantling (Seghezzi & Masera, 2017). Among these parameters which can also apply to projects of solar architectural skins, initial and operational costs emerged particularly from the reviewed literature as influential factors in early design choices.

6.3 Design Variations

The previously discussed types of factors that may contribute to decisions in the early design of visually engaging solar building envelopes can lead to a variety of possibilities for architectural skin configurations. While design options may be

potentially countless and may increase as new solar technologies for building integration become available, classes of possible design variations emerged from the reviewed literature and from the examined case studies, which are presented below.

6.3.1 Visual Strategy

The term *visual strategy* is proposed here to identify the approach used to convey dynamic content, and thus to trigger visual engagement. In the present research it refers particularly to different types of motion impressions or illusions to be produced through static, solar architectural skins. This results from the findings of Section 2.3, suggesting that among the features which may stimulate visual engagement when displayed on architectural skins, motion is a very strong visual attractor, and a sense of motion can be conveyed without any actual movement. It can be produced, for instance, with illusory patterns. Considering the findings of Section 2.4.4, displaying motion impressions on static artefacts was chosen in this research as an approach to explore for reducing operational issues that are typical of dynamic media facades, including the need for electric power and for maintenance. As noted in Section 5.3, the analysis of case studies presented in Chapter 5 suggested four main ways of producing motion impressions through static architectural skins, which may also be combined together. These strategies can be indicated as *environmental reflections*, *illusory motion*, *change with perspective*, and *blur*.

The visual strategy identified as *environmental reflections* is characterised by the display of motion from the surrounding environment by means of reflective surfaces, also enhanced by colour. The case studies in which this strategy can be recognised were presented in Section 5.2.6.2, Section 5.2.6.5, Section 5.2.6.10, Section 5.2.6.11, Section 5.2.6.12, and Section 5.2.6.13.

The strategy indicated as *illusory motion* encompasses ways of creating motion impressions through patterns based on colour or luminance contrast, that can be two- or three-dimensional. This strategy can be found in striped, black and white Op Art Paintings or in the motion illusion by Akiyoshi Kitaoka *Rotating Snakes* (see fig. 9.) indicated in Section 2.3.2.3. It can also be recognised in the case studies presented in Section 5.2.6.7 or Section 5.2.6.8. Shadows created by three-dimensional patterns may be exploited to achieve the desired luminance contrast.

Change with perspective identifies the visual strategy involving patterns or images displayed in distinct portions to form content that appears to vary with viewers'

perspective and movement, which is exemplified by Yaacov Agam's art mentioned in Section 2.3.2.3. This strategy can be found in case studies presented in Section 5.2.6.4 and Section 5.2.6.6. It appears particularly suitable for open spaces which are shaped in a way that facilitates the flow of people.

Blur indicates the strategy for evoking motion through the display of forms with indistinct contours. According to Cutting (2002), using blur is maybe 'the most obvious way to represent motion' in static images, although it depicts objects as unclear due to the 'indistinctness of edges' (Cutting, 2002:1182). The analysed case studies exemplifying the use of a *blur* strategy through varying transparency can be found in Section 5.2.6.9 and Section 5.2.6.15.

It may be possible to combine the above visual strategies to produce more striking visual effects, and additional approaches may emerge potentially from further research. For instance, more strategies besides blur, which are used to evoke motion in static representations, could be explored to be translated into architectural skin designs.

6.3.2 Skin Morphology

The term 'morphology' was previously used in research on kinetic facades (Moloney, 2011) and indicates 'the study of physical form', such as that of living organisms and artefacts (Kropf, 2009:107). 'Design' itself may be interpreted as morphology, as Steadman (2008) pointed out that 'it is concerned above all with the *arrangement* of elements or components – material or spatial – in different two- or three-dimensional configurations' (Steadman, 2008:232). Therefore, with a focus on the building envelope, the *skin morphology* identifies its overall shape.

Throughout the literature review and analysis of case studies, some features were found to contribute particularly to the form of an architectural skin, impacting both its capacity for triggering visual engagement and the effectiveness of integrated solar arrays. The morphological aspects of solar architectural skins conceived to produce visual engagement can be summarised as *orientation and tilt*, *scale*, *modular configuration*, and *module geometry*.

Orientation and tilt angles are especially relevant to the effectiveness of solar installations, as they can increase or decrease the amount of solar radiation absorbed by solar modules. Both angles can characterise the whole architectural skin and the individual modules composing it. The optimal orientation or azimuth was indicated as close to the direction of the South (Sick & Erge, 1995:92; Reijenga

& Kaan, 2012:700) in the Northern hemisphere (Sick & Erge, 1995:160), while being the opposite in the Southern hemisphere. To collect about 95% of the available solar energy, an orientation between approximately +20° and -20° of due south was recommended (Thomas, 2003:18). On the other hand, the optimal tilt of solar modules was said to be close to the value of the latitude (Sick & Erge, 1995:92; Reijenga & Kaan, 2012:700) at the considered location. Given this relation between optimal tilt and latitude, solar skins or their individual modules characterised by steeper or vertical tilts can perform better at higher latitudes. Similarly, higher tilt values may also be applied to solar arrays facing the East or the West, having incident radiation with lower angles in the morning or afternoon (Sick & Erge, 1995:92). When modules of a solar skin are individually angled, a three-dimensional configuration with luminance patterns formed by shadows can be created, which may produce visually engaging effects as exemplified by case studies analysed in Section 5.2.6.5 and Section 5.2.6.11. However, three-dimensional arrangements may cause shading or inhomogeneous irradiance on solar cells, solutions to which may be found by carrying out shading simulations in early design stages. Alternatively, the issue may be addressed through an electrical design integrating micro inverters or power optimisers, as suggested in Section 5.2.6.1, but this goes beyond the scope of the present research.

Scale indicates the overall size of a solar architectural skin in relation to the size of the building it covers, as well as the size of the single skin modules. The latter determines the number of skin modules in relation to the whole, which was indicated by Moloney (2011), referring to kinetic facades, as ‘granularity’, and was compared to ‘resolution’ in computer graphics (Moloney, 2011:87). The relative scale of a skin and of its components greatly affects the way it is perceived from different viewpoints. A higher ‘resolution’ can allow the display of well-defined visual content to be viewed from a close distance. On the other hand, it can be observed that the size of the overall active area of a solar envelope determines the amount of energy that can be generated, stored and used within the building.

Modular Configuration echoes what was indicated as ‘pixel configuration’ in relation to media facades (Halskov & Ebsen, 2013:665), and identifies the geometric pattern or grid within which the building skin modules are assembled. It can be noted that it may affect or be affected by the shape of the individual modules.

Module geometry reflects what was indicated as ‘pixel shape’ in the context of media facades, referring to the ‘physical form’ (Halskov & Ebsen, 2013:665) of a building

envelope's modular component. It can be observed that in the design of solar architectural skins, the shape of a module can be determined to some extent by the solar technology used. This may require active surfaces to be optimally angled or may include optical devices like solar concentrators mentioned in Section 3.4.6, which are characterised by precise geometries to increase the incident radiation on solar cells. In the analysed case studies of visually engaging architectural skins, various module forms were encountered. Shape variations ranged from stereoscopic modules, as found in Section 5.2.6.10, to predominantly two-dimensional elements such as glass panels or fins as found in Section 5.2.6.15, or approximately one-dimensional elements as shown in Section 5.2.6.7 and Section 5.2.6.8. The shape of an architectural skin's module may include openings, which can create the porosity typical of screens covering car park buildings, as noted in Section 5.3.

It can be observed that all the above aspects of the skin morphology are intertwined in the design of a solar building envelope aimed at producing visual engagement, and that they can influence each other. Orientation, tilt and module shape are strictly interrelated, just as modular configuration, scale and module geometry are closely interdependent.

As found through the analysis of case studies and discussed in Section 5.3.5, the skin morphology can be determined through a process that makes extensive use of digital simulations, including 3D modelling and algorithmic design. Utilising visualisations from early design stages also appears to be beneficial, as it enables the imitation of natural lighting.

6.3.3 Visual Quality

Visual quality echoes the term 'light quality' proposed in a study which offered a framework for the design of media facades, where it indicated the brightness of the emitted light and the smoothness of the displayed colours, as well as effects produced by reflectors and light diffusers (Halskov & Ebsen, 2013:665). Since the present research explores ways of deploying photovoltaic-based technologies on architectural skins rather than artificial lighting systems that are typical of media facades, the term *visual quality* is here proposed to indicate visual properties of materials, which describe their interaction with natural light. Some of the visible features of solar technologies, such as colour and surface texture, were highlighted in previous studies providing guidance for designing architecturally integrated solar energy systems (Farkas, 2013; Munari Probst & Roecker, 2013). However, further

qualities of materials can be considered, which may contribute to producing the effects indicated in Section 6.3.1 as *visual strategies* and may be added to a design by deploying photovoltaic-based technologies reviewed in Chapter 3.

Colour indicates a type of visual property of materials that effectively emerges inside the human mind as the light spectrum is translated into colour representations within the visual system (Lindsey & Brown, 2014:511), thus resulting from the wavelength of light reflected by a material. As emerged in Section 2.3, aspects of colour are among the most salient visual features (Ware, 2013:154–155; Schall, 2014:907), and certain static colour patterns can generate ‘illusory motion’ (Chi et al., 2008). As presented in Section 3.3, colour can be found in a variety of solar products for building integration, including multi-crystalline silicon wafers, semi-transparent photovoltaic glass and photovoltaic tiles. It also distinguishes third-generation photovoltaics such as dye-sensitized, organic and perovskite solar cells. As found in Section 3.4, photovoltaic technologies for building integration with improved performance, which also feature colours, can include the use of holographic and luminescent concentrators as well as of light filters.

Texture refers to the ‘tactile quality’ (Oxford University Press, 2017e) and thus to the smoothness of a visible surface on an architectural skin, which affects the way light is reflected. Relatively small angled modules on an architectural skin can give it a textured quality as in the case analysed in Section 5.2.6.14 where it was suggested that a comparable effect could be produced by arranging in a similar configuration small reflective concentrators (Van Dijk et al., 2015) which were mentioned in Section 3.4.

Transparency identifies a material’s capacity for ‘allowing light to pass through’ (Oxford University Press, 2017f). Different degrees of transparency can be exploited to compose visually engaging architectural skin designs, as exemplified by the case studies presented in Section 5.2.6.9 and Section 5.2.6.15. It is also an important property of encapsulants protecting photovoltaic modules, through which sunlight is transmitted onto the absorber, as well as of dielectric materials filling certain types of concentrators that were presented in Section 3.4.6.

Reflectivity identifies ‘the property of reflecting light or radiation’ (Oxford University Press, 2017c), which was found in several solar technologies and visually engaging artefacts throughout the literature review and analysis of case studies. While it tends to characterise to some extent materials that protect photovoltaics, such as glass,

reflectivity particularly distinguishes some concentrating devices generically indicated as 'reflectors', which emerged in Section 3.4.6, and was observed especially in case studies featuring environmental reflections, such as those presented in Section 5.2.6.2 and Section 5.2.6.13.

Refractivity indicates the capacity of certain materials to cause 'refraction' of light, occurring when this is 'deflected in passing obliquely through the interface between one medium and another or through a medium of varying density' (Oxford University Press, 2017d). It is the optical property characterising some types of solar concentrators, such as Fresnel lenses (Shanks et al., 2016:397).

Diffraction refers here to the capacity of causing diffraction of light, occurring when light is 'spread out as a result of passing through a narrow aperture or across an edge, typically accompanied by interference between the wave forms produced' (Oxford University Press, 2017a). This property can be found in planar holographic concentrators (Kostuk et al., 2009) and lenses which can improve the performance of solar cells by diffracting on them the bandwidth of the light spectrum to which they are most sensitive (Chemisana et al., 2013). The diffraction of sunlight, manifesting its rainbow colours, was observed in the case study analysed in Section 5.2.6.12.

Luminescence identifies 'the emission of light by a substance that has not been heated, as in fluorescence and phosphorescence' (Oxford University Press, 2017b), and characterises the solar technology of 'luminescent' or 'fluorescent' concentrators, containing molecules of a dye capable of absorbing and re-emitting light with a shift to longer wavelength (Chemisana, 2011:608). 'Total internal reflection' concentrators also present the luminescence property as well as refractivity (Shanks et al., 2016:395). Similarly, luminescence distinguishes light filters for spectral conversion, which can improve the performance of photovoltaics, as presented in Section 3.4.7.

6.3.4 Solar Technology

The visual properties of materials presented in the previous subsection can characterise a solar architectural skin depending on the deployed solar technology as well as on non-active components associated with it. As emerged from the literature review in Chapter 3 and from suggestions made throughout the analysis of case studies in Chapter 5, various photovoltaic-based technologies appear to have potential for effective deployment on architectural skins that may prove visually

engaging. Chapter 3 presented several photovoltaic-based technologies for building integration, which can be distinguished considering some main features.

As emerged in Section 3.2, there are different types of photovoltaic cells. Photovoltaic materials which absorb sunlight converting it into electrical energy continue to be researched and have been identified as ‘absorbers’ (Zakutayev, 2017). These can be distinguished as first, second and third generation photovoltaics, as clarified in Section 3.2.3, which identifies a range of *absorbers* from established solar cells based on crystalline silicon to emerging thin films.

As presented in Section 3.4, there are various ways of increasing the efficiency of photovoltaics, which can be indicated as *performance enhancement strategies*. These include the use of high-efficiency absorbers as well as of three-dimensional or bifacial configurations. They also encompass cooling techniques which can be active or passive, as well as the use of low concentration devices and of spectral converters. Explained in Section 3.4, such strategies were referred to in Chapter 5 where it was suggested they may be deployed on building skin configurations that are similar to those of the analysed case studies.

The material photovoltaic modules for building integration are applied onto can be identified as the *substrate*. As emerged in Section 3.2, substrates can range from glass to metal or plastic. However, further materials may be found suitable as substrates. For instance, in Section 3.2.5 photovoltaic tile products were mentioned. The façade configurations which were examined in Chapter 5 feature components that are largely made of glass or metal and could be adapted potentially for the integration of photovoltaics.

6.4 Conclusions

Several aspects were found to be involved in the design of effective solar architectural skins for visual engagement, which are intertwined and can be distinguished as *influences on design* and *design variations*. Among the influences on design there is an overarching element which is the *location* of the building, affecting the other factors. These include characteristics of the *building* and its *outdoor environment*, the *content to be conveyed* through the solar skin, and *economic factors*. Possible *design variations* in the solar envelope range from the overall *visual strategy* used to features of the *skin morphology*, of the *visual quality* of surfaces, and of the *solar technology* deployed. The latter refers to photovoltaic-

based systems in this research, and comprises an *absorber*, a substrate and a *performance enhancement strategy* which may also involve multiple methods.

The above aspects which emerged from the secondary research can be condensed into a framework that may serve as a design tool for conceiving solar architectural skins aimed at stimulating visual engagement. A tool for supporting the decision-making process in the design of solar envelopes could have been outlined potentially in different ways. For instance, it could have shown detail about relationships between variables, perhaps directing the process as a flow chart. Alternatively, it could have included questions to guide the design strictly towards selecting or excluding options according to starting conditions. However, the researcher considered that a tool aiding the early design stage which is characterised by creative design at a strategic level needed to be flexible rather than to indicate specific directions. It needed to provide design guidance to architecture professionals and students while giving them freedom of choice and allowing potential new links between variables to emerge. Therefore, the researcher chose to suggest a strategic framework which could offer a set of broad design criteria without imposing rigid rules. Thus, the framework was outlined in the form of a diagram summarising general aspects, as well as some of their distinctive features, which are relevant to the early design of photovoltaic architectural skins aimed at stimulating visual engagement (see fig. 73.). Proposing a strategic framework involved presenting general concepts without lengthy descriptions. Expert knowledge of solar technologies could not be conveyed by the design tool alone, so the contents of this chapter and Chapter 3 may be referred to for explanations. The suggested framework, which may be refined through further research and testing, could be potentially improved in the future by embedding web links to online resources or references to learning materials as well as visual contents, which may facilitate designers' understanding of solar technologies.

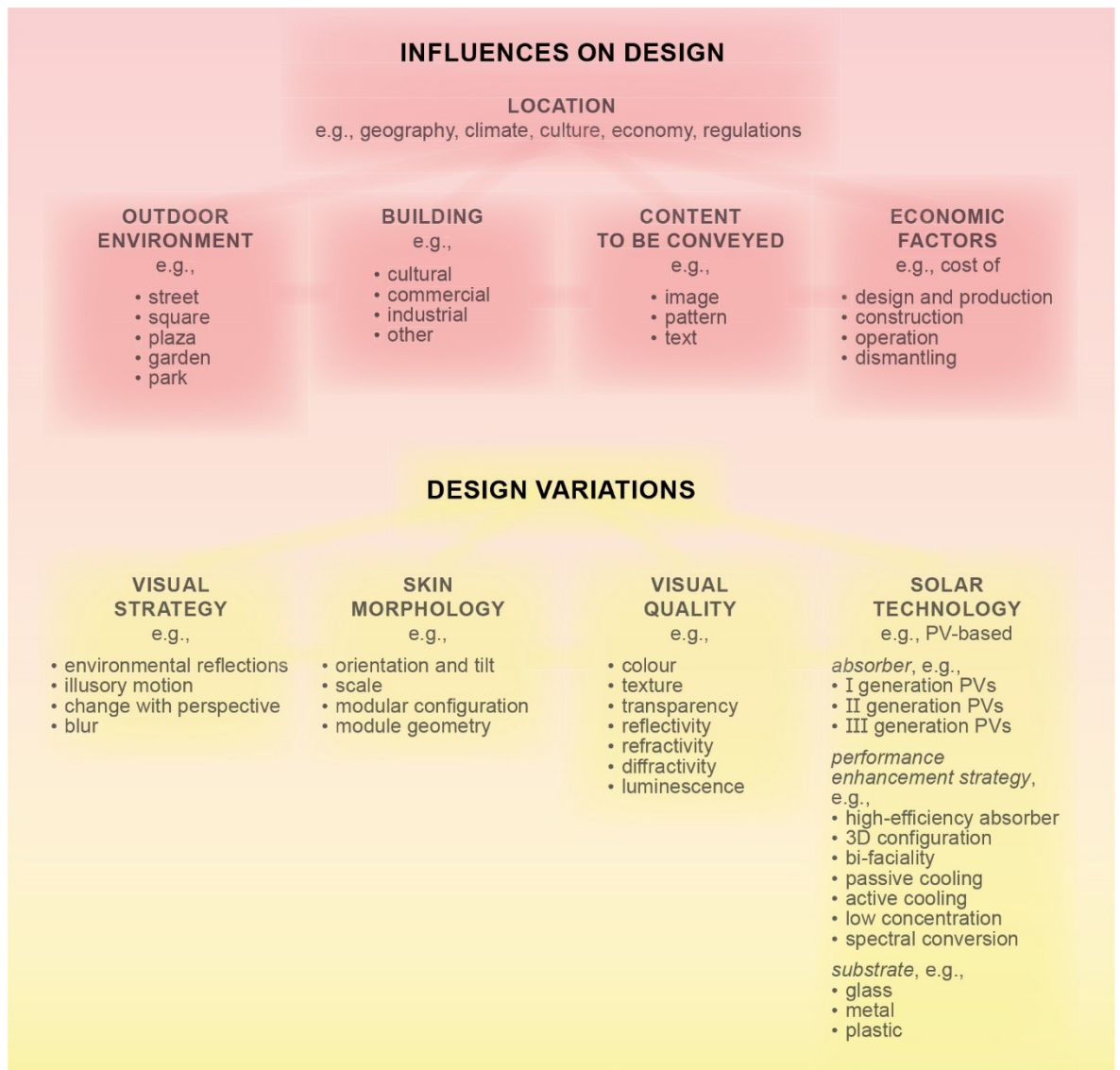


Fig. 73. *Aspects Involved in the Design of Solar Architectural Skins for Visual Engagement* (2017)

Chapter 7: Generating a Concept for a Solar Architectural Skin

7.1 Chapter Overview

The content of this chapter illustrates the first part of the primary, practice-based research phase of the present exploration, aimed at testing the framework that was outlined in Chapter 6. The suggested approach was applied to an example of an early design process for generating a concept of a solar architectural skin aimed at stimulating visual engagement.

The second section introduces the context chosen for the design. Following the framework outlined in Chapter 6, information is provided, through five subsections, on factors influencing the design. These include the site location as well as characteristics of the outdoor environment and of the building to be clad, the semantic content to be conveyed through its skin, and economic factors.

The third section describes the generation of a design concept, based on the proposed approach, for a visually stimulating solar façade for the considered context. It illustrates, through four subsections, the choice of a visual strategy, the definition of the skin morphology, the choice of the visual quality of materials and the selection of a solar technology.

The fourth section discusses the outcome of the described creative process, with considerations that emerged from the design.

The fifth section draws the conclusions of the chapter, commenting on the role played by the framework in providing guidance to the design and hinting at further directions for its testing.

7.2 Starting Conditions for the Design

The framework (see fig. 73.) which was introduced in the previous chapter is aimed at facilitating the process of conceiving solar building skins that are capable of triggering visual engagement. In order to test its effectiveness, the researcher applied the suggested approach to the design of a solar skin for an existing building in Doha, which she was familiar with thanks to her work outside academia. Belonging to Qatar Museums, the site chosen for experimenting with the early design of a solar architectural skin presented a number of favourable characteristics.

7.2.1 The Location: Doha

The site selected for the exploratory design of a solar façade aimed at stimulating visual engagement is part of the Fire Station Artist in Residence, an arts centre situated in Doha, Qatar (Qatar Museums, 2016b).

The geographic location offers a favourable as well as hostile climate for the use of solar energy. Characterised by high levels of insolation but also by adverse climatic conditions such as dust storms, the city of Doha is located approximately at a latitude of 25° North and at a longitude of 51° East (Abdallah, et al., 2016). Given its abundance of solar energy, Qatar has a high potential for the deployment of solar technologies (Martín-Pomares et al., 2017:1244). It shares with other Arab countries the intense sunlight, the high temperatures and the sand storms prompting the need for protection, which caused the fabric of traditional urban settlements to be compact and organic (Ajaj & Pugnali, 2014:286–287). In response to the climate, historic Arab architecture developed features such as courtyards that acted as thermal regulators for the buildings, facilitating natural ventilation, and Mashrabiyas which served as multifunctional screens controlling natural light, air flow, temperature and humidity as well as privacy in the interiors (Ajaj & Pugnali, 2014:287–288).

Doha is the capital city of Qatar, and thanks to its economic growth it has undergone rapid development in recent years, involving large-scale projects ranging from new infrastructures to urban and architectural interventions which are partly still under construction. The city presents examples of vernacular buildings as well as contemporary architecture of western appearance. The former can be seen in the Souq Waqif district, characterised by a meandering market dating back to the 19th century, whereas the latter can be exemplified by the West Bay Financial District featuring several towers that reach heights of 150 metres and above (Furlan, 2016). Traditionally, Qatari architecture is shaped by physical and socio-cultural influences which, besides the climate, include Islamic religious values (Furlan, 2016:3; Al-Mulla, 2017:689).

Doha has been rapidly urbanised since the middle 1990s thanks to oil production. Its overall urbanisation process can be understood as a sequence of phases, starting from an unstructured ‘pre-oil settlement’, followed by a speculative expansion, and progressing to a more coherent development which considers social and environmental aspects as well as economic interests (Wiedmann & Salama, 2013). Currently Doha is inhabited by about 1.7 million people, representing 80% of the country’s diverse population, which prompts the need for high-quality urban

open spaces to be enjoyed in different ways by varied user groups (Salama et al., 2016:181–182).

7.2.2 The Outdoor Environment: An Open Plaza

The Fire Station Artist in Residence sits in an area of Doha that unlike the West Bay Financial District is not characterised by very tall high-rises. The site is delimited by two main roads on the south and west sides, with the largest building complex in the immediate vicinity being the Ministry of Interior to the west. The other sides of the arts centre are surrounded by the vast Al Bidda Park and its facilities (see fig. 74.).

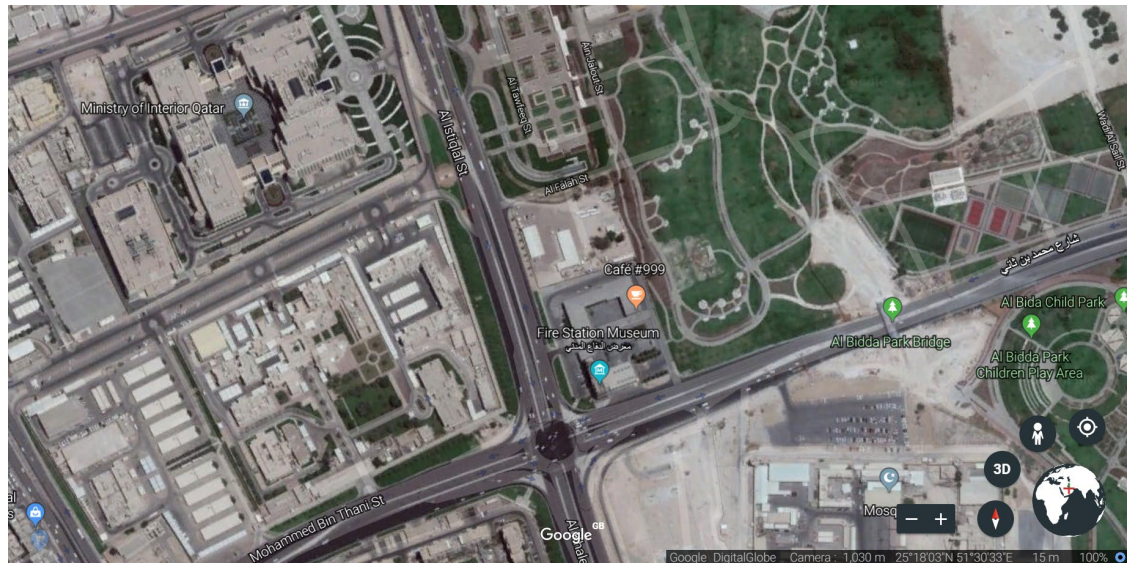


Fig. 74. *Aerial Photograph of the Fire Station Plaza within Its Context* (2018)

The outdoor space examined is a plaza measuring approximately 40 m east-west and 75 m north-south. The paved plaza is partly open on the east and south sides while also having other accesses (see fig. 75.). Therefore, the outdoor space of the plaza allows the circulation of pedestrians in multiple directions between the outside and different parts of the arts centre.



Fig. 75. *Aerial Photograph of the Fire Station Plaza (2018)*

The building facades delimiting the plaza show that the complex is relatively recent. While traditional Arab architecture is made of materials such as stone, brick or wood (Ajaj & Pugnali, 2014:287), the Fire Station plaza is surrounded by facades in which modern materials such as concrete, metal and glass prevail. As revealed by the name, the Fire Station used to be occupied by the base of the fire brigade. Originally built in 1982, it was ceded to Qatar Museums in 2012 to be converted to its current use. The transformation, which preserved original details, was led by the Qatari architect Ibrahim Al Jeidah (Qatar Museums, 2016b). Besides the building facades framing it, the plaza includes elements such as trees, outdoor furniture, artworks, and symbolic remnants of the fire station use. Just like the water features found in courtyards of traditional Arab architectures (Ghiasvand et al., 2008:23), there are pavement fountains on the east side of the Fire Station plaza (see fig. 76.).



Fig. 76. *The Fire Station Plaza Viewed from the South-East Corner (2017)*

Coloured architectural features and taller buildings stand out in the southern part of the plaza. The south-western corner is characterised by a multi-storey structure

covered with a three-dimensional metal screen of golden shade, filtering light to the interiors (see fig. 76.). Towards the south-eastern corner, there is a preserved tower (see fig. 77.) that is intended to be an attraction in night lighting (Qatar Museums, 2016b).



Fig. 77. *The Fire Station Plaza Viewed from the North-West Corner* (2017)

With its multiple points of interest, the plaza can be experienced by its users in various ways, by walking in multiple directions, by standing still or by sitting. This suggests the plaza can be a high-quality open space offering varied experiences to diverse users. However, there seems to be some potential for improving a sense of place, as according to a study on Doha's open spaces the places which are distinctive due to their form, character or history appear to be more memorable for people (Salama et al., 2016:199).

7.2.3 The Building: A Multifunctional Arts Centre

Since its conversion to an arts centre, the Fire Station complex has hosted a variety of cultural activities. It includes gallery spaces, a café and restaurant, an art supply shop, a bookshop and a cinema (Qatar Museums, 2016b). The latter shows an opaque, blank façade characterised by a weathered steel cladding integrating ventilation grilles, and by a small door (see fig. 78.). The exterior with minimal openings responds to the needs of the interior, which being used as a cinema, requires darkness. However, the blank façade could potentially be replaced with a more communicative building skin enhancing the character of the plaza. Additionally, the façade of the cinema is approximately facing the south, which means its orientation is almost optimal for the integration of solar technologies. Therefore, the possibility of replacing the weathered steel façade with a photovoltaic skin was investigated in this study, as a design exercise aimed at testing the

framework outlined in Chapter 6. The design had to consider the constraints of the existing façade in terms of size and openings.



Fig. 78. *On the Right, the Weathered Steel Façade of the Cinema (2017)*

7.2.4 The Content to Be Conveyed: A Reference to Islamic Art

The Fire Station Artist in Residence belongs to Qatar Museums, the organisation that acts as a 'cultural instigator' (Qatar Museums, 2016a) aiming to preserve the Qatari culture as indicated in the *Qatar National Vision 2030* (Qatar General Secretariat for Development Planning, 2008). Among the principles for developing sustainable communities in Qatar, is the promotion of a considerate design of façades which embed elements that evoke the local tradition and improve visual stimulation towards heritage (Alfaraidy & Furlan, 2017:398–399). In this study, the researcher sought a reference to the Qatari cultural identity that could be conveyed through a solar architectural skin in the Fire Station plaza. This led her to investigate the Arab culture in which the Qatari identity finds its roots, considering that there are elements which are believed to reflect the Qatari architecture and can be integrated into contemporary buildings (Ibrahim, 2013).

Ornament is an essential element of historic Arab environments. Traditionally, surface decorations played a major role in defining the spaces of Islamic architecture. They conveyed a sense of 'weightlessness' through media which

included mosaics and painted ornaments among others. Excluding representations of human or other animal figures, traditional decorations depicted highly complex designs, such as geometric or floral patterns and calligraphic inscriptions. Perforated screens filtering light to the building interiors contributed to the sense of weightlessness conveyed by the surface decorations and created patterns of shadows (Ghiasvand et al., 2008).

Even when they did not explicitly communicate verses of the Koran through calligraphic inscriptions (Abas & Salman, 1995:2), traditional Arab decorations were informed by the religious beliefs of Islam. Their aim to inspire a sense of weightlessness as well as of purity, perfection and unity was an expression of faith in a divine presence. Such belief showed in the juxtaposition of contrasting colours as well as in the symmetry characterising the decorative patterns (Farazmand & Satari Sarbangholi, 2014), besides being the reason for the absence of human or animal figures in artistic representations, regarded as being in the realm of God, (Ghiasvand et al., 2008:22). Therefore, Islamic decorations convey a distinctive message and are the product of Islamic spirituality. They manifest the faith in the existence of a divine being that is considered the source of everything and the perfection to aim for, as well as the love for all the creatures that originated from the godly presence (Saeed, 2011).

Islamic geometric patterns were also inspired by the passion for astronomy, which was related to that for the divine realm, for the pursuit of unity, and for abstraction. This was expressed through the repetition of geometric cells using complex polygons, and sometimes arcs, with symmetric transformations, which generated designs based on a grid recalling that of mosaics. The resulting forms were often star-shaped with rectilinear elements that frequently appeared interlaced. While the above distinctive characteristics can be found in Arab decorations created between 900 AD and 1500 AD for Muslims or in places where the Islamic culture prevailed, the definition of Islamic patterns can include geometries derived from the originals and embedding their shapes in a recognisable way (Abas & Salman, 1995:2–72).

A typical Islamic pattern was chosen to be displayed through a solar skin design for the Fire Station plaza, as a reference to the Qatari culture. The selected geometry simply constitutes one example among many possible Islamic patterns. It was presented by different sources (Abas & Salman, 1995:177; Wade, 2019) and features star-like shapes based on an isometric grid. It was adapted by the

researcher through scaling and repetitions of the basic cell to fill a rectangle with the proportions of the considered façade (see fig. 79.).

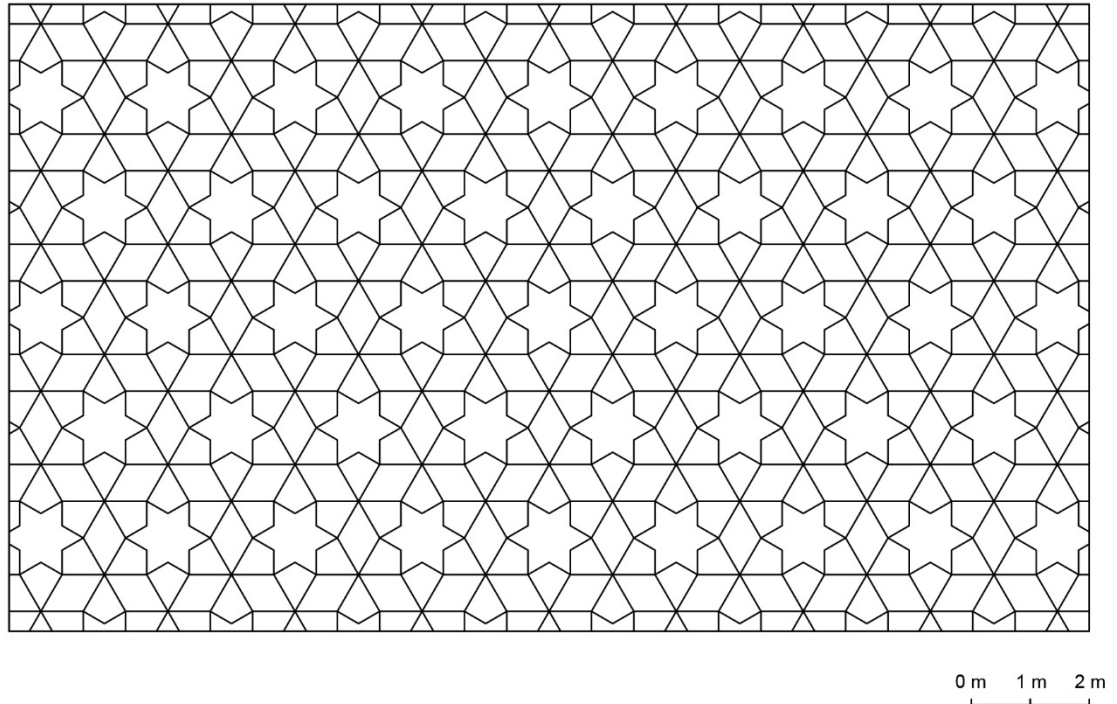


Fig. 79. *Islamic Pattern Adapted to the Form and Size of the Façade Selected for the Integration of Photovoltaics* (2018)

7.2.5 The Economic Influences: Solar Energy in Qatar

As emerged in previous chapters, the design of solar architectural skin is subject to economic factors that may influence the feasibility of integrating solar energy systems into buildings as well as the choice of an appropriate technology. To design a solar architectural skin for the Fire Station plaza in Doha, the researcher examined the economic context of Qatar in relation to energy generation and use.

As previously mentioned, Qatar has experienced rapid economic growth thanks to the production of fossil fuel. There is a lack of regulations and incentives to promote the use of solar energy in the country, where natural gas is largely available, but Qatar intends to generate 20% of its electricity from solar energy by 2030 (Martín-Pomares et al., 2017). Photovoltaic systems are currently not competitive in Qatar, where there is high availability of gas resources; however, they are expected to gain traction (Griffiths, 2013). Thus, there is potential for lowering carbon emissions in Qatar by reducing the use of gas and increasing that of solar energy in the future.

Besides its lack of competitiveness with fossil fuels in terms of cost, solar energy and photovoltaic systems in particular have to face other challenges in Qatar. Among climate-related issues which include heat, humidity and dust, there is a lack of 'interaction and knowledge dissemination' on solar energy (Munawwar & Ghedira, 2014:3200). This could be partly tackled with visually engaging solar installations showing the importance of solar energy within the built environment.

Cost factors related to climatic conditions have a major impact on the effectiveness of photovoltaic arrays in Qatar. In this country, solar panels are highly prone to soiling and require regular cleaning (Guo et al., 2015), ideally on a weekly basis (Martinez-Plaza et al., 2015), which elevates their maintenance cost. Due to the soiling problem, amorphous silicon can perform better than crystalline silicon in Doha (Touati et al., 2013). Commercially available anti-soiling coatings do not seem to overcome the soiling issue, and fixed-tilt configurations are preferred to tracking systems (Martinez-Plaza et al., 2015). There is ongoing research in Qatar aimed at reducing solar costs, including studies on thin films, perovskite solar cells, cooling and anti-soiling solutions (Varghese, 2016). All these aspects need to be considered in the design of a solar building skin for the Fire Station arts centre.

7.3 Generating a Concept

The identified conditions influencing the design of a solar building skin for the Fire Station plaza led the researcher to choose certain features to be embedded in the design. This was done following the possible design variations for the solar skin indicated by the framework, which ranged from the *visual strategy* and the *skin morphology* to the *visual quality* of the surface and the *solar technology* to be deployed.

7.3.1 Choosing a Visual Strategy

The outdoor environment examined is a plaza which allows pedestrians to move in multiple directions as well as to experience the space from stationary positions. This means that to create a visually engaging effect on the solar skin, the content needs to be displayed in a way that generates a sense of motion and that can be appreciated from multiple viewing angles. Among the visual strategies outlined in Chapter 6, the one identified as *environmental reflections* was excluded because, due to the activities carried out in the building and to the brightness of sunlight in Doha, dynamic reflections within the plaza could potentially cause disturbance to people. Additionally, in Doha reflective materials are expected to be frequently covered in dust, which could reduce the effectiveness of the visual stimulation.

Given that the selected portion of the building envelope needed to remain opaque, it was also believed that *blur*, a visual strategy relying on the transparency of materials, was less appropriate for the project.

The researcher decided to adopt a strategy which combined *illusory motion* with *change with perspective* to produce a seemingly dynamic effect perceivable from multiple angles when viewed by the users of the arts centre. To achieve this, the researcher explored the idea of overlapping two layers with reciprocally rotated dotted patterns to create a moiré effect. The two layers were to be separated by a distance, within which a supporting structure could be placed. The dots acted as pixels composing the image to be displayed which was distinguishable on the outer layer (see fig. 80.). The exterior surface had to allow the inner one to be visible enough for the vibrating visual effect to be perceived by viewers moving by the façade. Therefore, a porous configuration for the outer layer was proposed, and its dots became perforations. This solution was expected to allow natural ventilation and, in turn, assist passive cooling of photovoltaic modules. The dotted pattern, to be painted on white background on the inner layer, was conceived as an opportunity for the seamless integration into the wall of ventilation grilles with the same dotted configuration.

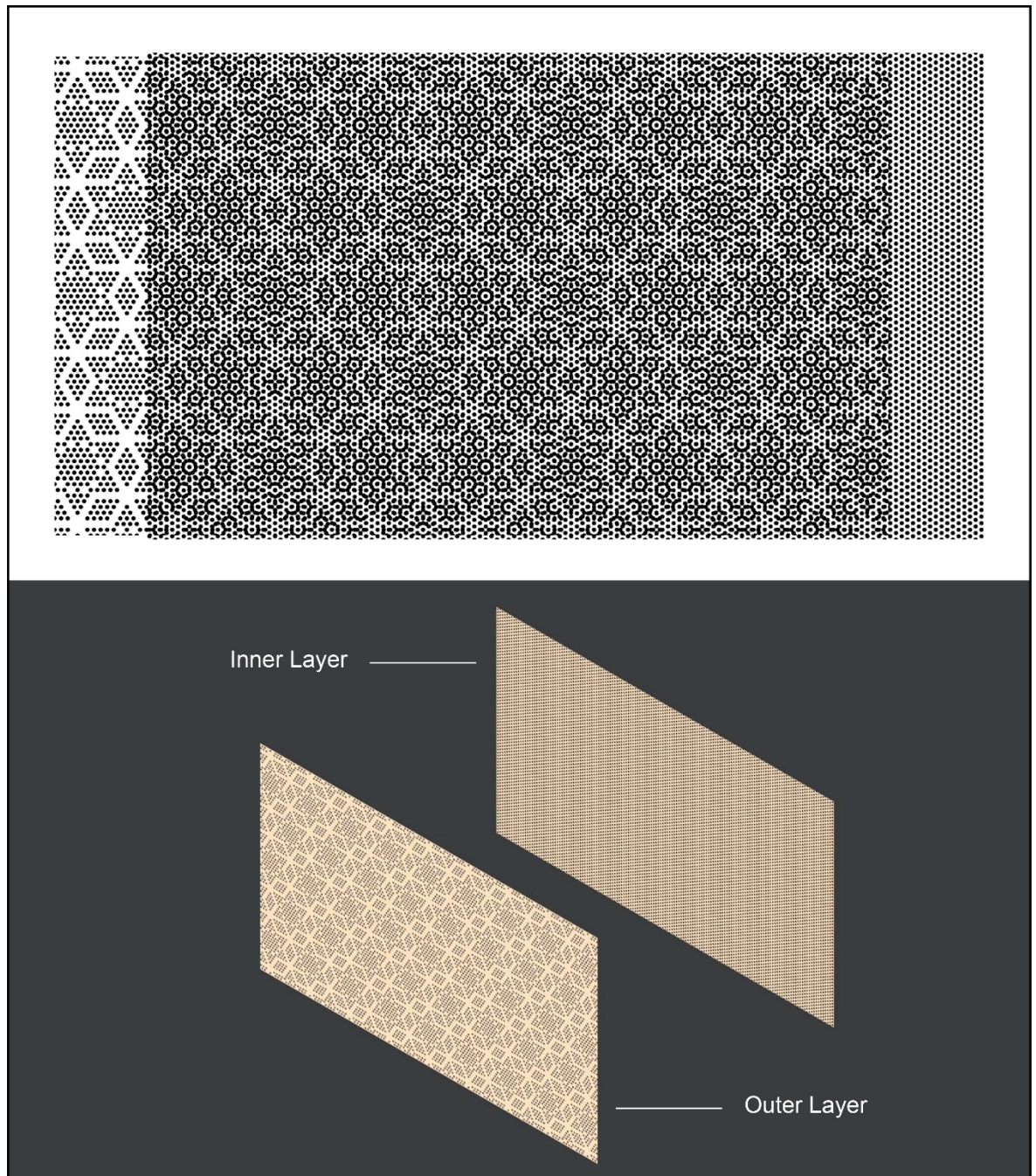


Fig. 80. *The Visual Strategy: Overlapping Two Layers with Dotted Patterns* (2018)

As discussed in Section 2.3.2.3, moiré patterns may cause discomfort or more serious side effects in particularly sensitive individuals, which was exemplified by Bridget Riley's paintings. However, some of the case studies of visually engaging architectural skins analysed in Chapter 5 were based on the concept of moiré patterns. It may be possible that when these patterns are perceived by viewers in motion in an outdoor environment the effect can be different from that produced when they are stared at for a prolonged time within an indoor environment and from a stationary position. For the purpose of this example of a design process, the researcher embraced the positive potential of moiré patterns for producing visually

dynamic effects in outdoor urban environments. However, further research could be directed at investigating the effects on human well-being of embedding such patterns in architectural facades.

7.3.2 Determining the Skin Morphology

To define an appropriate skin morphology for a solar installation to be integrated into the selected façade of the Fire Station plaza, the researcher conducted environmental computer simulations. These allowed her to understand the insolation levels of the site and especially of the designated building surface, expected to impact the performance of a potential solar installation. The software used for this purpose was Ladybug, a tool that allows the analysis and interactive visualisation of climate data (Ladybug Tools LLC, 2018), running within the algorithmic design environment of Grasshopper (Davidson, 2018) in the 3D modelling program Rhino (Simply Rhino Limited, 2018). To better understand the impact of shading on the solar skin, rendering in V-Ray for Rhino (Chaos Software, 2018) was also used.

In the various types of environmental analysis it allows, Ladybug employs weather data obtained from EnergyPlus Weather files (Ladybug Tools LLC, 2018). As the weather data for Doha could not be retrieved in that format, the insolation conditions for the chosen location were analysed utilising the weather file available for Abu Dhabi which is relatively close to Doha. The analysis conducted in Ladybug used as inputs both the weather data and the approximate geometry of the site with its existing buildings, the 3D model of which was constructed in Rhino thanks to dimensional data in architectural drawings provided by Qatar Museums.

The tests carried out analysed sunlight hours, solar radiation, shading and the potential electrical output of photovoltaics. As explained within the Ladybug interface, the sunlight hours analysis enables the calculation and visualisation of how many hours a day a designated geometry receives direct sunlight, whereas the solar radiation analysis quantifies and illustrates the energy radiated by the sun onto it. Therefore, the researcher analysed the sunlight hours (see fig. 81.) and the solar radiation (see fig. 82.) on the selected existing façade on four illustrative dates to understand the annual insolation levels on it throughout the year. The simulations revealed that some parts of the designated surface receive less direct sunlight, which appeared to be due to the shadows cast by other parts of the building. This finding was supported by further analysis showing the effect of shading throughout the year on the output energy of a hypothetical photovoltaic installation on the

selected surface (see fig. 83.). It was also confirmed by renderings of the site produced with V-Ray for Rhino (Chaos Software, 2018), which simulated the sunlight and shading conditions on four illustrative days of the year (see fig. 84.). It resulted that the façade is characterised by lower insolation in summer than in winter, which is understandable given the low latitude at which Doha is located and therefore the high sunlight angle characterising its summers.

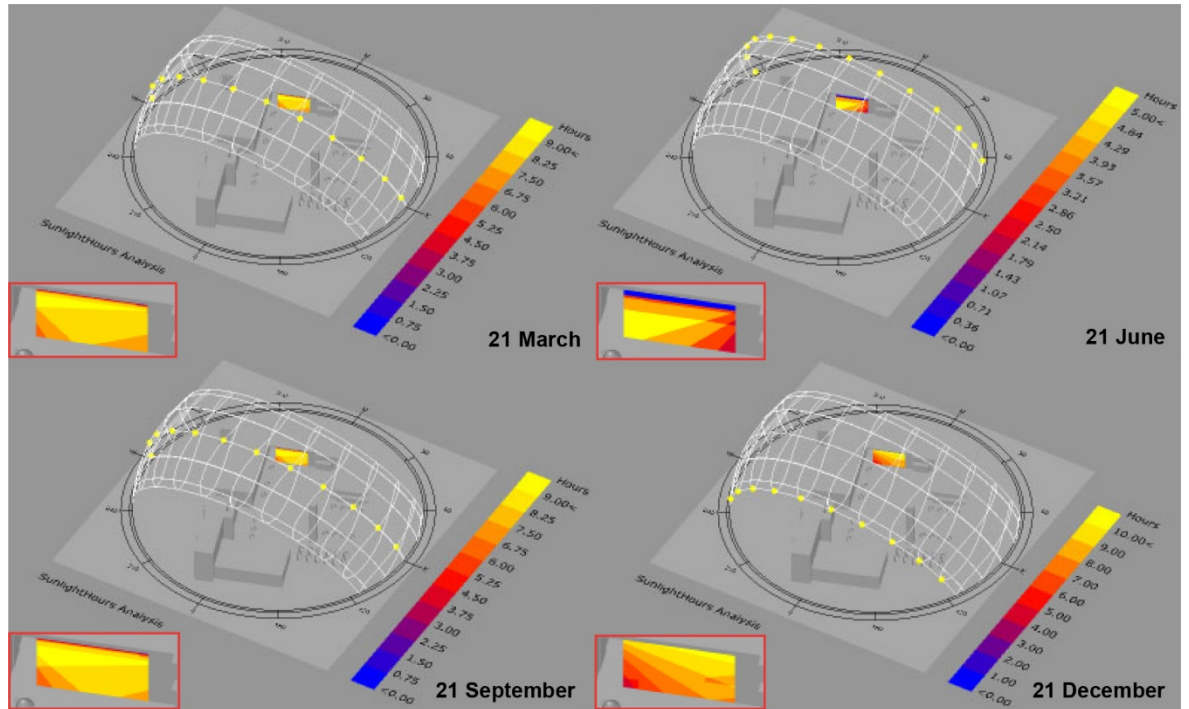


Fig. 81. *Sunlight Hours Analysis for the Existing Vertical Façade, Conducted with Ladybug (2018)*

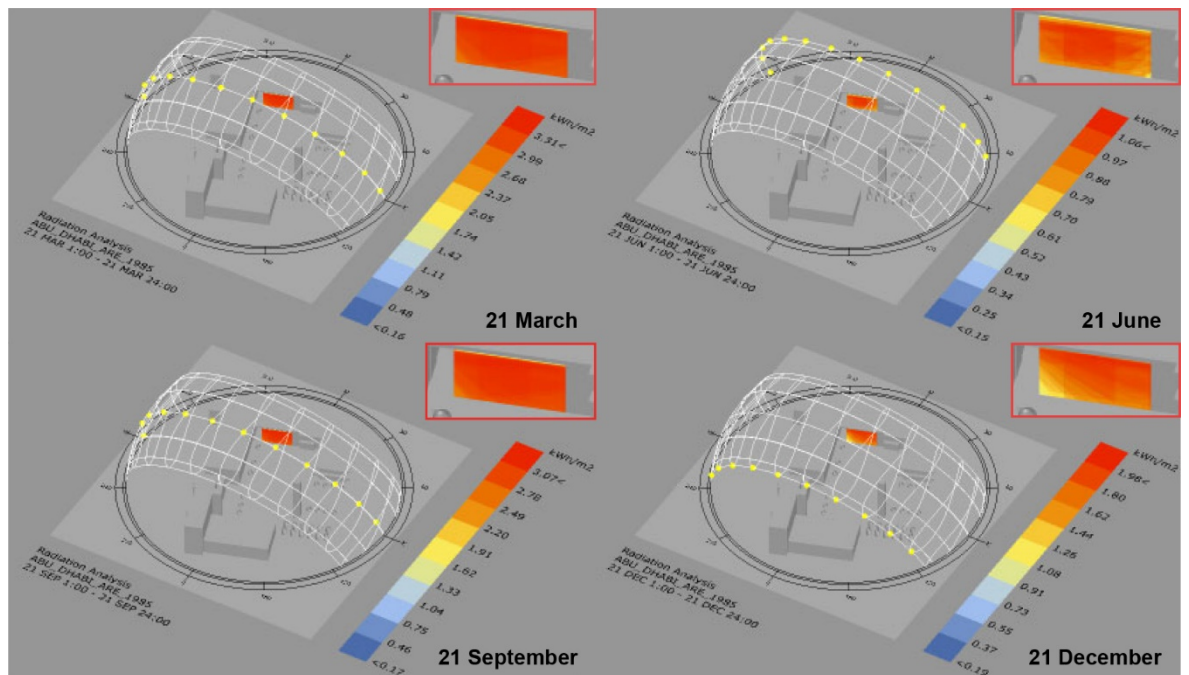


Fig. 82. Solar Radiation on the Existing Façade on Four Dates, Simulated with Ladybug (2018)

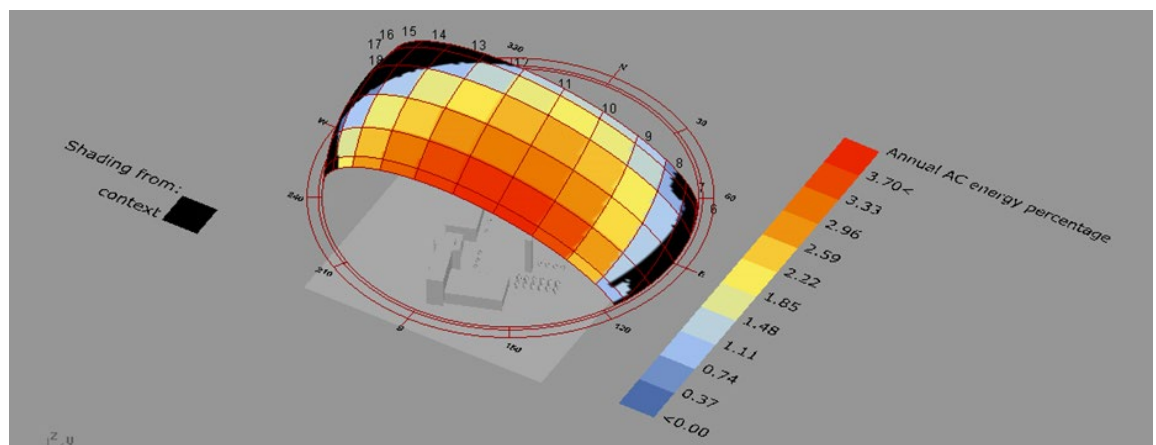


Fig. 83. Annual Shading and Percentage of PV Energy Output for the Existing Façade, Simulated with Ladybug (2018)

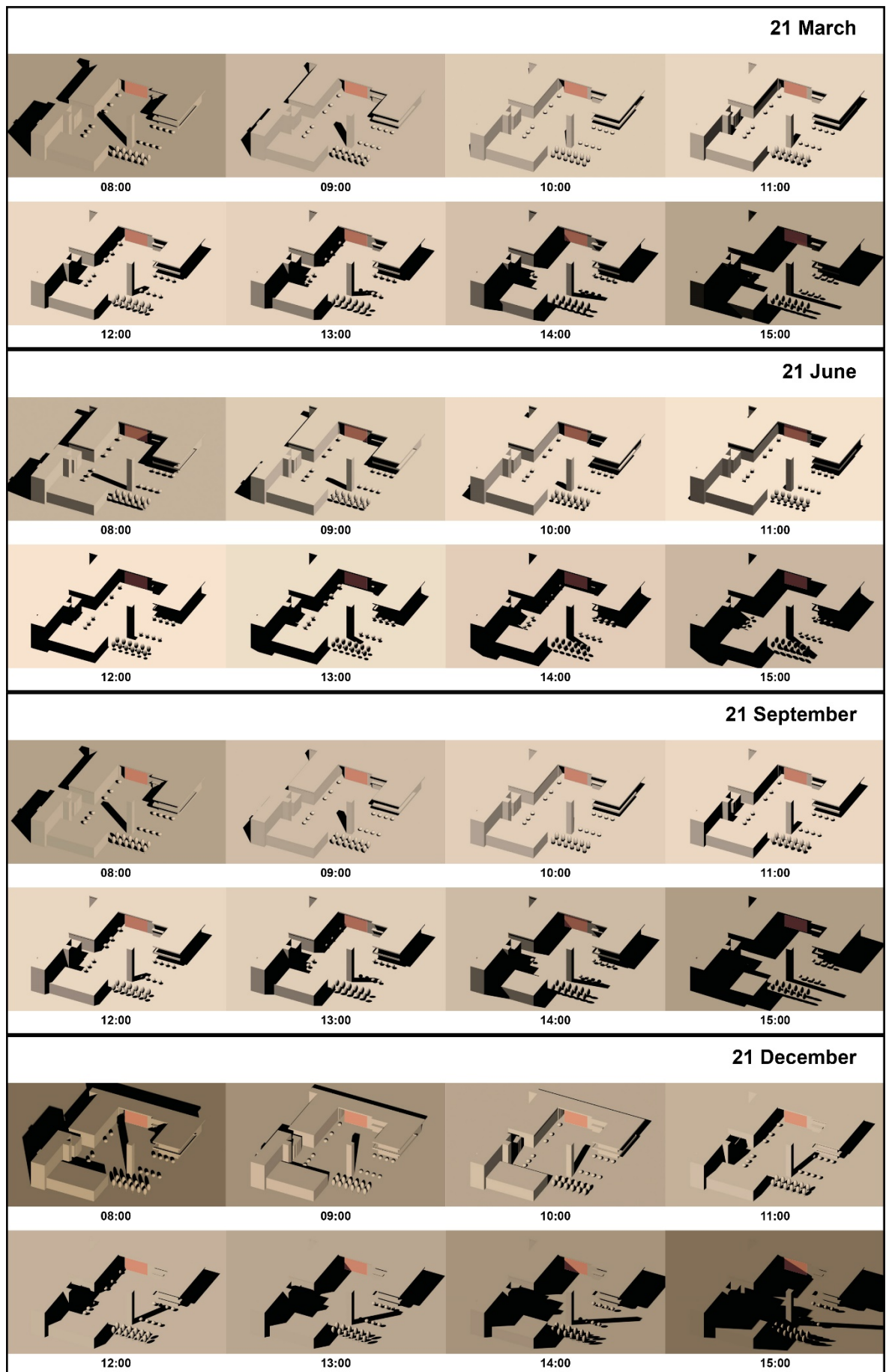


Fig. 84. *Shadow Study Conducted through Rendering of the Site Geometry Using V-Ray for Rhino (2018)*

As can be observed from the outcome of the sunlight hours analysis conducted for the whole building (see fig. 85.), the roof receives more direct sunlight than vertical facades do, thus it would be hypothetically more suitable for a solar installation. However, a photovoltaic array on the flat roof of the Fire Station building would not be visible to the public, therefore it would not contribute to disseminating knowledge on solar energy, promoting its use in Qatar. Due to its visibility, the chosen vertical façade, if converted to a solar skin, could serve that purpose much better. Additionally, the façade's vertical surface could be possibly less prone to soiling, as dust could tend to fall and be easier to wash off with water. Hence, the selected façade was thought to have potential for becoming an effective solar skin capable of stimulating visual engagement.

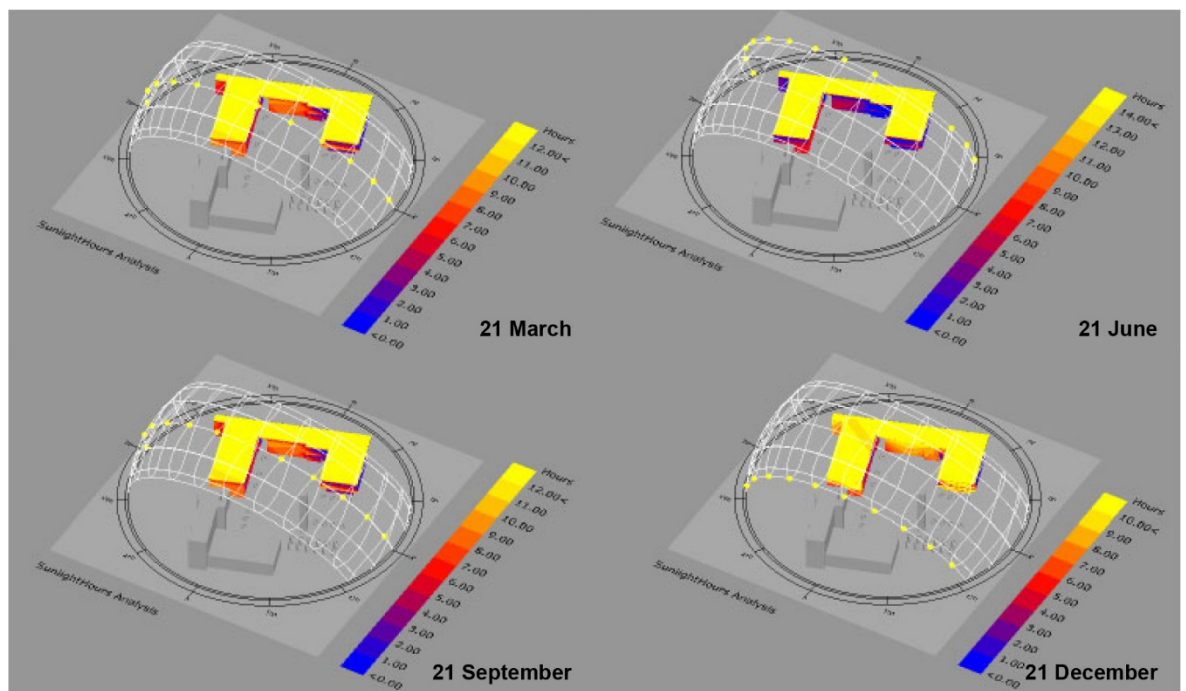


Fig. 85. *Sunlight Hours Analysis of the Chosen Building on Four Illustrative Days, Simulated with Ladybug (2018)*

The analyses indicated that the slightly protruding roof reduced the insolation on the upper part of the façade, which suggested the possibility of redesigning the building front by moving it forward to reduce shading on it. The impact on the performance of a photovoltaic skin due to shading from other parts of the building could not be reduced through changes in the façade configuration. However, this is an issue that could be compensated for with the electrical design of the photovoltaic system, which goes beyond the scope of this research. Moving the façade surface forward like the roof also offered the opportunity to add depth to the building skin, which was

needed to apply the visual strategy described in the previous section as well as to facilitate natural ventilation on the back of the photovoltaic layer.

As mentioned in relation to the visual strategy, a porous skin configuration was chosen to create the effect of illusory motion while facilitating the passive cooling of photovoltaic modules and the concealing of ventilation grilles. What remained to be determined was the shape of the façade elements supporting the photovoltaic modules and displaying the visual content to be conveyed. This required carrying out further simulations to test different tilts and orientations for the solar modules. As suggested by existing studies on solar power in Qatar, optimally angled solar panels in the country are tilted by 22° and facing the south (Abdallah et al., 2016). The electrical performance of a hypothetical photovoltaic skin in the designated location was calculated with Ladybug (see appendix 1) considering four different angles, by improving either the surface tilt or its orientation only, or both. The best results were obtained with the optimally tilted and oriented surface (see fig. 86.), although the improved orientation appeared to have little influence on the performance, as the existing surface was already close to facing the south. On the other hand, the improved tilt showed to increase the electrical output of the photovoltaic surface significantly. Therefore, the possibility of a three-dimensional façade configuration in which photovoltaic modules could be optimally tilted was considered worth exploring further.

FAÇADE ANGLE		ELECTRICAL OUTPUT	
TILT	ORIENTATION	YEARLY (kWh)	DAILY (kWh/day)
unchanged	unchanged	22106	61
improved (~ latitude)	unchanged	41800	115
unchanged	improved (south-facing)	21795	60
improved (~ latitude)	improved (south-facing)	42203	116

Fig. 86. *Electrical Performance of a PV Surface for the Chosen Facade at Four Different Angles, Simulated with Ladybug (2018)*

The researcher tested the feasibility of a three-dimensional configuration with tilted modules by examining the arrangement of smaller panels across a vertical surface, for which shading simulations through rendering in V-Ray for Rhino were conducted. These were performed on a 1-metre wide sample of façade geometry, so that the sunlight conditions typical of Doha during four illustrative days of the year could be observed. The simulations showed that partial shading on the tilted modules tended to occur most of the time. This resulted for a geometry aimed at covering 100% of the vertical façade with PV modules (see fig. 87.), as well as for a configuration

aimed at covering 50% of the surface with PV material (see fig. 88.), for which a chequered layout was also assessed (see fig. 89.).

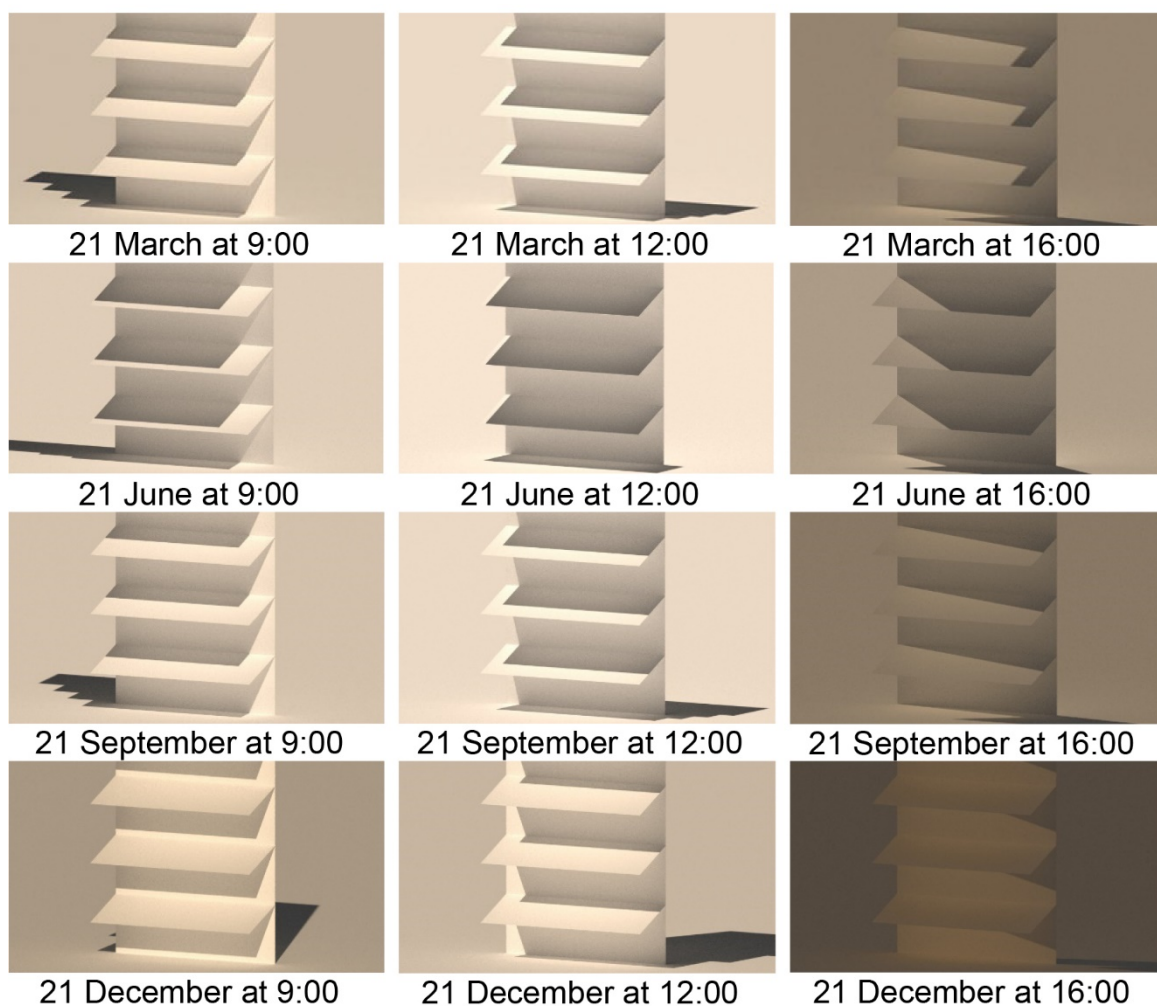


Fig. 87. *Shading on a Sample of Façade Geometry with Tilted Modules Aimed at Covering 100% of the Building Skin with PV Material, Simulated through Rendering in V-Ray for Rhino (2018)*

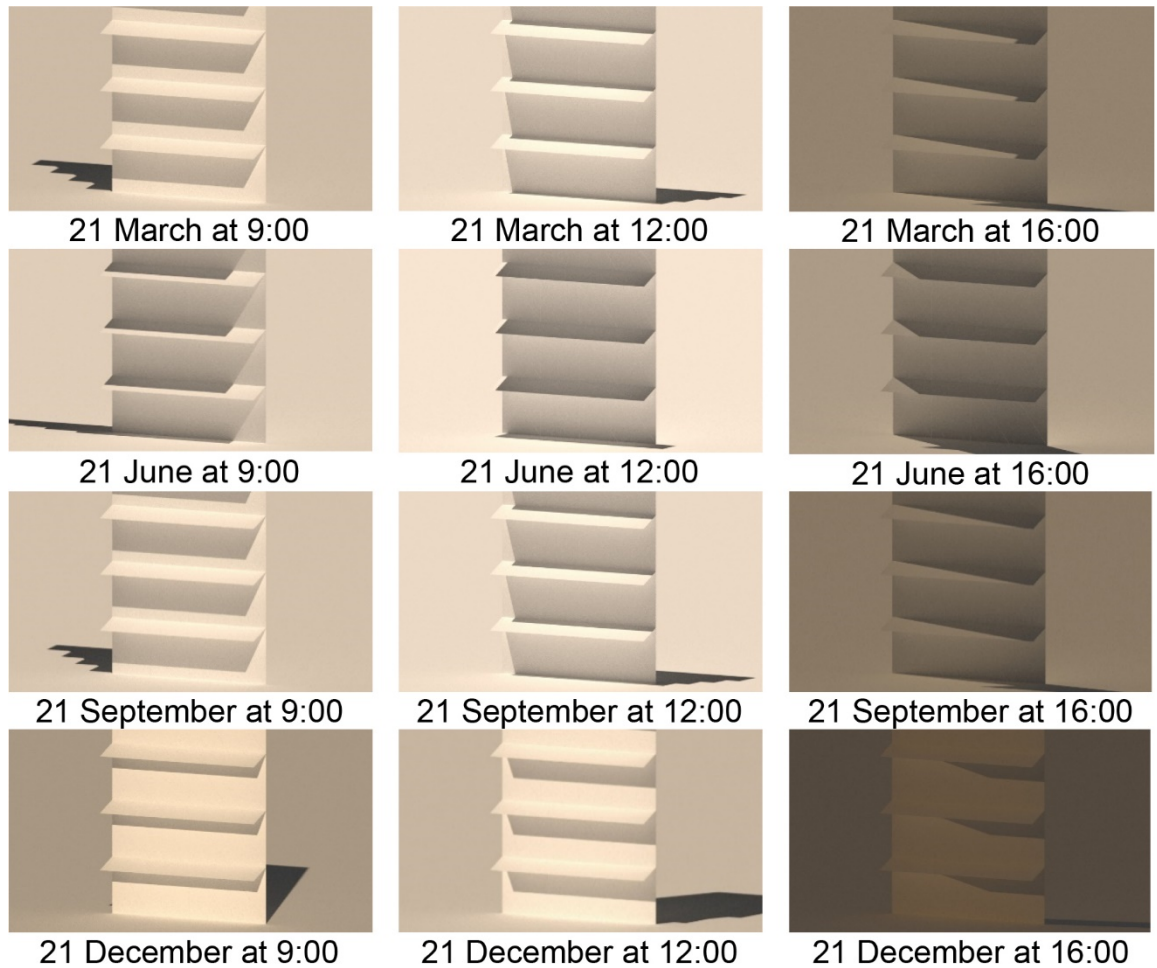


Fig. 88. *Shading on a Sample of Façade Geometry with Tilted Modules Aimed at Covering 50% of the Building Skin with PV Material, Simulated through Rendering in V-Ray for Rhino (2018)*

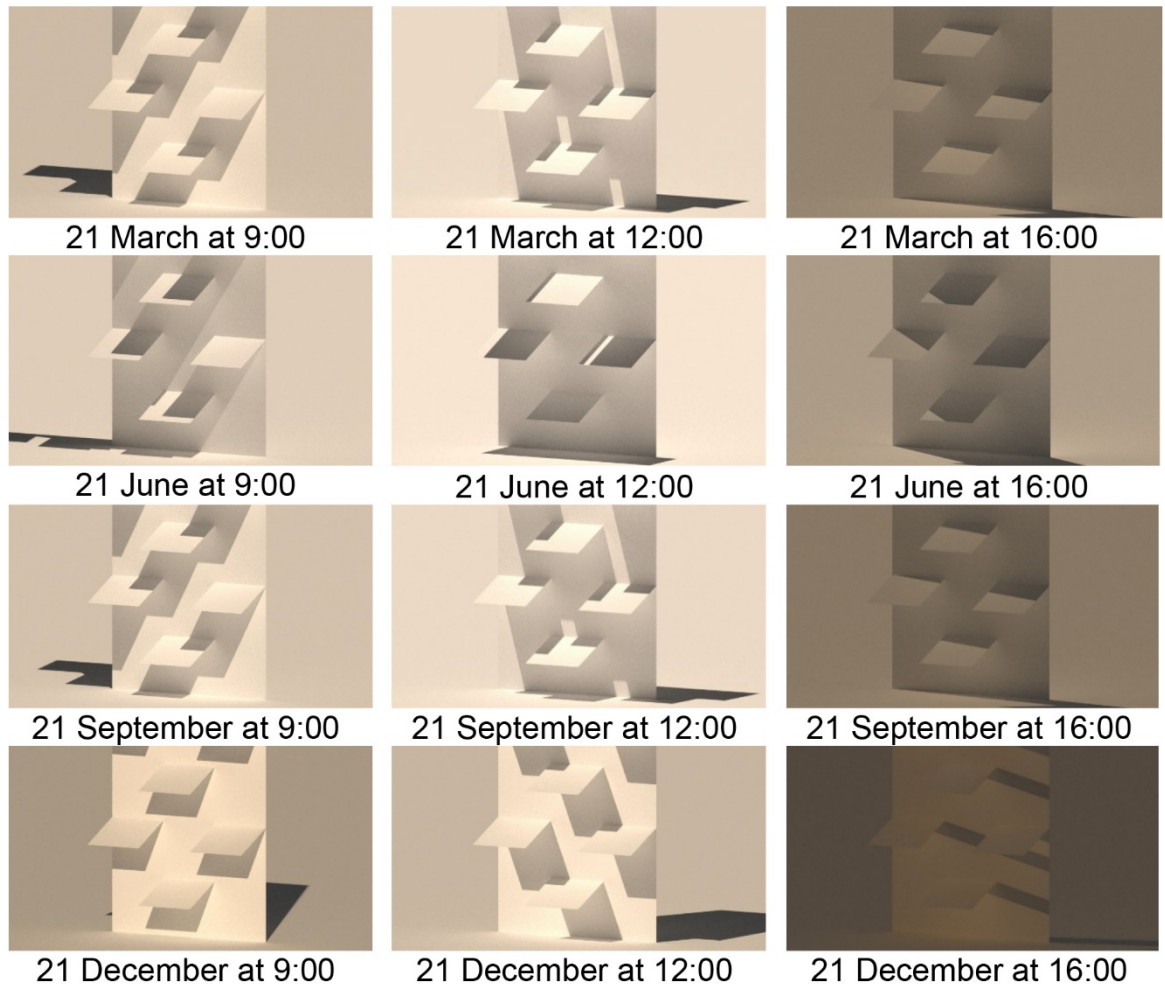


Fig. 89. *Shading on a Sample of Façade Geometry with Chequered Layout and Tilted Modules Aimed at Covering 50% of the Building Skin with PV Material, Simulated through Rendering in V-Ray for Rhino (2018)*

It was observed that minimising self-shading on a three-dimensional configuration required increasing the spacing between tilted modules, or making them smaller, or both, which had the inevitable effect of decreasing the overall size of the PV array and its electrical output subsequently. Shading due to a three-dimensional façade configuration was also considered in simulations of the PV skin's electrical performance conducted with Ladybug (see appendix 2). It resulted that a simply vertical PV surface without self-shading problems and one affected by self-shading due to tilted panels had a similar electrical output (see fig. 90.). Therefore, the three-dimensional configuration with titled modules appeared undesirable and it was decided that the solar skin geometry could remain planar and vertical. A building skin with this configuration was also expected to be potentially less prone to soiling and relatively easy to clean regularly.

FAÇADE TILT	PV SURFACE (%)	SELF-SHADING (%)	ELECTRICAL OUTPUT	
			YEARLY (kWh)	DAILY (kWh/day)
unchanged	50	0	11053	30
improved (~ latitude)	50	50	9980	27

Fig. 90. *Electrical Performance of a PV Façade with Self-Shading on a Configuration with Tilted Modules, Calculated with Ladybug (2018)*

As anticipated in the description of the chosen visual strategy, the researcher opted for a porous type of skin to produce the illusion of a kinetic effect as well as to allow ventilation. Therefore, the shape and size of the dots that acted as ‘pixels’ and constituted the perforations in the outer layer had to be determined. This was achieved through iterative scaling of circular dots and of the isometric grids on which both the Islamic motif and the dotted patterns were based, which was carried out using Grasshopper. Ultimately the size of the dots, or ‘pixels’, was chosen as the best compromise between allowing optimal visibility of the desired visual effect and maximising the area to be covered with PV material, thus providing a higher electrical output. This allowed the researcher to finalise the pattern for both the outer layer of the skin, to be covered with PV material and displaying the Islamic pattern (see fig. 91.), and the inner layer characterised by a simple dotted pattern (see fig. 92.).

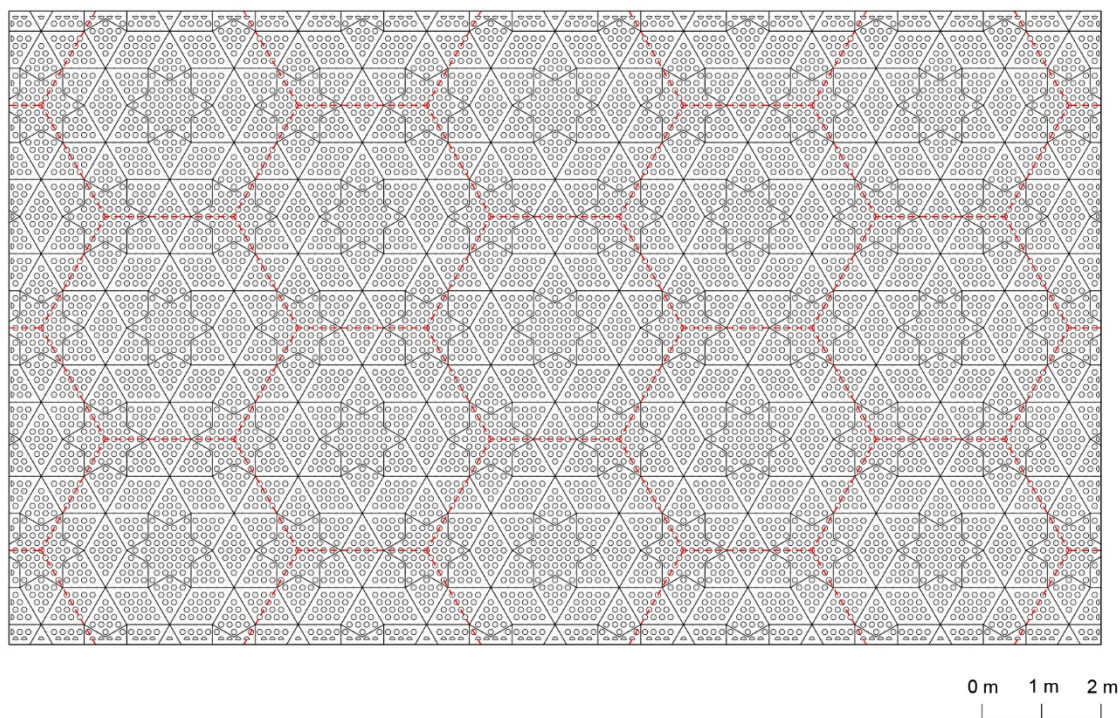


Fig. 91. *Constructing the Design of the Solar Skin's Outer Layer, Combining the Islamic Motif with a Dotted Pattern (2018)*

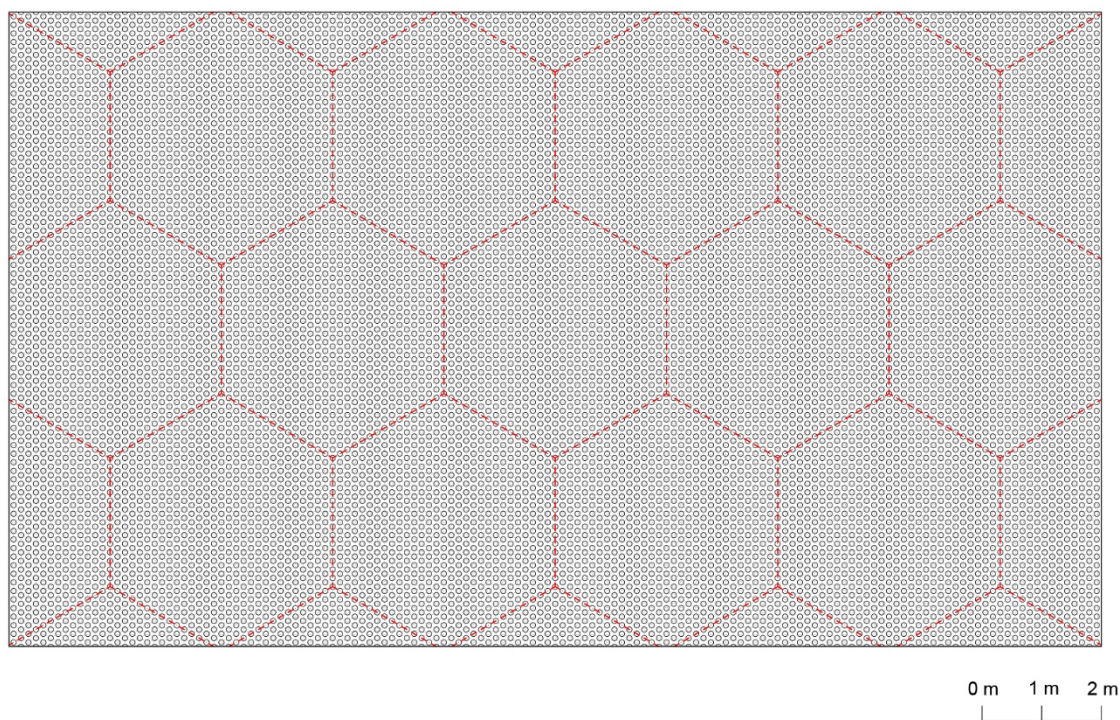


Fig. 92. *Constructing the Design of the Solar Skin's Inner Layer, Rotating the Outer Layer's Dotted Pattern by 60° (2018)*

7.3.3 Selecting the Visual Quality

To preserve the character of the place, the researcher decided that the visual quality of a newly designed solar skin had to be similar to that of the existing façade made of weathered steel. It was considered that highly reflective surfaces could have caused glare and disturbed members of staff at work inside the building as well as visitors, besides reflecting heat. On the other hand, sandstorms could have caused soiling of the surfaces and prevented any reflections from being seen. Additionally, the façade needed to remain opaque overall, which made the choice of transparent materials appear inappropriate. Therefore, the researcher pursued a visual quality characterised by low reflectivity and by a warm colour tending to red, similar to that of the existing façade (see fig. 93.).

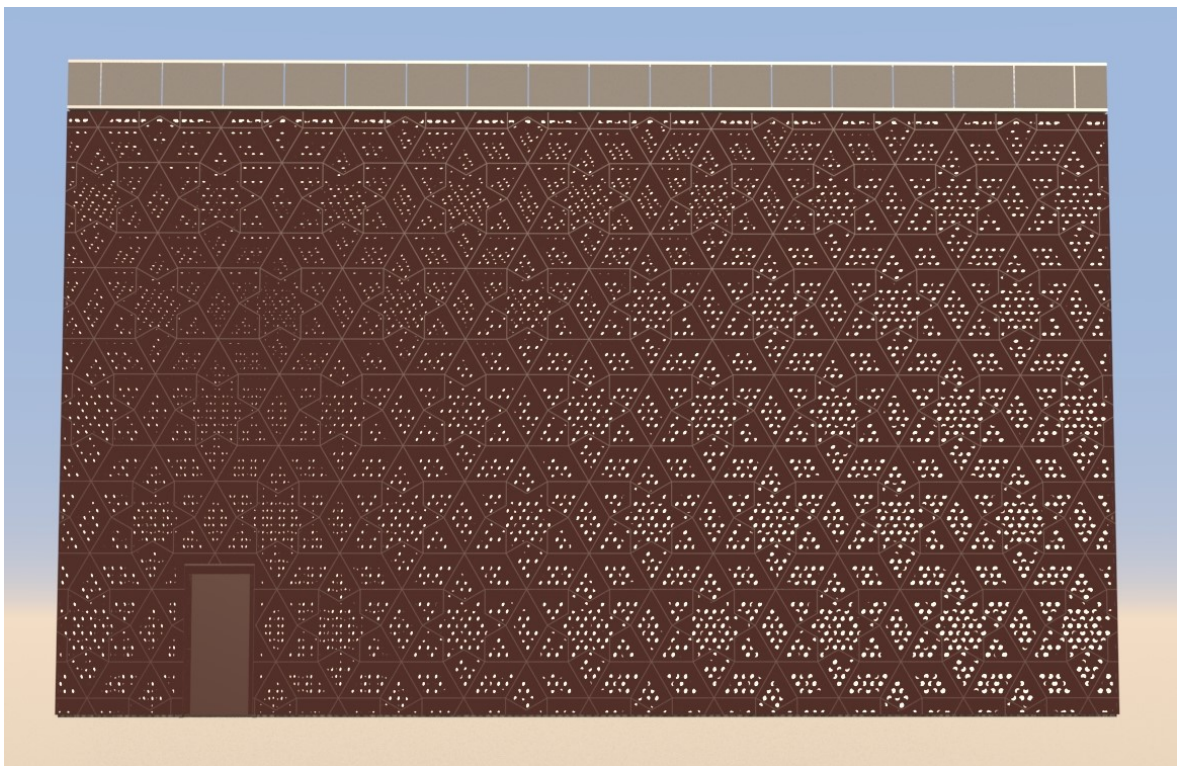


Fig. 93. *Rendering of the Solar Skin Design Showing Its Visual Quality, Produced with V-Ray for Rhino (2018)*

The effectiveness of the chosen visual quality was repeatedly tested through iterative rendering using V-Ray for Rhino. The researcher also created short animations by assembling rendered images of the façade in sequence to simulate a person's walk in the proximity of the solar skin. Produced with the video editing software Adobe Premiere Pro CC (Adobe, 2018), the animations helped the researcher check during the design process whether the desired visual effect was attained (see fig. 94.).

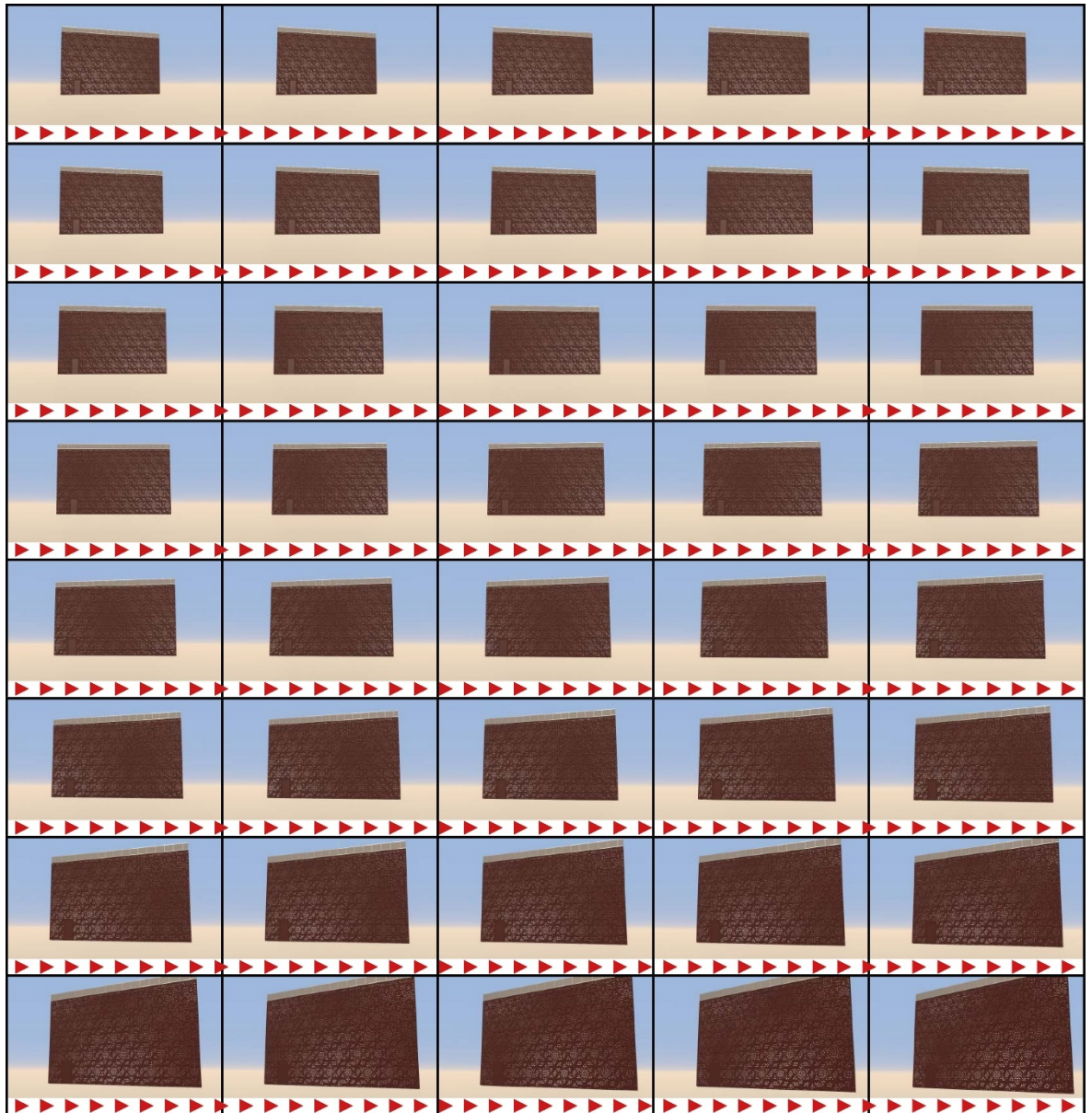


Fig. 94. *Example of Short Animation Created by Assembling Rendered Images of the Façade in Sequence* (2018)

7.3.4 Choosing a Solar Technology

While Doha's adverse climate conditions causing soiling of solar panels can be detrimental to their performance in general, the performance of amorphous silicon was found to be less affected by dust accumulation than that of crystalline silicon (Touati et al., 2013). Therefore, amorphous silicon was believed to be the appropriate photovoltaic material for the proposed façade design, among those that are commercially available. Given the proposed skin morphology, it was envisioned that amorphous silicon could be integrated in the form of small, thin-film modules applied on a metal substrate in the spaces between the perforations. These were thought to facilitate passive cooling. Such a solution is achievable specifically with thin-film PV modules rather than with conventional, larger solar cells made of

crystalline silicon. The electrical performance of the solar skin with its finalised configuration was tested using Ladybug as a simulation tool (see appendix 3). This was done considering the properties of amorphous silicon, which can have an efficiency of up to 14% according to NREL (see fig. 26.), and a temperature coefficient of -0.2%/°C (Shah, 2010:248). The simulation showed that the designed solar architectural skin with an active surface of nearly 150 m², may be capable of generating 29 KWh/day with a solar cell efficiency of 10% (see fig. 95.).

FAÇADE SURFACE (m ²)	PV SURFACE (%)	ACTIVE AREA (m ²)	PV EFFICIENCY (%)	ELECTRICAL OUTPUT	
				YEARLY (kWh)	DAILY (kWh/day)
~ 195	76	148	10	10598	29

Fig. 95. *Electrical Performance of the Designed Solar Skin, Calculated with Ladybug (2018)*

Having chosen amorphous silicon as the *absorber* and metal as the *substrate*, the researcher also thought of a possible *performance enhancement strategy* for the photovoltaic technology to be embedded in the building skin, as indicated by the framework in Chapter 6. The suggested configuration for a ventilated façade can improve the efficiency of the PV modules through passive cooling. To increase the electrical output of the thin-film a-Si modules, the application of a coloured filter acting as a spectral converter was proposed. Such a converter allows the PV material to better absorb the portion of solar radiation that it performs best with, which for silicon is radiation in the visible or near infrared region (McKenna & Evans, 2017:2). The addition of such a filter to the design was proposed to improve the PV material's absorption of solar radiation in the visible spectrum while avoiding other portions of it such as radiation in the infrared range that would cause the solar cells to overheat. Of red colour and containing a fluorescent dye, the filter could serve as an encapsulant besides improving the efficiency of the photovoltaic material and changing its appearance (Hardy et al., 2013). It would contribute to creating the desired warm colour tending to red for the solar skin, in contrast to the predominantly black appearance of conventional amorphous silicon modules. Superimposed on the outer layer of the composite solar skin, the spectral converter becomes an integral part of the façade concept here proposed (see fig. 96.). As further solar technologies become commercially available in future years, different thin-film photovoltaic materials, such as perovskite cells, could be chosen instead of amorphous silicon.

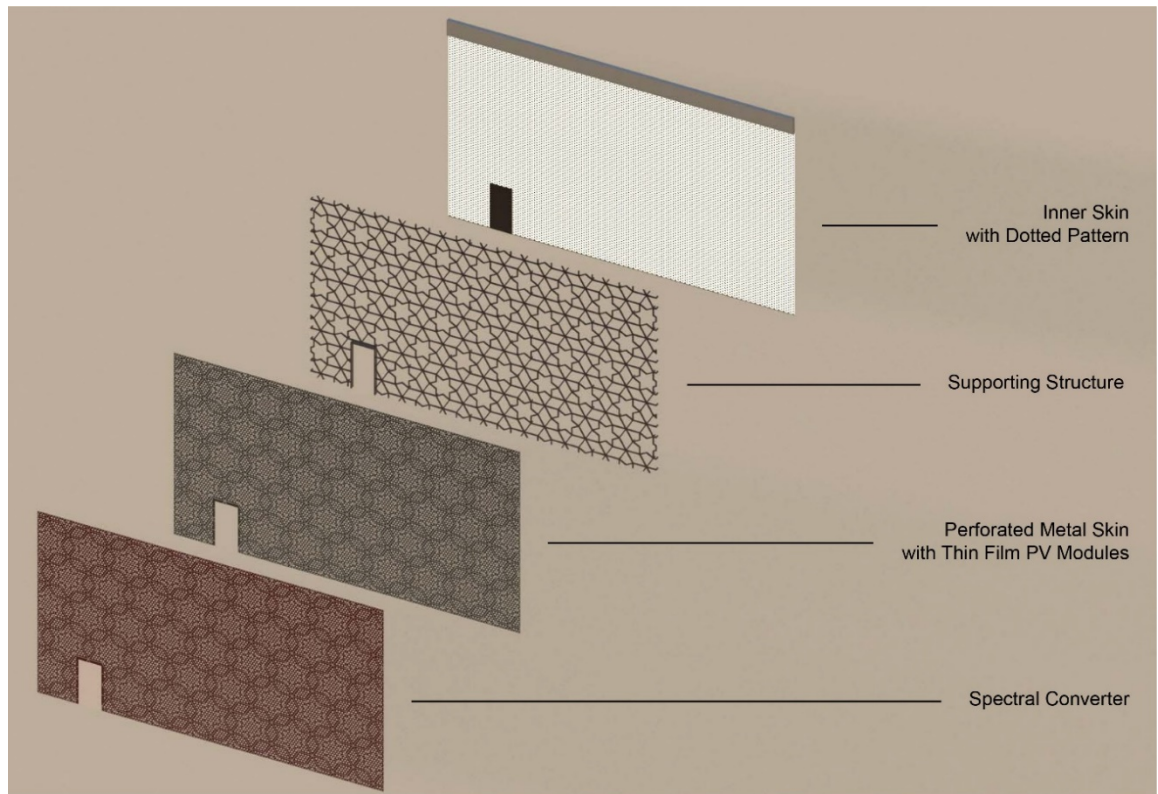


Fig. 96. *Exploded Diagram Illustrating the Proposed Concept for a Composite Solar Skin* (2018)

7.4 Discussion

7.4.1 The Framework's Guidance to Understanding the Design Context

The previous sections of this chapter presented an example of the process for conceiving an architectural skin design aimed at stimulating visual engagement and integrating photovoltaic technology.

The illustrated practical design example demonstrated that referring to the approach outlined in Chapter 6 facilitated an understanding of the design problem to be solved. The framework helped the researcher discern important starting conditions for the design, that were relevant to the generation of a concept for a solar façade configuration. By referring to the framework, the researcher was able to pay attention to features of the considered location that affect the use of solar technologies, such as the local urbanisation and the climate characterised by abundance of sunlight, high temperatures and sandstorms. The framework also prompted the researcher to distinguish important traits of the examined outdoor urban environment. This was recognised as a plaza experienced by people in multiple ways and characterised by conventional, modern façades, but also by some potentially eye-catching features. The approach proposed in Chapter 6 also assisted the researcher in identifying essential attributes of the examined building with an

impact on the design of the solar skin, such as its current uses and the need for an opaque, partly porous façade. Additionally, following the framework led the researcher to investigate the cultural identity for the chosen location, finding its roots in the Arab tradition deeply influenced by Islam, which provided a semantic content to be conveyed through a solar façade. The adopted approach also simplified the identification of economic factors affecting the design of a solar skin for the designated site, such as the lack of competitiveness of solar technologies and of incentives for their use, as well as maintenance costs related to the local climatic conditions.

7.4.2 The Framework's Guidance to the Generation of a Concept

The framework also proved helpful at providing guidance on generating an idea for a solar building skin, as it offered structure to the decision-making process through which the appearance of the façade was determined. By instigating the choice of a visual strategy, the framework induced the researcher to clarify what was the overall visual effect to be produced through the façade. It prompted the selection of features concerning the skin morphology which responded to physical characteristics of the site and of the location climate as well as to cultural and economic factors, impacting the practicality of the façade as well as the communication of meanings through it. Thanks to the framework's guidance the researcher was urged to decide on the visual quality of the materials composing the solar building skin, such as the opaque appearance and the warm colour tending to red. This was also considered in the selection of a suitable solar technology for integration into the designated façade, which was simplified by breaking down the problem into three components. Such constituents of the solar technology were identified in the framework as the *absorber*, the *substrate* and the *performance enhancement strategy*, which in the illustrated design example were represented respectively by thin-film amorphous silicon, metal and spectral conversion as well as passive cooling. The framework facilitated a rough selection of the materials to be employed in the design already at an early stage, by guiding the researcher through the definition of the desired visual properties and of a suitable solar technology.

7.4.3 The Process for Generating a Solar Skin Concept

It can be observed that while the framework offered structure to the process of conceiving the solar skin design, it did not impose rigid constraints limiting creative exploration. The multiple aspects considered in the design thanks to the framework's guidance were intertwined, so they were often thought of at the same

time, rather than in sequential order with a clear hierarchy. For instance, aspects of the *skin morphology* and of the *visual quality* of materials emerged already while the *visual strategy* was being determined. The design process was comprehensive and iterative: multiple aspects were considered simultaneously, and variables were tweaked several times as simulations were conducted repeatedly. The design generated with the framework's guidance also took into account the potential of technological solutions that are still under development, such as the use of a spectral converter to improve the performance of photovoltaics and of perovskite cells which could be an alternative to silicon in the future. The resulting design showed that the 'pixels' composing an image or pattern on a solar architectural skin may not be the same as the PV modules, but rather non-active elements or spaces between the PV modules. Hence, while the design process was far from being linear, it could consider multiple variables in a creative and future-oriented way.

Unlike previous studies suggesting approaches to the design of solar building envelopes, reviewed in Chapter 3, the present research outlined a framework for designs which are intended to stimulate visual engagement. Consequently, this project employed visualisation techniques consistently in the early design of a solar architectural skin. It emerged that rendering images and creating short animations, to test whether the desired visual effect is achieved, play a key role in the process of generating new ideas for visually stimulating architectural skins that embed solar technologies. Such techniques enable the designer to quickly and repeatedly assess the visual effectiveness of the design during its computer-generation.

7.4.4 The Challenges of Conceiving a Solar Skin for Visual Engagement

7.4.4.1 Trade-Off between Visual and Energy Effectiveness

The design example presented in this chapter demonstrated that conceiving a solar architectural skin with the intent to stimulate visual engagement entails a trade-off between the impact of the pursued visual effect and the efficiency of the solar installation. This was demonstrated, in the design example, by the choice of a planar, vertical configuration for the photovoltaic façade despite the unfavourable angle for the absorption of sunlight. The decision resulted from balancing multiple factors which included the need to display the photovoltaic installation with a communicative purpose, as well as the necessity to ease its maintenance while also avoiding self-shading of the PV modules. Nonetheless, using performance enhancement strategies may compensate to some extent for performance losses incurred due to design choices while adding visual qualities to a solar skin.

7.4.4.2 Early Design and Technology Limitations

It can be observed that the illustrated process for the generation of a concept for a solar architectural skin focused on an early stage of design, thus the project was not developed to a high level of detail. Being centred on the overall visual effect produced by a building skin, the design did not reach the advanced stage in which the shape and size of the single PV modules would have to be accurately illustrated. These were not defined in detail in the illustrated example, although their shape and size were somewhat suggested implicitly as part of the *skin morphology*, since each PV module would constitute a small, regularly repeated portion of the outer skin layer. The simulations carried out as part of the presented design process, particularly to determine features of the *skin morphology*, did not replace the highly accurate type of environmental analysis that would need to be performed at a more advanced design stage. For instance, they were conducted referring to approximate geometries and to climate data from a geographic location that was not exactly the chosen city. Simulations and visualisations were found to be relatively time-consuming even if conducted roughly, as they needed to be run iteratively. This prevented the researcher from exploring more design possibilities, due to the time constraints of the project. However, as the present study focuses on the earliest stage of design, approximations were considered acceptable. It is expected that further design developments would require more considerations and precise analysis, which could involve the use of further methods and tools. Therefore, the design process exemplified proved that the framework outlined in Chapter 6 can be useful for guiding the initial, creative stage of designing a solar architectural skin, while assessing its relevance to later project developments goes beyond the scope of this research.

The presented design example, like the proposed framework, focused on the deployment of photovoltaic-based systems only, rather than considering other solar technologies. This choice was justified by the higher compositional flexibility offered by photovoltaics which appear easier to integrate into visually captivating building fronts through pixelated configurations similar to those of media facades. Perhaps the framework outlined in this research could be considered, adapted or further developed for the design of visually engaging building skins embedding other technologies, such as solar water heating systems. However, this goes beyond the scope of the present study and could be explored through further research.

7.4.4.3 Exploring Semantic Content

It may be noted that the illustrated design example did not delve into thoroughly exploring and defining the semantic content to be conveyed through a solar building skin, which potentially gives space to creativity and can lead to diverse visual outputs. As the content to be communicated represents a manifestation of culture, the possibilities for its choice may be countless. For instance, the content may express the designer's imagination, elements of the local culture, or both. Depending on the project as well as on the time and resources available, a designer could consider involving the users in the conception of a content to be communicated through a solar building skin for a specific site. However, limits to the designer's creativity are posed by the other factors influencing the design of solar skins, which are outlined in the suggested framework as characteristics of the location, of the outdoor environment, of the building, and economic influences. Furthermore, displaying certain types of visual content, such as moiré patterns, on building skins may potentially induce negative effects in sensitive individuals. This, however, could not be assessed as part of this study, and further research could explore the impact on people's well-being of embedding certain motion illusions into architectural skins.

7.5 Conclusions

This chapter presented the primary, practice-based research process of testing the framework for designing solar architectural skins aimed at stimulating visual engagement, which was outlined in Chapter 6, by applying it to an early design case.

The framework proved to facilitate an understanding of the design problem and to offer structure to the decision-making process for determining the solar skin's appearance. It enabled the generation of an idea for a photovoltaic building skin displaying seemingly dynamic visual content, inviting consideration of multiple aspects and their influences on the performance of solar technologies. The design process showed that the flexible framework was effective at supporting the formation of a solar skin concept. Characterised by the iterative use of computer simulations and visualisations, the latter of which were particularly useful for testing the solar skin's visual effect, the process was non-linear, creative and future-oriented.

The design process revealed some challenges. Conceiving a solar architectural skin with the intent to stimulate visual engagement entails a trade-off between achieving the most desirable visual effect and generating energy efficiently. The design results

from balancing multiple factors among which the need to convey a certain meaning through a visually engaging appearance may weigh more heavily than others in the designer's judgement. Performance losses may be contained through the use of *performance enhancement strategies* which may also add qualities to the visual design. Conveying a semantic content through a solar architectural skin may face limitations but also offer potentially countless possibilities for creative expression, which could be explored further. Testing the overall visual effect to be achieved and the expected performance of a photovoltaic installation in the early stage of design can be time-consuming due to the iterative use of digital prototyping techniques, including parametric climate-based simulations and visualisations such as image and video rendering. Constraints to the communicative potential of a solar building front are posed by the factors which affect the design of solar skins beyond the semantic content, such as characteristics of the location, of the outdoor environment, of the building and economic influences.

According to the above findings, which are summarised in the table below (see fig. 97.), the framework proved useful at supporting the initial formation of an idea for a potentially stimulating solar skin design. This also needed to be assessed for its ability to trigger visual engagement when experienced by people. The evaluation phase of the early design process is presented in the next chapter.

Generating a Concept for a Solar Architectural Skin: Key Findings	<p><u>Framework's Guidance</u></p> <p>Support in identifying, within a particular context, design factors impacting a solar skin's performance (as from Chapter 3) and people's visual engagement with it (as understood from the study of visual perception in Section 2.3.2), including characteristics of:</p> <ul style="list-style-type: none"> • the location • the outdoor environment • the building • the content to be conveyed • economic factors <p>Support in choosing a solar skin's features, suitable for a particular context, which can stimulate visual engagement (as understood from the study of visual perception in Section 2.3.2) and facilitate effective energy generation (as from Chapter 3), including:</p> <ul style="list-style-type: none"> • Visual Strategy • Skin Morphology • Visual Quality • Solar Technology <p><u>Early Design Process</u></p> <ul style="list-style-type: none"> • Using iterative simulations and visualisations (the latter especially for testing visually engaging effects as understood from the study of visual perception in Section 2.3.2) • Flexible, non-linear, creative and future-oriented process <p><u>Challenges</u></p> <ul style="list-style-type: none"> • Trade-off between visual and energy effectiveness, but with potential for performance enhancement with multiple strategies (as from Section 3.4) • No design development beyond initial stages (with acceptable approximations) • Time-consuming design process • Design not considering the potential of solar technologies other than photovoltaics • Limitations in conveying semantic content (e.g., context characteristics or potential for discomfort) as well as possibilities for exploration
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Fig. 97. *Key Findings from Generating a Concept for a Solar Architectural Skin* (2019)

Chapter 8: Evaluating Visual Engagement with a Solar Architectural Skin

8.1 Chapter Overview

This chapter presents the primary, practice-based research process of the experiment conducted, using virtual reality, to evaluate people's visual engagement with the proposed concept for a solar architectural skin. The evaluation was aimed at assessing the effectiveness of the framework informing the design.

The second section illustrates the process of preparing the virtual experience for the simulation, by describing through two subsections the creation of the virtual environment including the conceived design and the production of a 360° video rendering.

The third section presents the virtual reality experiment to test participants' visual engagement with the solar skin design. It reports, through four subsections, the testing of research methods, how volunteers were recruited, their responses observed by the researcher during the simulation, and their feedback collected afterwards.

The fourth section discusses the findings of the experiment and highlights the most interesting aspects that emerged from the study, including its constraints and opportunities for further research.

The fifth section draws the conclusions of the chapter, summarising the experiment conducted and its findings.

8.2 Simulating the Visual Experience of a Solar Architectural Skin

In the previous chapter, it emerged that creating short video renderings of a solar architectural skin throughout the design process can help the designer assess the visual effects produced by the proposed configuration in a relatively quick way. This can lead to gradual and iterative modifications of the design variables until the desired results are achieved. To then evaluate whether the proposed layout is capable of triggering human responses indicative of visual engagement, it is appropriate to simulate the visual experience of the conceived artefact within its context. This appears necessary to assess whether the suggested design acts as a visual attractor in comparison with other features that are situated in the immediate vicinity.

From the literature review on visually engaging architectural skins in Chapter 2, it emerged that the capacity of urban features such as public displays for attracting visual attention depends on the nearby presence or absence of distracting factors (Memarovic et al., 2014). Similar to public displays, solar architectural skins aimed at stimulating visual engagement can be evaluated through lab or field studies, using different methods such as observations, interviews and questionnaires (Alt et al., 2012). In the present research, the choice of a lab study was determined by the controlled setting characterising this type of research, which allows an easier observation of people's reactions. However, rather than taking people to a lab, this was taken to them, as the simulated virtual environment containing the proposed solar skin concept was designed to be experienced anywhere by wearing a portable, virtual reality headset.

8.2.1 Creating the Virtual Environment

The virtual environment surrounding the proposed design for a solar architectural skin was created through computer-based 3D modelling and rendering techniques. The process for the reproduction of an urban setting with 3D modelling software is normally preceded by the collection of dimensional information on the built site, for which a variety of procedures can be used. Methods for retrieving 3D data of existing buildings such as cultural heritage monuments include the analysis of maps and plan drawings, surveying, laser scanning and photogrammetry. Each of these presents distinctive limitations and benefits and should be combined with other techniques in the presence of complex architectures (Grussenmeyer et al., 2008). Although this preparatory phase of the simulation process is worth mentioning, it was not part of the present project as the researcher had previously received dimensional data of the Fire Station site from Qatar Museums.

Based on the obtained dimensional information, the 3D model of the site was constructed with Rhino 3D and gradually improved to achieve higher realism. This was increased by repeatedly comparing the virtual model with the real setting as shown in photographs provided by Qatar Museums, that were included in Chapter 7. The geometry of each building facing the open space of the plaza was refined through the progressive addition of architectural details. However, smaller or non-permanent elements that were considered less relevant to the appreciation of architectural aspects in an early design evaluation were not included. For instance, features such as security cameras and urban furniture were not incorporated in the virtual 3D model to be rendered for the assessment of people's visual engagement

with the solar skin. Although the presence of less architectural details also affects people's perception of spaces, introducing them in a 3D model at an early stage of design can slow down the evaluation process, creating many distractors that can interfere with the assessment of visual engagement with a design. In the present study, including a too high number of potential visual attractors in the simulation would have reduced the researcher's control of relevant variables, making the assessment of people's visual engagement with the proposed solar skin considerably more difficult.

Possible visual distractors beyond the main architectural and landscape elements were not included in the simulation. The real site may comprise moving people or occasional vehicles and exhibited artworks as well as features of the building interiors that may be visible through glass facades and windows. Such details were not considered within this study, which focuses on early design, but they could be introduced in simulations at later design stages and in studies aimed at evaluating their visual impact specifically. In the present research, the emphasis of the 3D modelling work was therefore on the definition of each building façade's geometry. Trees were also integrated into the 3D model due to their permanent presence and their role in shaping the environment of the plaza. A suitable 3D model of a tree, made by Ferran Bruguera, was sourced on the website *FlyingArchitecture* (flyingarchitecture.com, 2018) and was placed in multiple positions within the virtual environment, after being scaled appropriately.

Following the 3D modelling of geometries, the rendering program V-Ray for Rhino (Chaos Software, 2018) was used to virtually apply materials to objects in the model of the Fire Station plaza to make it look close to real. Materials such as glass and concrete were applied to the facades delimiting the plaza. To reproduce the visual effect of the pavement, a material was created with a texture sourced on the internet from *texturelib.com* (Chugai, 2018), and edited to evoke the look of tiles covered in sand as in the real site. The proposed design for a solar architectural skin, previously constructed in a different 3D model, was inserted into the model of the site and positioned on the northern side of the plaza in place of the existing weathered steel façade.

Lighting was also added to the model. A directional light simulating sunlight on the 21st December at 10 a. m. was added in V-Ray along with an effect of atmospheric blur on the horizon, evoking that observed in Doha due to the presence of dust in the air. The environment beyond the site was not embedded in the model, as it was

considered less relevant to the study and even a potential distractor. The choice of a date and time of the day for the simulation of sunlight was justified by the optimal conditions provided for viewing the proposed façade design without any shadows on it. The selected lighting conditions constitute an example only, therefore other dates and times of the day could have been chosen as well. With more time available, further lighting conditions could have been tested for the whole site. They could have been then simulated using virtual reality to assess the environment's variability and its effect on people's visual perception of the solar skin. However, the time constraints of the project did not allow the researcher to create 360° videos for testing the experience of the site in multiple lighting conditions.

The resulting virtual environment resembled the plaza of the Fire Station Artist in Residence, differing from it in that the existing weathered steel façade was replaced by the proposed concept for a solar skin. This was designed to be distinctive within its surroundings due to its configuration displaying a recognisable Islamic pattern and a subtle effect of illusory motion (see fig. 98.). The nearby façades, largely made of concrete and glass, showed a more conventional appearance in the virtual site as in reality (see fig. 99.). The southern part of the plaza includes some coloured architectural features as well as a building envelope comprising a three-dimensional metal screen (see fig. 100.). These were expected to compete potentially as visual attractors with the proposed solar skin design, along with a prominent concrete tower (see fig. 101.). Nonetheless, the lighting conditions chosen for the simulation left the southern part of the virtual site largely in the shadow.

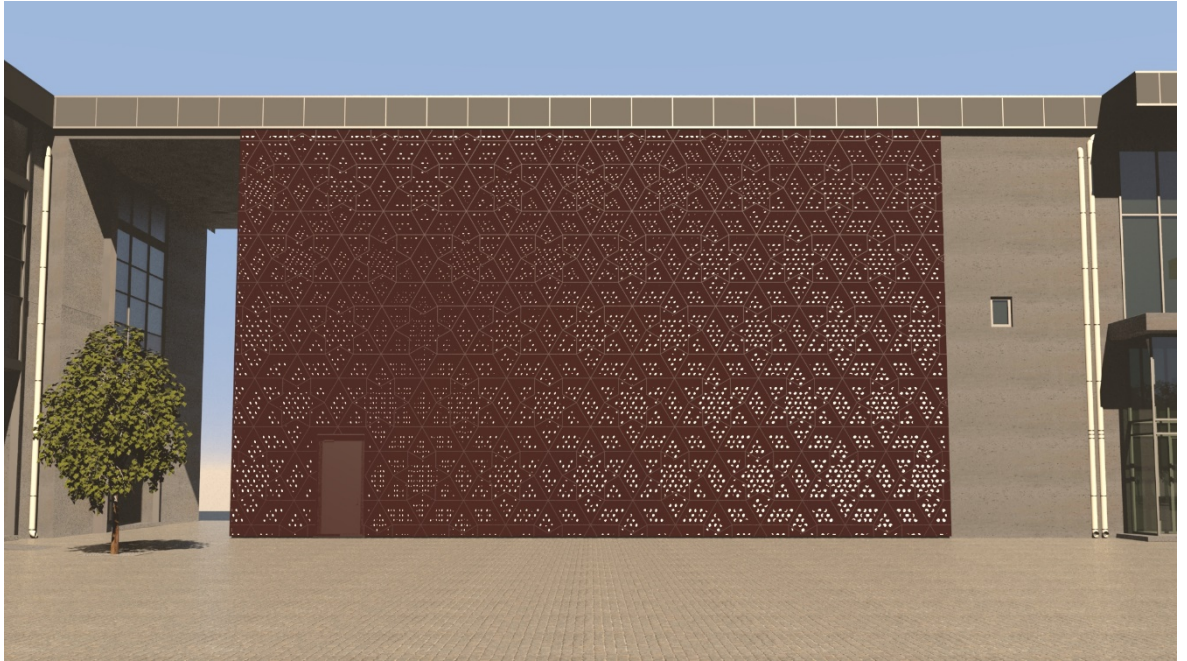


Fig. 98. *Rendering of the Proposed Concept for a Solar Façade in the Plaza of the Fire Station Artist in Residence (2018)*

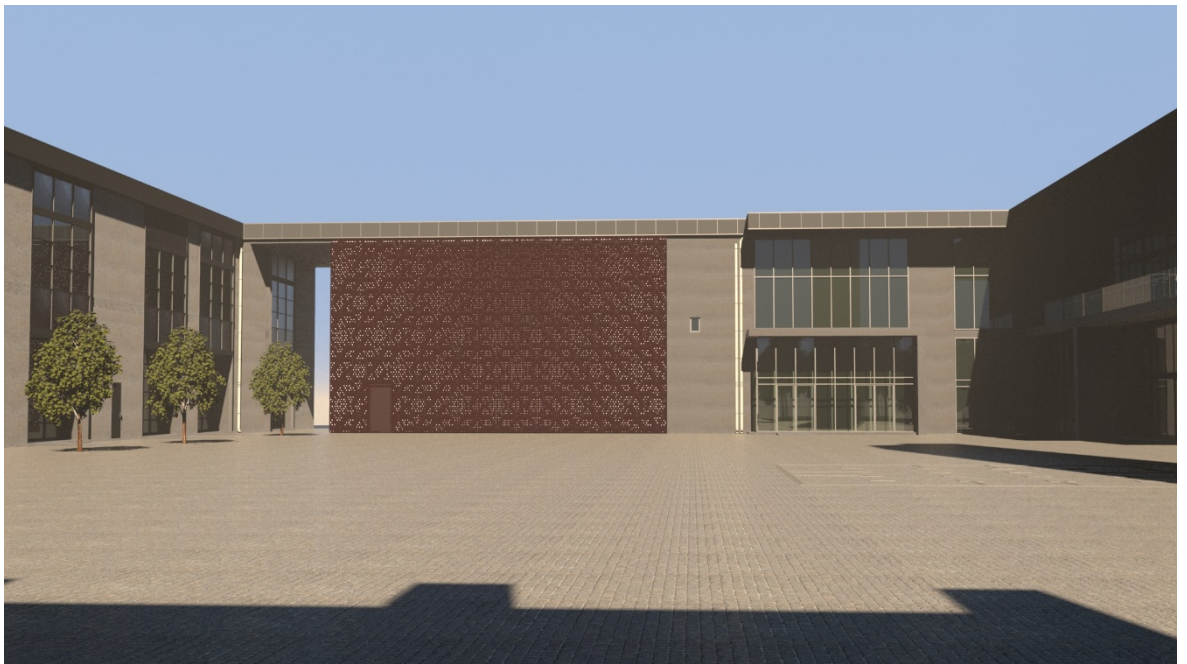


Fig. 99. *Rendering of the Proposed Concept for a Solar Skin Surrounded by Conventional Façades (2018)*

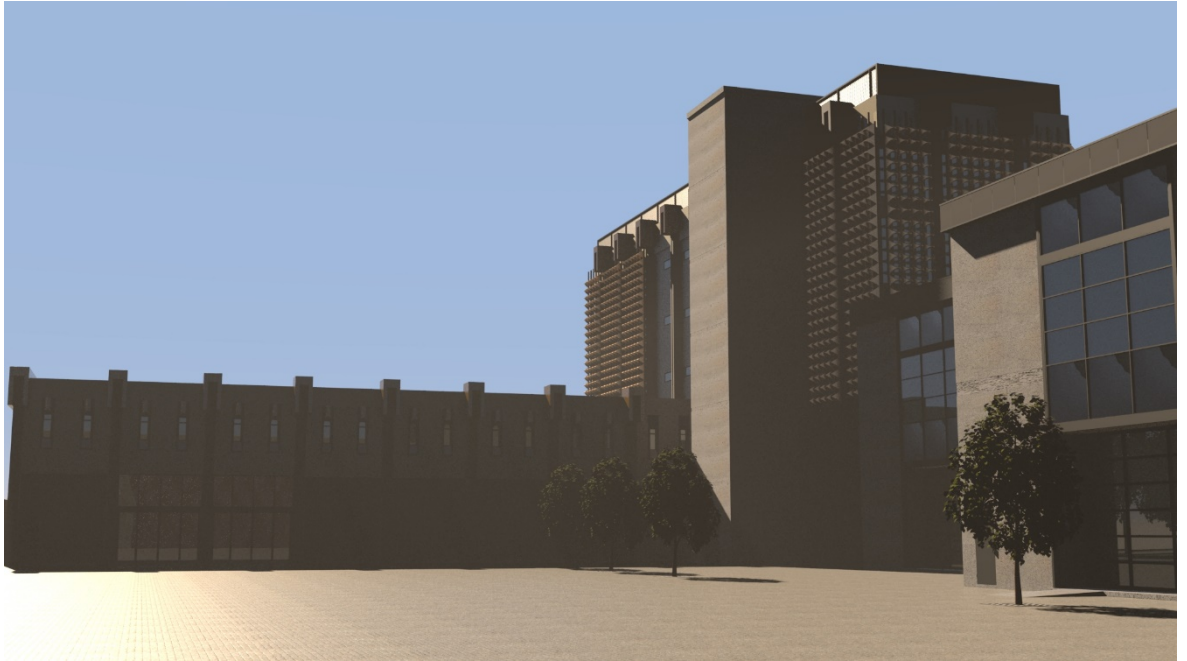


Fig. 100. *Rendering of the Façades Characterising the Southern Part of the Plaza* (2018)

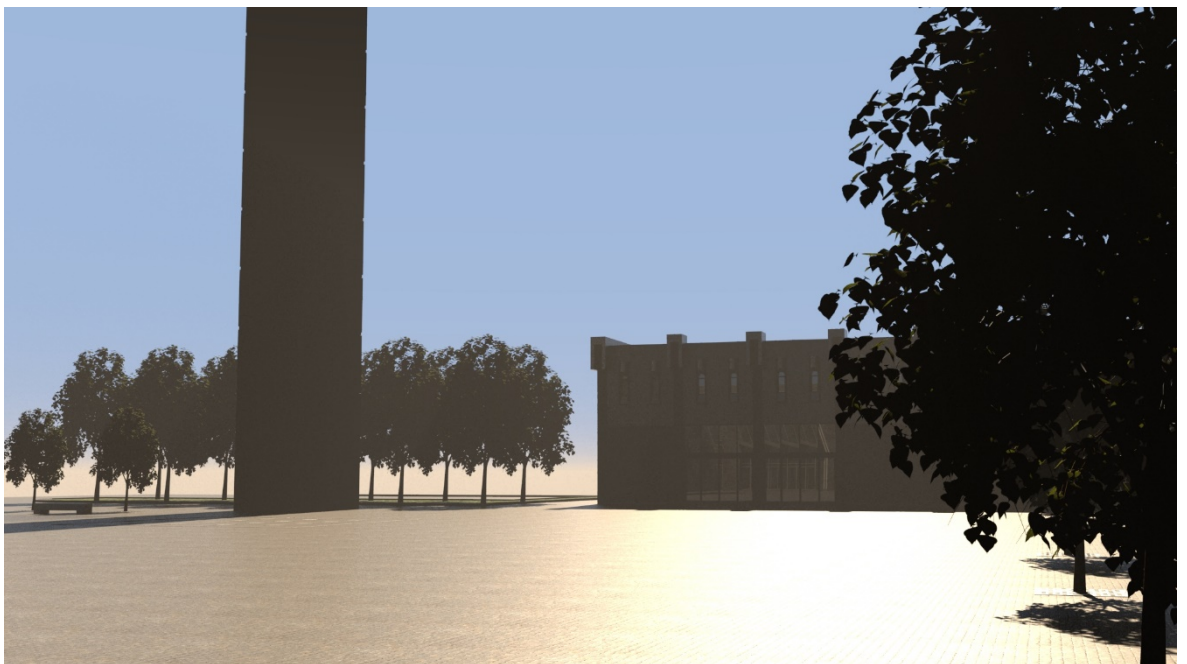


Fig. 101. *Rendered View of the Southern Part of the Plaza, Comprising the Tower* (2018)

When the model was completed, the virtual environment displaying the entire plaza and including the solar skin concept had to be shown to people in a way that could simulate a person's visual experience of being in the plaza. This was achieved through rendering of the virtual site in a form that could be displayed in virtual reality.

8.2.2 Creating the Virtual Experience through 360° Video Rendering

On completion of the computer-generated 3D model simulating the Fire Station plaza and integrating the proposed design, the virtual site needed to be presented to people in an appropriate format. An immersive virtual reality simulation was chosen for this purpose, due to its capacity for giving people the illusion that what they are experiencing is real, and thanks to the easy control of variables that it allows (Rovira et al., 2009). Offering opportunities for participatory design, virtual reality lets people experience, within a controlled setting, computer-generated spaces that may not exist yet or be easy to access, by mimicking the appearance of real environments with accuracy that can vary depending on the application (Portman et al., 2015). Augmented reality (AR) could also be used in studies aimed at evaluating the visual impact of new designs on existing environments (Cirulis & Brigmanis, 2013:72). However, using AR entails that computer-generated data is visually superimposed on real spaces (Chi et al., 2013:116), which requires access to the physical site. As the present research was conducted in the United Kingdom, far from the site of the design located in Doha, the possibility of employing AR was excluded, and VR was chosen as a simulation method for the evaluation of a solar façade concept.

Presented on head-mounted displays, immersive virtual reality experiences can be of different types. They can be more interactive, allowing head motion as both 'rotation and translation', or they can be experienced through head rotation only. The former, often associated with the 'true VR experience', entails more complex, real-time rendering of full 3D scenes, typically run through a game engine, as well as sensors installed within a dedicated room, whereas the latter, allowing viewers to only look around by turning their head, can be more simply created with pre-rendered spherical images (Chaosgroup, 2016:4–5). For the purpose of this study, the less interactive type of VR experience was preferred due to its higher simplicity and versatility, as it offered the opportunity to carry out the experiment anywhere, without the need for a dedicated room. Given that the aim was to assess whether people's visual attention was attracted by the proposed design shown within the virtual environment, allowing them to turn their head only was considered sufficient to let the researcher observe where their gaze was directed to. Creating the experience through pre-rendered images offered the researcher the possibility to use architectural design software she was already familiar with instead of a game engine. It also allowed the researcher to present the virtual experience on a portable

VR headset in multiple locations where people could be met, rather than being restricted to using a dedicated laboratory specifically set up for the simulation.

The VR experience was generated in the form of a short 360° video. This was composed of frames rendered with V-Ray for Rhino. As exemplified below (see fig. 102.), each frame comprised two identical spherical images to allow stereoscopic vision. The panoramic views were captured by placing the camera in the 3D model at 157 cm from the virtual ground, simulating the average eye height of a standing person (Chaosgroup, 2016:16). The resolution chosen for the rendered frames was the highest recommended for 360° videos with slower motion and displaying lots of details (Chaosgroup, 2016:32). As illustrated below (see fig. 103.), the frames were then combined in sequence at the minimum recommended frame rate of 30 frames per second (Chaosgroup, 2016:32) to compose a video with the video-editing software Adobe Premiere Pro (Adobe, 2018). Choosing a higher frame rate could have improved the quality of the video but would have required rendering many more frames, slowing down the evaluation of the solar skin and therefore the overall early design process.

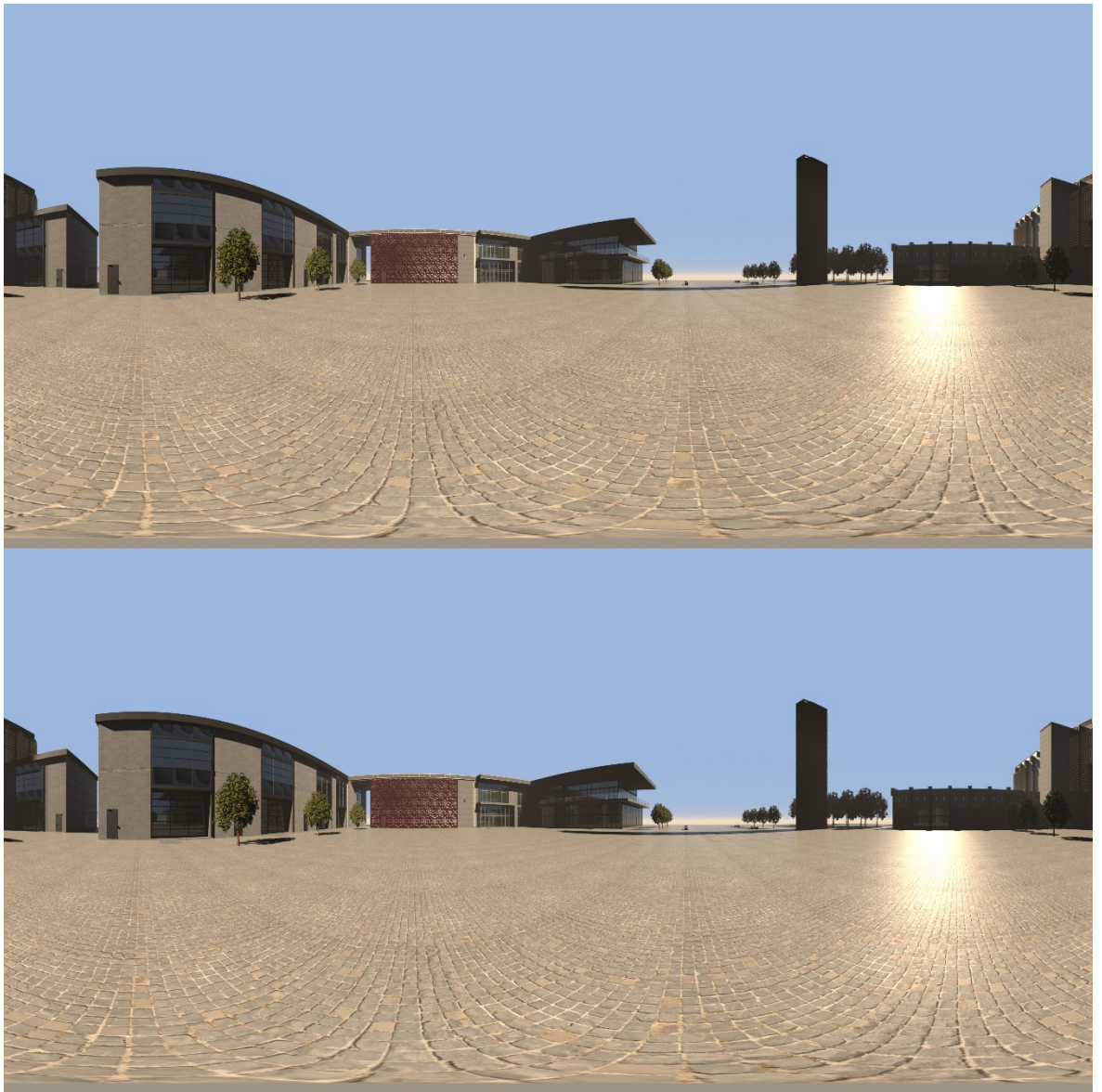


Fig. 102. *Example of Frame Rendered for the Creation of the 360° Video (2018)*

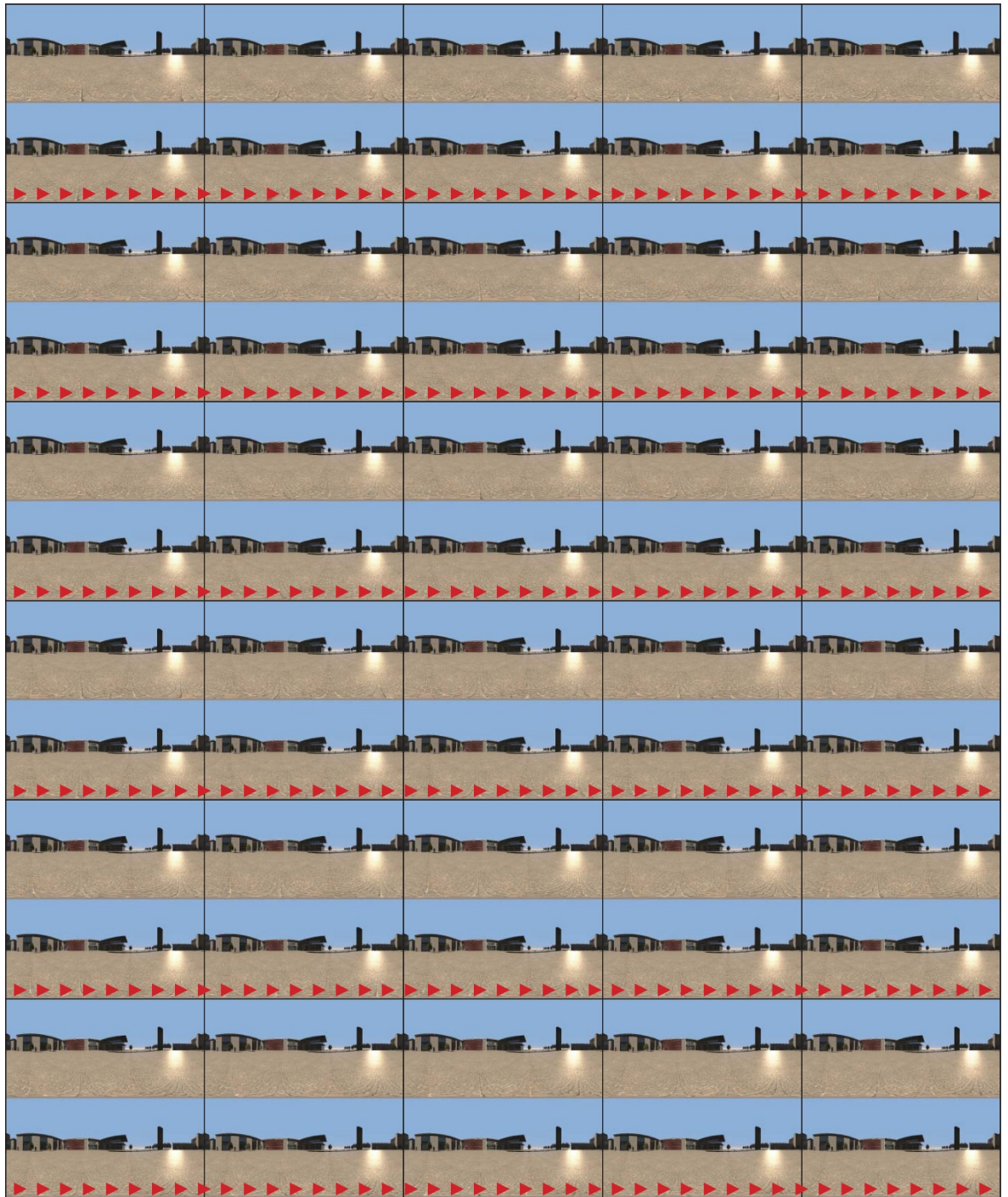


Fig. 103. *One-Second-Long Portion of the 360° Video, Represented through the Sequence of Its Frames (2018)*

As already mentioned in Chapter 4, virtual reality simulations can cause discomfort. To prevent this effect, it is recommended that a 360° video simulates an appropriate speed for the experience to be mimicked, such as looking around while walking or while driving, and that the rendered frames capture the environment keeping the camera position preferably constant (Chaosgroup, 2016:31). Besides following the above recommendations, the researcher further prevented the eventuality of discomfort for the viewers in this study by limiting the duration of the 360° video,

which did not exceed one minute. The dynamic viewing experience mimicked within the animation was also minimised. It was inserted between prolonged static panoramic views and its duration was reduced to a few seconds only. The 360° video started by showing a panoramic view of the site as experienced by a standing person in a stationary position. It then simulated some walking steps along a typical route that a visitor would follow when moving across the plaza from the western gate to the north-eastern doors (see fig. 104.) and ended by offering a static panoramic view again. The reference speed used for simulating the walking motion was 1.4 m/s, approximating a typical speed for pedestrians under the age of 65 (Knoblauch et al., 1996), as this was expected to be the broader age range of the viewers taking part in the virtual reality experiment. Composing a video with the required frame rate of 30 frames per second entails rendering a large number of high-quality images, which is a relatively time-consuming process. Therefore, keeping the video short and minimising the duration of the simulated motion helped the researcher both prevent discomfort for the viewers and deal with the time constraints of the project.

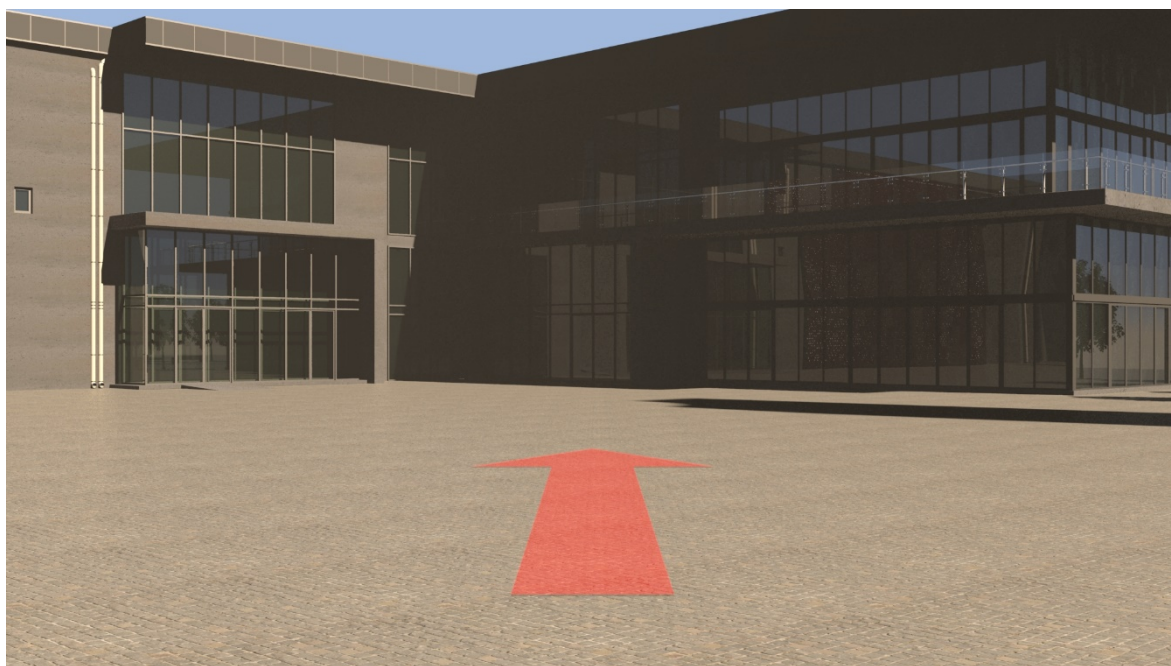


Fig. 104. *Direction of the Simulated Walking Motion* (2018)

The one-minute-long 360° video was then saved on a smartphone embedding a gyroscopic sensor and an accelerometer, to be played using the VR viewing application VRTV VR Video Player (Google, 2018) inside a headset compatible with Google Cardboard (Google, n. d.).

8.3 Assessing the Visual Experience of a Solar Architectural Skin at Early Design Stages

8.3.1 Testing the Experiment Methods

When the creation of the 360° video showing the proposed design within its urban context was completed, the virtual environment was shown to people through a head-mounted display. This could allow the researcher to detect whether the suggested concept for a solar architectural skin was capable of stimulating visual engagement by attracting people's attention and triggering interest.

As anticipated in Chapter 4, the methods chosen to evaluate the solar skin's capacity for producing responses indicative of visual engagement consisted of a combination of observations and interviews conducted within a controlled VR experiment involving fifteen participants. To try the selected methods prior to conducting the experiment, the researcher ran an informal trial with three volunteers recruited among friends. This allowed her to test the efficacy of the chosen techniques towards evaluating visual engagement and the efficiency of the overall process. The volunteers were two women and one man of three different ages (30, 36 and 45). One of them had some professional experience in the architectural design field, while the others did not. They were all sighted but while experiencing the simulation one of them found out they did not see well.

The researcher repeated the experiment process with each of the volunteers separately at their home, starting from a briefing phase to then let each volunteer wear the headset and experience the virtual environment for one minute. During that minute, the researcher took notes of the volunteer's head movements and of other reactions which included exclamations of surprise. Immediately after each volunteer had taken the headset off, the researcher asked them a single question: whether there was a façade that they had found more interesting than others, and if so, what it looked like. During the simulation, two out of three volunteers were observed turning their head to the left, which suggested they potentially looked where the new façade design was situated within the virtual environment. The same volunteers then responded that they had noticed a façade with a decorative pattern. The volunteer with architectural expertise was clearly drawn to the new solar façade design. On the other hand, the third volunteer only looked all around during the simulation, claiming they could not see well. Afterwards, the same volunteer could not recall a particularly distinctive façade within the virtual environment.

From running the informal test, the researcher could learn the following points.

- To collect data more efficiently during both observations and interviews, it was preferable to obtain it in written form.
- Given the speed of the observed reactions during the VR simulation, notes needed to be taken very concisely, preferably using symbols.
- Knowledge of architectural design could cause bias that needed to be avoided.
- Participants with even just mild vision problems, who could not experience the simulation adequately, had to be prevented from taking part in the experiment.

The above findings informed the design of the experiment to be conducted with a larger sample of participants, as described in the following sections.

8.3.2 Recruiting Participants

It was decided that to evaluate the proposed design's capacity for triggering visual engagement, a number of volunteers that could take part in the VR experiment, by watching the 360° video within a head-mounted display, needed to be recruited. Volunteering participants were recruited by the researcher within the Epsom Campus of the University for the Creative Arts, where there are no educational programmes in architectural design. Therefore, potential participants in this location were expected not to be biased by previous knowledge of the subject investigated within the study. The researcher decided to recruit fifteen participants. This choice of sample size was based on the average numbers of participants in related lab-based studies for the evaluation of urban media surfaces such as public displays, which used methods such as observations, interviews and questionnaires (Alt et al., 2012:5).

The recruitment of participants took place in different parts of the campus where the experiment was conducted during two consecutive days. An invitation had been circulated via email in advance and extended to all students and members of staff at Epsom Campus. However, the invite clarified that participation in the experiment was restricted to sighted people without ocular or neurological conditions, as individuals affected by these were susceptible to discomfort during the VR simulation. Attracted by the novelty of the VR experience, most participants decided on the day of the experiment to take part in it, so they were recruited randomly as they turned up.

During the first day at Epsom Campus, the researcher could conduct the experiment in a room that was available and could be reserved for the purpose of the study. To

involve more volunteers than those who turned up thanks to the circulated email, the researcher invited people to take part in the experiment by approaching them directly in nearby classrooms and offices or as they walked in the corridors. Later in the day, she moved with the equipment to the canteen where she could involve more participants. On the second day at Epsom Campus, she conducted the experiment in multiple areas within the library where she could meet and involve both members of staff and students.

Each participant was thoroughly briefed about the characteristics of the experiment, also through a written document, and was asked to notify the researcher immediately if they had felt any form of discomfort during the simulation, so that this could be discontinued. However, the information provided by the researcher was relatively generic about some aspects of the study. Participants were told they were about to experience a virtual urban environment while being observed by the researcher, and that they were going to be asked a question about the virtual experience after the simulation. Nonetheless, they were not given in advance any details of the location shown or of the question to be asked, as this type of knowledge could have affected the outcome of the experiment by influencing participants' visual attention.

Each volunteer agreed to participate in the study by signing the consent form given by the researcher, after reading an informative document which described the experiment within the context of the overall research project. The consent form ratified the agreement between each volunteer and the researcher, guaranteeing that the privacy of each participant's personal details was protected according to the Data Protection Act 2018 (Data Protection Act, 2018). Such details were collected by the researcher to discern the data gathered through observations and interviews, as well as to note the variety within the sample of participants. These were selected randomly to increase the validity of the study and included people of different genders, ages and occupations as well as nationalities. Overall, the small sample could not represent the global human population, as it did not include, for instance, children or people affected by ocular and neurological conditions, who were prevented from taking part in the experiment. However, the sample could be considered representative of a relatively large portion of the adult population, with a strong representation of studying young female adults (see fig. 105.).

PARTICIPANT	GENDER	AGE RANGE	OCCUPATION
1	F	41-45	Staff
2	F	51-55	Staff
3	M	61-65	Staff
4	M	31-35	Staff
5	F	51-55	Staff
6	F	26-30	Student
7	F	26-30	Student
8	M	18-25	Student
9	M	56-60	Staff
10	F	36-40	Staff
11	F	18-25	Student
12	F	36-40	Staff
13	F	26-30	Student
14	F	18-25	Student
15	F	18-25	Student

Fig. 105. *Demographic Data of the Sample (2019)*

The potential side effects of the VR experiment presented some obstacles for the involvement of people, which were overcome as much as possible with a preventive strategy. One individual who offered to take part in the experiment was prevented from doing it because they had a history of migraines, an episode of which could have been triggered potentially by the 360° video. Another individual experienced the simulation declaring only towards the end that they were feeling some dizziness and that they had forgotten to mention they had a history of motion sickness. Therefore, the simulation was interrupted immediately when they informed the researcher. Their contribution to the experiment was also considered invalid, as it was impossible to determine to what extent their responses were affected by their mild discomfort, and another participant was recruited in their place. All the other volunteers successfully took part in the experiment, allowing the researcher to observe their reactions as they were viewing the proposed solar skin design in VR, and to collect their written feedback after the simulation.




















8.3.3 Observing Participants' Reactions

During the first part of the experiment, each participant experienced the virtual environment reproducing the Fire Station plaza and showing the proposed design

for a solar building skin. Each volunteer was asked to wear the virtual reality headset provided by the researcher for about one minute to watch the 360° video rendering. While the video was being played within the headset, the researcher observed the participant's reactions to the visual experience, recording on paper any responses that could suggest an interest in some part of the virtual environment, of which concise notes using symbols were taken. As presented in Section 4.4.3, the decision of conducting observations was justified by the non-invasive nature of this method for the evaluation of people's reactions, which has been used in the evaluation of urban media surfaces such as public displays. The choice of a recording method was determined by the outcome of the informal trial run prior to the formal experiment, as noted in Section 8.3.1. The observed reactions mainly consisted of head movements and of sporadic verbal communications.

The 360° video was designed to simulate a combination of static and dynamic experience of the Fire Station plaza, which started from a virtually standing position that faced from a distance the entrance at the north-eastern corner of the open space. If a participant turned their head to the left, this potentially indicated that they were looking at the proposed design for a solar façade.

The plan was to invite fifteen participants in total, but as the experiment with one participant had to be considered invalid, one more participant who was curious about the virtual experience was involved eventually. Each participant reacted to the simulation differently, but some recurring behaviours could also be observed (see fig. 106.).

PARTICIPANT	REACTIONS	
	Head Movements	Other Reactions
1		
2		
3		
4		
5		
6		
7		
8		
9		
10		
11		 'Oh!'
12		 'Um...'
13		
14		  'Ah!'
15		

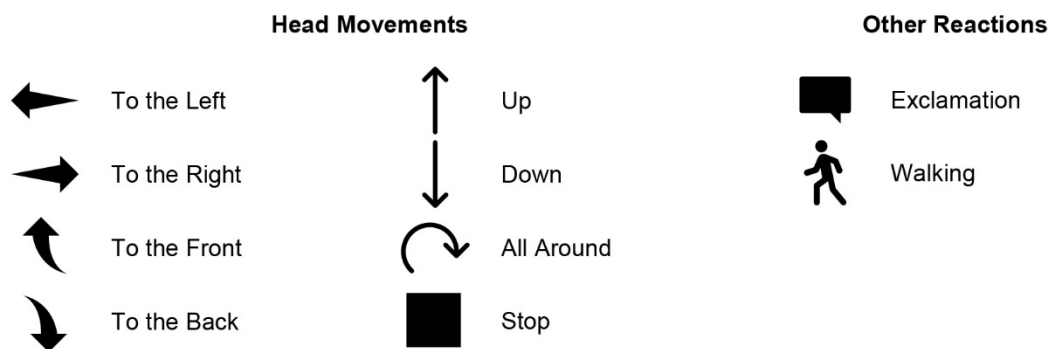


Fig. 106. *Participants' Reactions Observed during the VR Simulation (2018)*

Thirteen out of fifteen participants were observed turning their head to the left, which potentially indicated they paid attention to the proposed concept for a solar façade. Three participants looked to the left more than once. *Participant 7* looked in that direction three times, while *Participant 4* and *Participant 13* turned their head to the left twice, also stopping for some time. This could suggest their attention was particularly attracted by the solar skin. However, as emerged in Section 2.3.2.1, gaze does not necessarily reveal attention. Therefore, more evidence was needed to prove whether the solar skin was capable of attracting participants' attention and thus of stimulating visual engagement. Hence, the fifteen volunteers were also asked to provide some written feedback on the virtual experience following the simulation.

8.3.4 Interviewing Participants about the Virtual Experience

Immediately after watching the 360° video by wearing the headset for one minute, participants were given a pen and a sheet of paper which included their identification number, a single printed question on the virtual experience and some blank space where they could write their answer. The choice of using structured interviews in written form, which enabled the easier and faster collection of participants' feedback, was justified by the time constraints of the project and encouraged by the results of the informal trial. Asking an open-ended question was preferred because it was important for the researcher to prevent biased responses as much as possible, which could have been induced, instead, by a closed-ended questionnaire. Each participant was asked the same single question which was directed at unveiling whether attention and interest had been attracted by the proposed facade design so that this could be remembered after the simulation. The question asked was this: 'Was there a building façade that you found more interesting than others, and if so, what did it look like?'.

Participants answered the open-ended question in written form as they could according to their knowledge of the English language. Their answers (see appendix 4) are reported below in a partly paraphrased form for better clarity (see fig. 107.).

PARTICIPANT	FEEDBACK ABOUT WHICH BUILDING FAÇADE WAS FOUND INTERESTING
1	The building with a red surface was the one they looked at the most, and they were also drawn to the tall, dark building on the right.
2	The red-looking building was interesting as they did not understand what it was made of.
3	What they found interesting was the building looking like a tower or an obelisk.
4	The façade of red hue was the most 'eye-catching' due to its colour and to its 'subtle pattern'.
5	They noticed a 'large red building' while looking around. It stood out because of its colour and its being different from other buildings they could see.
6	The most interesting building was the first they saw, characterised by a dark glass surface.
7	They stated that 'the building with the red façade was really nice' as it reminded them of 'red windows', although they also enjoyed looking at natural features in the video, like the trees.
8	They found 'the taller buildings' more interesting to view and intriguing.
9	They noticed one façade in front of them, 'with the swirls.'
10	They were 'maybe' interested in a building characterised by a glass façade, situated on the right. They were also intrigued by the tower behind them.
11	They remembered a taller building behind them, looking like a 'chimney' and being very dark because of the shadow. They also remembered another building in front of them, characterised by white figures on its surface, which they thought they liked more.
12	They mostly remembered a building façade characterised by windows, seeming less plain than the others to them.
13	What they found interesting was a façade characterised by Arabic motifs, perhaps because of its red colour and pattern.
14	They remembered 'a tower.'
15	They noticed 'a red wall building.'

Fig. 107. *Participants' Feedback on the Building Façade Which Was Found Most Interesting during the VR Simulation (2018)*

It can be observed that nine out of the fifteen participants involved in the experiment responded, using different words, that they had found the proposed façade design interesting. In their answers, the solar skin was identified by its red colour or by the presence of a pattern that was described in multiple ways but always making the façade recognisable. Six participants claimed to remember either the tower or more generically tall buildings, which may have attracted their attention due to their size

and to the dark colour, as they were in the shadow. This showed that even if the solar skin stood out overall, there were competing visual attractors within the virtual site, the perception of which seemed to have been partly affected by the rendered lighting. Different lighting conditions in the virtual environment could have shifted the visual attractors and could have produced different results in terms of people's attention. There were also isolated cases of responses revealing that some individuals' attention was attracted by a glass façade, by one with windows, and by trees. These unexpected answers might be due to the fact that visual attention is a subjective process to some extent, as emerged in Section 2.3.2.1.

8.4 Discussion

8.4.1 Outcome of the Primary Research Process

The previous sections presented the process of evaluating people's visual engagement with a solar architectural skin at an early stage of design using virtual reality. The results indicated that the number of participants who proved to have paid attention to the proposed façade design within its simulated context exceeded that of participants who apparently did not notice it. The observed reactions suggested that most participants potentially looked in the direction of the solar façade within the virtual environment, although later their feedback did not always confirm that. The protracted or repeated act of looking in one direction appeared to be a potentially more reliable indicator of visual engagement than simple gaze revealed by head movements. The interviews conducted by asking volunteers one question on the virtual experience after the simulation to collect their answers in written form revealed that nine out of fifteen participants had found the proposed design for a solar architectural skin interesting enough to be remembered.

The fact that several participants recalled the appearance of the solar façade after the simulation, as emerged from their written feedback, confirmed that the photovoltaic skin had attracted their visual attention inspiring their interest. This seems to demonstrate that the proposed concept was overall relatively successful at stimulating visual engagement. It also suggests that the framework applied to the design, which condenses the findings of this project's secondary research, was also effective. Yet, having time available to further edit the design, the researcher could have chosen to improve it by tweaking some of its variables, such as the scale of the pattern displayed. In this case, the researcher would have conducted the experiment again after modifying the solar skin design. It also has to be noted that

the results obtained are indicative rather than definitive, as the experiment presented both strengths and weaknesses.

8.4.2 Strengths of the Primary Research Process

As emerged in Section 2.3.2.1, virtual reality has introduced opportunities in the study of visual perception. As noted in Section 4.4.3, it can be used in studies related to perception or architectural design (see fig. 42.). VR was utilised in the exploratory design of a kinetic solar façade (Panya et al., 2019) but without the involvement of participants or a focus on attracting attention or interest. The particular use of VR as a participatory research tool to explore the design of solar architectural skins for visual engagement, which is proposed in this study, may be a novelty.

Ultimately the created VR experience, even if non-interactive, proved satisfactory for simulating what it would be like to view the proposed design for a solar architectural skin while being in the Fire Station plaza. It was relatively realistic in the way it rendered forms, materials and lighting mimicking those of the real urban site in Doha. Unlike an immersive VR simulation, neither a physical scale model nor a real-scale prototype representing a small portion of the façade could have triggered reactions comparable to those elicited by a real environment. On the other hand, augmented reality might be considered as a viable option for evaluating designs in similar projects, but it appears unsuitable for experiments conducted off-site as in the present study.

In this exploration which focused on early design and on visual engagement, using a non-interactive type of simulation freed the researcher from the constraints of conducting the experiment with unfamiliar software and relatively expensive equipment or in a single location such as a dedicated VR laboratory. This made it easier for the researcher to involve people in the evaluation of the solar skin concept, suggesting that the simulation could facilitate participatory design. The choice of a non-interactive VR experience was justified by the minimal resources it required and by the need for control over variables which had to be easy to observe, such as the reactions participants could manifest. Allowing volunteers to explore the virtual environment by simply turning their heads and looking around was considered sufficient for testing the visual experience of a solar skin within its context at an early design stage. Observing participants' reactions during the simulation provided a potential indication of whether the proposed façade design was overall capable of stimulating visual engagement, without interfering with the spontaneity of people's responses.

Participants' feedback in the form of a written answer to a single, open-ended question proved effective at indicating whether their attention had been attracted by the proposed façade design. It showed that they could remember it after viewing it. Asking an open-ended question rather than using closed-ended questionnaires allowed the researcher to prevent biased responses, as did recruiting participants with no architectural expertise. Writing concise notes to record people's reactions and collecting their feedback in written form also enabled the efficient and reliable retrieval of data.

8.4.3 Weaknesses of the Primary Research Process

8.4.3.1 VR Production

It was noted that despite the relatively high quality of the visualisation, which rendered materials and lighting mimicking those of the real urban site in Doha, the simulation based on a virtual reconstruction of the real location was still far from being realistic.

The appearance of virtual materials is inevitably different from that of the real ones. Furthermore, in the reproduction of the site several details were deliberately omitted by the researcher, including those that would be visible inside the buildings through glass facades. Less permanent or less architectural elements that may have caused distraction to participants were not added to the 3D model of the site, including outdoor furniture, artworks, security cameras and even people or vehicles. Elements of the urban landscape on the horizon were also removed from the simulation and replaced with atmospheric blur resembling the typical dust in the air that can be seen in Doha. These choices were intended to reduce the number of visual distractors in the virtual setting and to increase the researcher's control over the experiment's variables.

On the other hand, some details may have been inadvertently omitted from the virtual environment by the researcher, as it emerged from literature reviewed in Section 2.3 that visual attention is selective and subjective to some extent. This means that when creating the virtual environment, the researcher may have paid attention to some visual features of the observed real site and failed to notice others.

Additionally, changes in sunlight throughout the day and the year, which may impact people's perception of the site and of the proposed solar façade design, were not considered in the simulation due to the time constraints of the project. For the same reason, the way different weather conditions would affect natural lighting could not

be considered either. Therefore, the created virtual environment represents just an example of what the experience of the site could be like. Further lighting conditions could be simulated with more time available, at a later stage of a design process or through further research. Testing the virtual environment in alternative lighting conditions could have produced potentially different results by leaving other artefacts in the shadow, which could have shifted the visual attractors competing with the solar skin. This suggests that for a thorough evaluation of a solar skin's capacity for producing visual engagement it would be advisable to test the design in VR under multiple lighting conditions. Although such iterative testing was not possible in the present research due to time constraints, conducting it could enable designers to assess whether a solar skin performs consistently throughout the year. Therefore, it can be said that, in the present study, the proposed solar skin design was able to produce visual engagement in the particular lighting used for the experiment, but more tests employing different lighting could be carried out through further research.

The realism of the simulation was also lowered by the choice of offering a non-interactive type of VR experience. An interactive VR simulation instead of a 360° video may be more appropriate at more advanced stages of a project, or for testing further human responses beyond those indicative of visual engagement.

Even though the overall simulation may be judged as relatively unrealistic, the process of creating the virtual experience was still time-consuming. To mimic the way objects of different materials responded to certain sunlight conditions in the chosen site, the 3D model of the environment surrounding the proposed building skin design needed to be highly defined. For the 360° video not to induce discomfort such as motion sickness, its quality also needed to be very high, which meant that the video needed to have a frame rate of at least 30 fps and each frame needed to be high-resolution. Therefore, it took a relatively long time to render just a few seconds of simulated walking motion through the site.

8.4.3.2 Sample of Participants

Evaluating a solar skin's capacity for stimulating visual engagement through an experiment using virtual reality entailed the selection of a sample of participants. Even though in the present study volunteers were recruited randomly, they still needed to meet certain requirements to take part in the experiment. They were selected among adults with no expertise in architectural design and limited knowledge of the overall research project, as there was a need to prevent their

responses from being biased. They had to be sighted, as the experiment investigated responses depending on the visual sense. They had to be relatively healthy, with no ocular or neurological conditions making them prone to discomfort during the simulation. Excluding sensitive individuals from the VR experiment did not allow an understanding of the effect on human wellbeing that the spatial frequency of architectural scenes may induce. This was suggested to be relevant to the design of urban environments (Le et al., 2017) and could be explored through further research. The small sample of participants chosen for the experiment was not representative of the entire human population, although it could be considered representative of a relatively large portion of it, with a strong representation of studying young women. Diversity within the sample could not be associated with the different responses observed due to the small number of participants involved but identifying any correlation besides that between the solar skin design and people's visual engagement was beyond the aims and scope of the research.

8.4.3.3 Observing and Interviewing

The recorded observations of participants' reactions revealed that thirteen out of fifteen volunteers turned their head to the left at some point during the simulation, which suggested they were looking at the proposed design for a solar architectural skin. Most participants looked in a different direction at first, which may indicate the solar façade was not strong enough as a visual attractor or that they had the instinct to look elsewhere due to other reasons. This hinted at the possibility that observing in which direction participants were looking did not necessarily reveal their visual engagement with an artefact, although previous research indicated that recording gaze distribution with eye-tracking may be used to understand people's visual engagement within an urban environment (Simpson, 2018). This has the inherent limitation of not discerning whether people really pay attention to what they look at (Simpson et al., 2019:16). For this reason, complementing observations with interviews in this research resulted particularly useful.

The interviews consisted of asking each participant a single question. While this appeared sufficient for assessing whether participants had noticed the proposed façade design, it also limited a more thorough understanding of people's responses. The volunteers' written feedback revealed that not all the thirteen participants who had looked potentially where the solar façade was in the virtual environment had paid much attention to it. However, those who had looked in that direction more confirmed through their feedback that they had been attracted to it. Therefore, while

the direction of gaze alone may be insufficient as evidence of visual engagement, the repeated or persistent act of looking in a particular direction might be a more reliable indicator.

It appears difficult to establish to what extent the novelty of the virtual experience distracted participants from observing the displayed environment with attention. Furthermore, it emerged that some participants were interested in elements of the simulation that were not expected to be very salient. This may be explained by the fact that visual attention remains a subjective process to some extent, as found in Section 2.3. Therefore, whether embedding features like patterns, colour and illusory motion in a solar architectural skin can make it more likely to trigger visual engagement, this effect may not always be achieved or predicted.

8.5 Conclusions

This chapter presented the primary, practice-based research process of evaluating at an early design stage the capacity of a solar architectural skin for stimulating visual engagement, through a virtual reality experiment involving fifteen participants. It described how the virtual environment simulating a real setting and including the solar skin design conceived by the researcher was created through the production of a 360° video following the 3D modelling and rendering of the site. It explained how research methods were tested, how participants were recruited and informed, how they were exposed to the virtual environment, and how they responded to the visual experience of the façade design created within this research. The information on participants' reactions, collected through observations and interviews, was then discussed along with the rest of the experiment process.

The overall experiment proved relatively successful for the evaluation of people's visual engagement with a solar skin at an early design stage. It showed that the proposed design triggered responses of attention and interest in most individuals within the sample of randomly selected participants. This demonstrates that the framework outlined in this research and applied to the design proved effective. On the other hand, the outcome of the experiment hinted at opportunities for improving the design further to impress an even higher number of people. It also showed potential for testing the design more with multiple lighting conditions, and for investigating the impact of architectural scenes that may induce discomfort, which could be addressed through further research.

As noticeable from the below recap of the findings (see fig. 108.), the experiment had limitations including the time-consuming VR production process, the incomplete realism of the simulation, the relative lack of inclusivity, the small sample of participants, the difficulty of detecting attention, and the interviews based on a single question, which provided indicative results. Yet, it showed that VR can offer a satisfactory research tool for testing new concepts of solar architectural skins aimed at triggering visual engagement. Side effects can be largely prevented, and a VR simulation of non-interactive type, allowing control over variables, can be conducted quite flexibly with limited resources and in different locations where people can be met. This makes the simulation accessible and potentially innovative as a method for participatory research related to design processes, which may be used by both professionals and students. The use of interactive VR could be explored through further research aimed at investigating responses beyond visual engagement in relation to solar architecture.

<p>Evaluating Visual Engagement with a Solar Architectural Skin: Key Findings</p>	<p><u>Evaluation Process</u></p> <ul style="list-style-type: none"> • Preparation through: <ul style="list-style-type: none"> - production of a non-interactive VR experience showing the proposed solar architectural skin concept within its setting - testing of research methods - briefing of 15 participants recruited relatively randomly and met in different places • Observation and recording of each participant's reactions to the VR simulation experienced individually • Collection of each participant's written feedback after the simulation, answering one question <p><u>Evaluation Outcome</u></p> <ul style="list-style-type: none"> • Relative success of the proposed solar skin design in stimulating most participants' visual engagement (as understood from the study of visual perception in Section 2.3), with potential for improvement • Relative success of the proposed framework in guiding the design of a solar architectural skin for visual engagement (as understood from the study of visual perception in Section 2.3) <p><u>Strengths</u></p> <ul style="list-style-type: none"> • Potential novel use of VR as a participatory research tool • Relative realism of the VR simulation • Control over variables • Low resource requirements • Flexible location of the research <p><u>Weaknesses</u></p> <ul style="list-style-type: none"> • Time-consuming VR production with relative lack of realism as well as of thorough testing due to time constraints of the project • Relative lack of inclusivity and of representativeness of the small sample of participants • Indicative results only, from observations and interviews with a single question, towards understanding visual engagement (since gaze does not always indicate attention, and this is influenced by multiple factors, as emerged from the study of visual perception in Section 2.3.2)
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Fig. 108. *Key Findings from Evaluating Visual Engagement with a Solar Architectural Skin* (2019)

Chapter 9: Discussion

9.1 Chapter Overview

Exploratory in nature, the present research intends to offer an approach to the design of solar architectural skins, which can facilitate the creation of new, visually stimulating concepts. Through comments and comparisons, this chapter looks back at the findings of the study, discussing them in relation to the aim of the project.

The second section reflects on the findings concerning the design of visually captivating building exteriors, towards answering the first research question of the current inquiry: ‘How can architectural skins produce visual engagement with minimal energy use?’.

The third section examines the findings related to the design of solar building envelopes, towards answering the second research question: ‘How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?’.

Through three subsections, the fourth section discusses the results about designing solar building skins with visually communicative potential, towards answering the third research question: ‘How can novel concepts of effective solar architectural skins be designed to produce visual engagement?’. Its last subsection includes a refined framework for designing visually captivating building skins through the deployment of photovoltaic-based technologies.

The fifth section reviews the challenges as well as the opportunities for further work in architectural research and design, which emerged throughout this exploration.

At last, the sixth section draws conclusions from the discussed topics, leading to the following chapter.

9.2 Implications for the Design of Visually Engaging Architectural Skins

The first research question of the present exploration is: ‘How can architectural skins produce visual engagement with minimal energy use?’. It enquires about an issue at the intersection of multiple topics within the broader domains of architecture, technology and human vision. To answer the question, a review of research spanning the fields of architectural and urban design, neuroscience, psychology, visual communication, and art, was undertaken and presented in Chapter 2, which revealed characteristics of visual and architectural compositions that can attract

attention and interest, with related drawbacks and opportunities. The review was underpinned by the analysis of selected case studies of architectural skins, based on secondary sources, as discussed in Chapter 5. These case studies represented ways of displaying on building fronts visually engaging effects with negligible operational energy use. Thus, relevant compositional strategies and visual properties that may be applicable to other designs emerged from their analysis. To some extent, the other chapters also contributed to answering the first research question by addressing two further questions which are closely related to it. Hence, this research demonstrated how ways of creating visually captivating building exteriors can be explored through an interdisciplinary, mixed-methods approach, considering knowledge, as well as practical examples, from scientific, technological and artistic fields.

The current exploration recognises the important communicative role of architectural skins, seeing visual engagement as what enables people's appreciation and experience of building exteriors. As emerged in Chapter 2, building facades can convey meanings and contribute to placemaking. This relies on architectural skins' capacity for attracting attention or interest, or in other words, for stimulating visual engagement which initiates the communication between buildings and the people in their proximity. Seeking effective ways of instigating such dialogue, and considering the physiological basis of visual experience, the current research approached the study of buildings' exterior appearance from a vision science standpoint more than that of philosophy, as demonstrated by the literature reviewed in Section 2.3. In Chapter 5, the analysed case studies of architectural skins exemplified how conveying messages to the outside can be relevant, for instance, for buildings with a cultural or commercial character. Conversely, there may be buildings for which attracting attention from public spaces is undesirable, such as private homes. It can be evinced that considering the communicative potential of the envelope in relation to the building uses can be instrumental in the success of architectural designs. At the same time, such expressive ability depends on the building skin's capacity for attracting attention. Therefore, it can be suggested that visual communication should be considered as one of the building skin's functions, which is based on the ability for attracting visual attention and thus can be studied with a point of departure in vision science.

By adopting the above perspective, the present research revealed that architectural skins can be made attention-grabbing through the integration of certain features in

their designs. As emerged from the reviewed literature on visual perception and communication in Section 2.3, salient qualities of form, colour and motion, as well as evocative figures and the complexity of patterns, are rapidly detected by humans and are likely to attract visual attention. This seems to be confirmed by the results of the virtual reality experiment described in Chapter 8, since the majority of the participants immersed in a simulated urban environment paid attention to the façade integrating salient features. On the other hand, it is evident that there are other factors affecting visual engagement. As noted in Section 2.3, there can be subjective influences on perception, as well as competing stimuli within the same environment. This finding seems to be backed by the outcome of the VR experiment reported in Chapter 8, since not all the participants involved were attracted by the façade design embedding salient features. Therefore, there is a possibility for the design of architectural skins aimed at producing visual engagement, as displaying prominent features can make them attention-grabbing. However, this alone does not guarantee that the desired effect is achieved and could be researched further particularly in relation to specific contexts.

Given that salient visual features have the potential to stimulate visual engagement, media facades can be looked at as a model of how to incorporate them into architectural skins. As emerged in Section 2.4, media facades are characterised by modular or pixelated interfaces through which dynamic visual content can be displayed. However, media facades tend to be power-intensive, since they conventionally use electrically operated components which may be light-emitting or mechanical. The latter which characterise kinetic facades are also associated with control and maintenance issues. Hence, despite their potential for producing visual engagement in public spaces, media facades present operational drawbacks which may affect buildings' capacity for reaching nearly zero-energy targets.

Whilst media facades commonly employ unfavourable technologies, their use of a modular grid to display attention-grabbing visual features is a principle that is applicable to creating visually engaging architectural skins of other types. As noted in Section 2.4, a similar compositional principle can be identified in mosaics which are a much older medium for displaying static content. The case studies of building facades analysed in Chapter 5 exemplified how salient features can be displayed through modular systems without the use of light-emitting or kinetic components that were found to cause operational issues. The early design example presented in Chapter 7 also demonstrated that the concept of a 'pixel configuration', which is

distinctive of media facades (Halskov & Ebsen, 2013:665), can be referred to in an abstract way. It showed that a geometric grid can facilitate the display of visual content such as an image or pattern on a building exterior integrating technologies that are not those typical of media facades. It also illustrated how the modules or 'pixels' can be interpreted differently, for instance as holes rather than as surfaces or solid volumes. Therefore, the modular principle characterising the design of media facades may be applied to the design of architectural skins employing other technologies which may potentially minimise the operational issues of light-emitting and kinetic envelopes.

Exploring ways of conveying a sense of motion without employing moving parts may lead to designs of architectural skins which can stimulate visual engagement with reduced operational problems. As emerged from the literature reviewed in Section 2.3, change is essential to perception, and motion, in particular, is a very strong visual attractor. At the same time, there are some types of static visual compositions that give the impression of being dynamic. These include, among others, illusions produced by particular patterns or induced by three-dimensional representations which appear to change when observed by moving viewers. The case studies analysed in Chapter 5 illustrated how motion impressions can be produced by unchanging building fronts. The design framework outlined by the researcher in Chapter 6 suggested some general ways of producing a sense of movement through static architectural skins, which were indicated as *visual strategies*. These can involve reflecting environmental changes, displaying illusory patterns, exploiting the viewers' movement, and evoking motion through blurred visual effects. The design example described in Chapter 7 and its evaluation presented in Chapter 8 showed that a static façade conceived to induce a subtle sense of motion can attract the viewers' attention and interest. Hence, the present study points at how seemingly dynamic, static architectural skins may produce visual engagement while causing potentially less operational issues than media facades.

This study demonstrated that sunlight can be exploited in creating attention-grabbing visual effects on architectural skins while it can also be converted into useful electrical energy for the buildings. While in Section 2.4 it emerged that solar technologies can complement light-emitting or kinetic systems to make them self-sufficient, in Chapter 3 it was suggested that it may be more beneficial to deploy them on the building envelope without power-intensive elements. In Chapter 7, the presented example of a design process for conceiving a captivating solar façade

showed that the building skin's interaction with sunlight can be tested through simulations and visualisations with regards to its potential for both producing visual engagement and generating energy. The evaluation of the resulting design visualised in VR, which was reported in Chapter 8, demonstrated, in Section 8.3.4, that sunlight and shading effects play a key role in influencing the viewers' attention to architectural skins or to other elements in the environment. Therefore, sunlight is an important ingredient to consider in the design of architectural skins for visual engagement. Not only it can be employed towards creating eye-catching visual effects, but it can also be converted into energy that is useful for the building through solar technologies deployed on the outside.

In summary, the first research question of this inquiry can be answered by saying that there are various ways of making architectural skins visually engaging with minimal energy use. Displaying salient features of form, colour, three-dimensionality, and motion, as well as patterns or figures, is likely to help a building exterior attract people's attention and fulfil its communicative role. However, this may be prevented from happening by environmental distractors and by subjective influences on individuals' perception. Applying the abstract principle of using the modular configuration typical of media facades to facilitate the display of captivating visual content may aid the creation of architectural skins which can stimulate visual engagement in energy-efficient ways. This may be achieved by displaying motion, which is a strong visual attractor, without the use of kinetic and light-emitting components causing operational issues, and by employing, instead, unmoving systems that only appear to be dynamic. Static architectural skins may convey a sense of motion by reflecting the surrounding environment, by producing motion illusions, by showing variations with the changing perspective of moving viewers, or by displaying blurred visual effects that evoke movement. Interacting with outer building surfaces, sunlight can contribute to creating visually engaging motion effects on architectural skins with reduced operational issues. Furthermore, it can be converted through solar technologies into useful energy for the buildings.

9.3 Solar Technologies and Visually Engaging Architectural Skins

The second research question of this study is: 'How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?'. This question determined the exploration of the potential for incorporating solar technologies into architectural skins to generate energy efficiently while also displaying visually stimulating effects to the outside. The

answer to the question was mainly sought through the review of literature on visually engaging architectural skins and on solar building envelopes, in Chapter 2 and Chapter 3 respectively, as well as through the analysis of case studies in Chapter 5. To some extent, later chapters contributed to answering the second research question by addressing the third question which is connected to it. Hence, it was shown how an interdisciplinary, mixed-methods approach can be adopted to pursue ways of deploying solar technologies in architecture that can be successful from both an energy output and a visual communication perspective.

A major implication of this research is that to deploy solar technologies on architectural skins, designers who intend to create visually engaging effects may refer to the modular compositional principle which is distinctive of media facades. As noted in the previous section, the 'pixel configuration' which is typical of media facades' interfaces (Halskov & Ebsen, 2013:665) may be looked at as a model of how to display on architectural skins features that are likely to attract people's gaze and attention, such as motion, patterns and figures. This can be applied to static designs capable of conveying a sense of motion, which may reduce the operational issues associated with conventional media facades. As emerged from literature reviewed in Section 3.3, building-integrated solar installations are also characterised by a modular configuration, which suggests the possibility of employing them as interfaces for communicating visual content similarly to how this is done through media facades. Hence, solar technologies may be integrated into static architectural skins conceived as modular displays through which visual messages, such as images or patterns, can be communicated by conveying a sense of motion.

The pursuit of visual engagement distinguishes this exploration from previous research about deploying solar energy systems on buildings. As presented in Section 3.3, previous studies examined the solar technologies for building integration stressing their multifunctionality. They broadly considered solar skins' appearance from an aesthetic perspective, emphasising design criteria such as 'harmony' and pleasantness (Schoen et al., 2001:2). Instead, the present exploration specifically seeks ways of deploying solar technologies on building skins with the aim to stimulate visual engagement, thus, to attract attention or interest. The researcher considered the 'formal' aspects which, according to prior studies, determine the visual impact of solar technologies, such as the modules' shape, size, colour and texture (Farkas, 2013:9; Munari Probst & Roecker, 2013:14). Earlier research suggested the possibility of creating 'urbanmarks' that can attract people's

attention through the use of photovoltaics (Scognamiglio & Røstvik, 2013:1322), yet it did not expand on it by referring to studies on visual attention. Whist building on existing research, this exploration stands out by crossing disciplines to question the issue of solar skins' appearance with a focus on their communicative function. In this perspective, it finds its foundation in vision science and draws inspiration from media architecture, as noted in the previous section.

It was found that when it comes to producing visually engaging effects through solar architectural skins promising possibilities are offered especially by photovoltaic technologies. As emerged in Section 3.3, consideration of formal aspects applies to the design of both photovoltaic and solar thermal installations, but the former benefits from higher compositional flexibility for architectural implementation. Prior research investigating ways of improving the visual appearance of building-integrated solar technologies gave special attention to the feature of colour. Thin films and especially third-generation technologies such as organic and perovskite solar cells expand further the possibilities for customising the colour and shape of PV modules. Using non-active elements in addition to active elements increases the visual design possibilities for building-integrated photovoltaic installations. This was also confirmed by the design example presented in Chapter 7, characterised by thin-film PV modules and by perforations as non-active elements with a compositional role. As recapped in the previous section, displaying salient features such as motion and patterns or figures creates possibilities for attracting attention. At the same time, conveying a sense of motion without kinetic systems may be preferable for operational reasons. Hence, there is potential for composing eye-catching visual content on static architectural skins using thin-film PV modules and non-active elements to induce an impression of movement.

This study showed that employing solar technologies on architectural skins with the aim to produce visually engaging effects as well as a useful energy output involves a high level of complexity. As emerged from the literature reviewed in Section 3.3, there are several barriers to the widespread integration of solar technologies into buildings. These obstacles range from the technical constraints of solar energy systems and the factors affecting their performance to the lack of knowledge limiting designers' creativity. In Section 7.3.2, the iterative simulations involved in the design of a solar architectural skin demonstrated the difficulty of balancing effective visual effects with a high energy output. Therefore, some guidance can be beneficial

especially in the early design of solar building exteriors, to facilitate imaginative thinking.

Throughout the present investigation, it became more evident that deploying photovoltaic-based technologies on architectural envelopes entails a trade-off between optimising the visual and the energy output. As emerged in Section 3.3, choosing to use established PV technologies with improved visual features such as coloured absorbers or with semi-transparent components can lead to lower energy outputs. Employing photovoltaics in combination with power-intensive systems such as LED displays does not seem advantageous either. On the other hand, high-concentration and sun-tracking systems designed to increase the efficiency of solar technologies present building integration and operational issues. Possibilities suggested through the analysis of case studies in Chapter 5 for deploying solar technologies on architectural skins also entail potential problems associated with the nonuniform absorption of sunlight. The design exemplified in Chapter 7 demonstrated, in Section 7.3.2, that potentially expressive, three-dimensional configurations may increase shading on PV modules, thus contrasting the performance-boosting effect of optimal orientation and tilt angles which vary with the building's location, as highlighted in Section 6.2.1. The design example in Chapter 7 showed how a compromise had to be reached between multiple conditions such as displaying the desired visual effect, maximising the absorber's exposure to solar radiation, reducing self-shading, and facilitating the cooling and the cleaning of PV modules. Therefore, the effective deployment of solar technologies on architectural skins entails balancing different aspects and ultimately depends on characteristics of individual projects.

While acknowledging the necessary trade-off, this research hinted at possibilities for improving performance when integrating photovoltaic technologies into building envelopes which display potentially engaging visual effects. As presented in Section 3.4, the energy output of photovoltaic systems can be lowered by environmental factors such as limited solar radiation, high temperature and dust accumulation. It can also be affected by factors concerning the electrical design, the maintenance and the cost of the system. Nonetheless, there are several ways of containing performance losses of BIPV installations, which were presented in Section 3.4 and grouped, in Section 6.3.4, as *performance enhancement strategies*. These encompass ways of avoiding the overheating of photovoltaic cells, of increasing the amount of sunlight hitting them, of preventing shading and dust accumulation, of

improving the absorption of light in specific wavelengths, and of reducing costs. They include the use of passive or active cooling techniques, of dichroic beam splitting techniques, of three-dimensional photovoltaic configurations, of low-concentration optical devices and of spectral conversion methods. Therefore, *performance enhancement strategies* may be adopted when photovoltaic technologies are deployed on visually engaging architectural skins, which may reduce performance losses exacerbated by design choices concerning the appearance of the skin.

By suggesting the adoption of *performance enhancement strategies*, this research implied that the techniques they involve may be considered also to manipulate the visual design of building exteriors. As emerged in Section 3.4, technologies such as dielectric-based concentrators, spectral converters, or luminescent and holographic concentrators can add visual qualities to solar building envelopes. The analysis of case studies in Chapter 5 suggested how conventional or non-active façade modules characterised, for instance, by three-dimensional forms, colour, reflectivity or refractivity could be potentially replaced by photovoltaic components complemented, for instance, by concentrating devices or filters. The design example presented in Chapter 7 and its evaluation in Chapter 8 showed how performance-enhancing spectral converters and passive cooling through natural ventilation can contribute to the appearance of a building skin and make it stand out from its context. Hence, technologies involved in improving the energy output of photovoltaic building skins may be exploited to alter their appearance in ways that can produce visual engagement.

While many technologies which can enhance both the visual effect and the energy output of photovoltaic building skins are still in development, their potential for architectural applications seems worth considering in new design projects. As found in Chapter 3, photovoltaic technologies continue to be researched heavily and to be improved. The field of thin-film photovoltaics is expanding further the possibilities for architectural design. With a wide range of semiconductor materials being explored, flexible, semi-transparent, and even printable solar cells may facilitate the creation of custom designed elements for architectural projects. Among third generation PVs, colourful perovskite solar cells appear to be particularly promising also in terms of energy output efficiency. Certain configurations for visually engaging architectural skins may be achievable only through the use of thin-film photovoltaic modules, as demonstrated by the design for a perforated solar skin, presented in Chapter 7.

While replacing large quantities of silicon is not a prime concern in term of cost, the technology of luminescent concentrators is expected to improve visually the integration of photovoltaics into facades (Meinardi et. al., 2017:1). Similarly, other low-concentration systems and more new solar technologies may have potential for producing enhanced visual effects when embedded in architectural skins. Hence, it seems worth exploring creatively the possibilities for deploying novel solar technologies on the building envelope. Envisioning new applications of such technologies may boost their development further.

To summarise, there is a wide range of possibilities for deploying solar technologies effectively on architectural skins in ways that can produce visual engagement. Greater opportunities may be offered by photovoltaics, and this potential may be expanded even more as new solar technologies for building integration become available to the construction industry. The pixelated configuration typical of media facades offers a useful compositional principle that may be referred to in the creation of solar skin designs displaying visual content such as images or patterns. Furthermore, conveying a sense of motion through static solar facade designs may produce eye-catching effects with minimal operational issues. Deploying solar technologies effectively on architectural skins for visual engagement involves a trade-off between a multiplicity of aspects, which may vary depending on characteristics of each particular project. New possibilities are offered by advancements in the field of photovoltaics, which are leading towards cheaper, customisable and yet high-performing modules such as perovskite solar cells. There are also strategies that can be adopted to enhance the performance of photovoltaic systems. Such strategies encompass technologies that can add visual qualities including colour, three-dimensionality or reflectivity to the building skin. They multiply the creative possibilities for designers and may compensate to some extent for drops in energy conversion efficiency determined by design choices regarding the architectural skin's appearance. By considering only some types of solar technologies which are overall in an ongoing state of research, the present study opens the way to further explorations on solar architectural skins for visual engagement.

9.4 Conceiving Solar Architectural Skins for Visual Engagement

The third research question of the present exploration is: 'How can novel concepts of effective solar architectural skins be designed to produce visual engagement?'. To address this question the researcher combined the findings of the literature

review in Chapter 2 and Chapter 3 with those from the analysis of case studies presented in Chapter 5, to outline a design framework as described in Chapter 6. The framework was then applied to a design example, described in Chapter 7, and was further assessed through the design evaluation focused on detecting visual engagement, which was presented in Chapter 8. Therefore, the whole research project ultimately contributed to addressing the third question of the present exploration, from the initial literature review to the evaluation of a design example. This gives a demonstration of the interdisciplinary, mixed-methods approach that can be adopted to investigate a design issue at the intersection of multiple fields of knowledge and practice.

9.4.1 Aspects Involved in the Design

A major finding of this research is the combined multitude of interdependent variables which are involved in the design of solar architectural skins aimed at stimulating visual engagement. Merging knowledge from seemingly disparate fields, the researcher parsed relevant factors which influence the early design of solar skins, as well as types of potential options to choose from in the generation of a concept. The framework outlined in Chapter 6 and its application to design in Chapter 7 revealed that among the interwoven influences on the design of solar building envelopes for visual engagement there is an overarching factor which is the location. This is characterised by particular geographic, climatic, socio-cultural, economic and regulatory conditions. The multiple circumstances to be pondered include characteristics of the outdoor environment, of the building with its uses, of the semantic content to be communicated to the outside, and economic costs, which ultimately trace back to the project location. Designers can respond to the above influences with a range of possible variations in the solar skin layout, which were ascribed by the researcher to four categories. These are the *visual strategy*, the *skin morphology*, the *visual quality* of surfaces and the *solar technology* to be deployed, which may be expanded potentially with further research. The design example described in Chapter 7 and its evaluation presented in Chapter 8 demonstrated that the variables offered for consideration within this study can successfully aid the decision-making process towards conceiving architectural skins for visual engagement.

The suggested approach to exploring the design of solar architectural skins differs from perspectives advanced in other studies. As emerged in Section 3.3, previous research addressed the appearance of building-integrated solar technologies from

an aesthetic point of view and distinguished formal aspects from functional and constructive aspects. Instead, this research focused on exploring solar skins' capacity for producing visual engagement which enables them to fulfil their communicative function. By doing so, the present study approached the appearance of solar envelopes with the perspective that emerged from Chapter 2, which is based on visual science and draws inspiration from media architecture. Concentrating mainly on visual aspects, this outlook favoured a predominantly qualitative investigation rather than the quantitative analysis of solar skins' performance, which can be essential to other studies. Unlike previous approaches directed at designing building-integrated solar arrays, the stance of this research encourages consideration of new technologies that are still in development because of their potential for improving the performance of solar skins, including their communicative function. Raised in Section 6.3, the suggestion of choosing a *visual strategy* for expressing content by conveying an attention-grabbing sense of motion through solar building envelopes is also a novelty. Therefore, this research proposes an overall unprecedented approach to the exploratory design of solar architectural skins.

9.4.2 Early Design Process

With its new perspective, the present exploration also exemplified the overall process for conceiving a new solar façade, which can be seen as approximately composed of three phases. Chapter 7 showed there is a first phase in which the multiple influences on the design are holistically considered. During this phase, information is gathered on the location and on related aspects of the project, so that the starting conditions for the design can be understood. This includes researching the local culture which can inspire the semantic content to be expressed through a new façade. In the second phase, alternative design variations are explored in response to the examined context, and features are chosen by the designer to form a solar skin concept. In the third phase, described in Chapter 8, the produced visual composition can be presented to people through an immersive virtual reality simulation. This allows the designer to evaluate through observations and interviews whether the solar skin layout is capable of triggering visual engagement. Hence, the present research proposes that three main steps can be identified in the creative process for conceiving a novel solar building skin.

The three-phase design process was similarly noted in previous studies. It recalls that presented by Kosoric et. al. (2011), in which the authors distinguished initial

stages characterised by the understanding of a project's characteristics from the subsequent design and evaluation of a building-integrated photovoltaic installation (Kosoric et al., 2011:195). The three phases also echo design thinking models which identify the design stages of 'data gathering, idea generation and testing' (Carlgren et al., 2016:40). As observed in Section 7.4, the steps leading to the definition of a concept for solar architectural skin are not necessarily sequential but rather iterative. In Chapter 8, it was also suggested that depending on the outcome of the evaluation stage a designer may consider repeating prior steps differently to improve the skin layout further and achieve more visually engaging results. Thus, the early design process for conceiving a captivating solar skin is eminently iterative but can be seen as approximately formed of three phases. These can be briefly identified as the *understanding of the starting conditions*, the *idea generation*, and the *evaluation of visual engagement*.

As part of the first phase, information is gathered on the site for the design and on its context, with special attention to the aspects that may have an effect on the configuration of a photovoltaic skin. As presented in Chapter 6 and demonstrated through a design example in Chapter 7, such features are interwoven and include, above all, the *location* of the building, with its broader characteristics, such as its geography, climate, society, culture and economy. Further related aspects comprise traits of the *outdoor environment* the building skin is facing and of the *building* the new facade is for, which may impact greatly, for instance, the form, size, position and other visual features of a solar array. The *content* or visual message to be conveyed through the skin can be given by the client or, as in the exemplified design, it can be inspired by the local culture. Potentially, it may also originate in other ways, for instance from ideas proposed by artists or by the building users, which may be explored through further research. There are also *economic factors* that cannot be ignored in the creation of a new concept for a solar skin, which can range from the cost of design and production to those of construction, operation and dismantling of the solar skin, thus including maintenance costs. Therefore, this research indicated a useful set of aspects to explore in the first phase of the design process for conceiving a solar building skin. The proposed range of criteria is however flexible and open to refinement with further exploration.

The present study exemplified how relevant information on the site and on its context can be sourced, but this may vary in practice depending on the particular project. For instance, the design example presented in Chapter 7 was based on a

site that the researcher had already visited and of which she had been given materials including photographs and architectural drawings. Thus, she completed the already available data with information from readings of academic publications and of other documents that could be accessed remotely. There may be cases in which data can or need to be retrieved through fieldwork and site surveys. When design work has to be conducted fully offsite, perhaps for some design competitions or for academic projects, information may need to be obtained largely from secondary sources. Hence, in the first phase of the creative process the site for the design and its broader context can be researched through a variety of methods which may vary from project to project, also depending on the availability of resources.

In the second phase of the design process alternative features of the solar skin configuration are considered and selected by the designer in response to the conditions examined in the first phase. As proposed in Section 6.3 and exemplified in practice in Chapter 7, a major decision to be made concerns the *visual strategy* for the design. It identifies the type of seemingly dynamic effect to be produced, such as *environmental reflections*, *illusory motion*, *change with perspective*, and *blur*, which are explained in Section 6.3.1. Choices can be made accordingly regarding the *skin morphology*, defined by features such as the *modular configuration*, the *scale*, the *module's geometry*, *orientation* and *tilt*. In relation to those, the designer can select the *visual quality* of the skin's surfaces, with properties such as *colour*, *texture*, *transparency*, *reflectivity*, *refractivity*, *diffractivity*, and *luminescence*. These may influence the choice of a suitable *solar technology*, which is based on the use of photovoltaics in this research. Decisions on the *solar technology* can be broken down into choosing three components: the *absorber*, the *substrate*, and the *performance enhancement strategy*. The *absorber* refers to the type of photovoltaic cell to be employed, which can be of first, second or third generation. The *substrate* identifies the building skin material supporting the photovoltaic modules, which may be, for instance, glass, metal, or plastic. The *performance enhancement strategy* comprises technologies such as solar concentration or spectral conversion, which can improve the energy output of photovoltaics while also adding visual qualities to the building front. Therefore, during the *idea generation* phase designers can select and combine layout features of the solar envelope, referring to the suggested categories of the *visual strategy*, of

the *skin morphology*, of the *visual quality*, and of the *solar technology* to be deployed, as explained in Section 6.3 and illustrated in Section 7.3.

This research demonstrated which methods can be used in the *idea generation* phase of the process for creating a solar architectural skin that is aimed at triggering visual engagement. In the design example presented in Chapter 7, the researcher employed parametric 3D modelling and climate-based simulations as well as visualisation techniques, as shown in Section 7.3. As noted in other research, parametric methods open new ways of thinking in the creative process, facilitating the quick generation and editing of designs through the change of parameters (Oxman, 2017). This was found particularly beneficial in the present study as the researcher could rapidly test alternative configurations digitally within the environment of Rhino 3D. The parametric simulations included the 3D modelling of a modular geometry displaying a given visual content, as well as rough predictions of how alternative configurations for a potential photovoltaic installation would perform, by estimating sunlight hours, solar radiation, shading and electrical output. Visualisation techniques, including image and video rendering, were helpful for the testing of shadows and of the overall visual effects of the concept. The example described in Chapter 7 showed the importance of using parametric simulations and visualisations iteratively to adjust the concept by altering features that affect both its visual appearance and the absorption of sunlight. Hence, during the *idea generation* phase of conceiving a solar architectural skin for visual engagement, design possibilities can be explored digitally through the iterative use of computer simulations and visualisations.

This research exemplified how the third phase of the process for conceiving a solar architectural skin can be dedicated to the *evaluation of visual engagement* when this is an important goal of the design. Chapter 8 showed how in the reported design example the concept generated by applying the suggested multi-criteria framework was tested with people's involvement. It was demonstrated that the assessment can be conducted through an experiment in which participants individually experience the proposed design in VR within a reproduction of the existing site. The experiment includes observations of participants' reactions to the simulation as well as interviews. These methods are typically employed in the context of media architecture and particularly in the evaluation of public displays, as mentioned in Section 4.4.3. Chapter 8 revealed that a non-interactive VR experience can be effective despite being less realistic than an existing setting or an interactive VR

simulation, as it allows both control and flexibility in conducting experiments while requiring limited resources. Without offering a virtual, immersive experience it would be challenging to present an innovative concept for a building skin at its actual scale, or to trigger realistic responses in people by using small-scale physical prototypes offsite. Although people's attention can be affected by individual or environmental factors as mentioned in Section 2.3, experiments with the combination of methods described in Chapter 8 can enable the assessment of visual engagement. This can be recognised from observations of participants' reactions, particularly of their recurring head movements during the VR simulation, in conjunction with the answers from the subsequent interviews, which can reveal whether and how often the proposed design was noticed. Therefore, VR experiences, even of non-interactive type, with observations and interviews provide a valuable mix of methods for evaluating in a participatory way whether new concepts of solar architectural skins can stimulate visual engagement.

9.4.3 A Design Framework

In light of the findings discussed in the previous subsections, the framework outlined in Chapter 6, which suggested factors and possible design variations to be considered in conceiving a solar building envelope, can be integrated with suggestions about the creative process. The diagram below (see fig. 109.) summarises the approach to the design of a solar architectural skin aimed at stimulating visual engagement, which resulted from the experience gained through this research. It represents the three-phase process as characterised by attention to multiple aspects from different areas of knowledge and by the iterative use of methods which include digital prototyping as well as qualitative research techniques. Rather than indicating rigid directions, the framework can offer designers and researchers some guidance by hinting at possibilities and at tactics which can be employed to explore them. It invites consideration of PV-based technologies which are not yet established, encouraging innovative thinking.

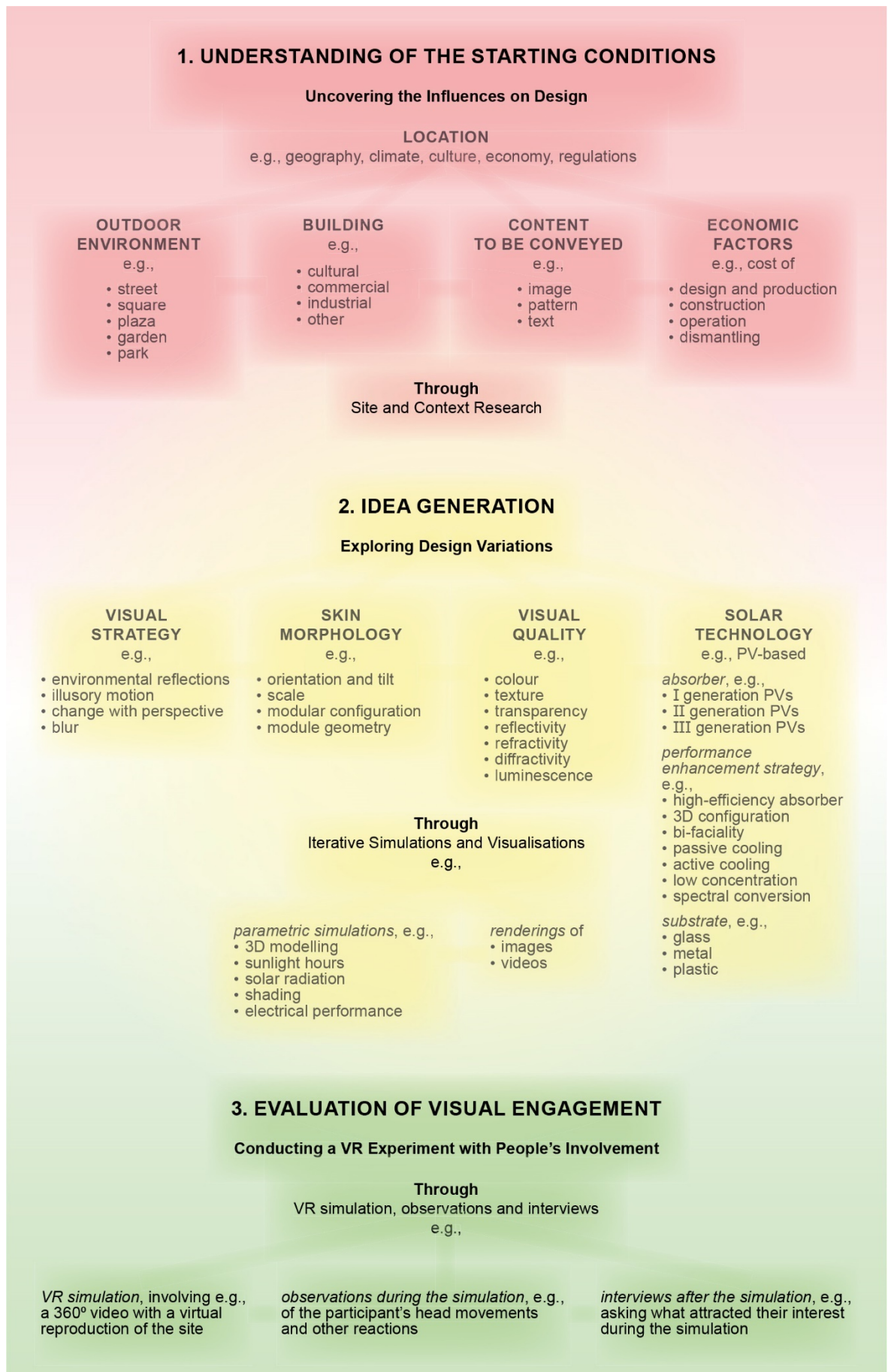


Fig. 109. *Designing Solar Architectural Skins for Visual Engagement: A Framework* (2019)

It can be noted that the designer has an important active role in weighing aspects and making decisions in the early design of a solar building skin for visual engagement. For instance, as part of the process exemplified in Chapter 7, the researcher chose a planar, vertical façade configuration despite its unfavourable angle for the absorption of sunlight, as shown in Section 7.3.2. Her decision resulted from balancing the façade's communicative character against shading and maintenance factors. Opting for a vertical configuration also seems reasonable given the ongoing improvements in the field of BIPVs such as decreasing costs, efficiency enhancements and possible combined deployment of photovoltaics on facades and on roofs (Freitas, 2018:191). In other cases, the designer may decide to prioritise a solar installation's energy output over its expressive role. While the framework suggested in this research may serve as a tool supporting design choices, it does not replace the designer's judgement and agency. As stressed by Plowright (2014), appropriate choices in architecture are made by designers who interpret the characteristics of each project with their own discernment and with the aid of frameworks, but these do not replace their skills (Plowright, 2014:48). Hence, while the framework proposed in this research can assist the early design of a solar skin for visual engagement, the outcome ultimately depends on the designer's judgement and ability.

The perspective advanced in this research offers a new holistic approach to the design of solar building envelopes. It connects multiple subjects to explore the communicative potential of architectural skins embedding photovoltaic-based technologies. Transcending disciplinary boundaries to connect domains of knowledge in a purposeful way is distinctive of 'systems thinking' (Arnold & Wade, 2015:678). The proposed approach also invites consideration of a wide range of design aspects which are intimately interlinked. As demonstrated by the framework outlined in Chapter 6 and by its successful application described in Chapter 7, the variables involved in the design of solar architectural skins are interwoven and influence each other. This reflects the defining character of systems, which is the interrelation and interdependence between elements that synergistically produce an effect (O'Connor & McDermott, 1997:2; Arnold & Wade, 2015). A 'systemic perspective' to understanding solar energy in architecture was previously recommended to address the issue of employing photovoltaics in net-zero energy buildings with concern for their energy balance (Scognamiglio & Røstvik, 2013:1333). A system can be understood through 'holistic thinking' (Checkland,

2000:S11), which involves recognising some 'rules' within it (O'Connor & McDermott, 1997:XIV). Applied to architectural design, this is not mere 'problem-solving', as it entails comprehending a 'complex layering' of aspects (Plowright, 2014:26). A solar architectural skin can be seen as a system and as part of a larger, intricate system which is its context, thus the framework proposed in this research offers a holistic approach to its creative design.

To sum up, designing novel concepts of solar architectural skins that can stimulate visual engagement entails considering an entangled multitude of aspects which can be approached holistically by drawing from different disciplines. The present research demonstrated how this can be done with a new interdisciplinary perspective connecting seemingly distant areas of knowledge such as vision science, media architecture and solar technologies, and with the use of mixed methods. Exploring the communicative potential of building envelopes integrating photovoltaic-based technologies, it suggested a framework for their design, which can provide structure to the early creative process by supporting designers' decision-making and by encouraging innovation. The proposed approach draws inspiration from principles and methods of media façade design while also hinting at strategies for conveying an attention-grabbing sense of motion through static, low-maintenance, solar envelopes. It recognises three phases in the design process while acknowledging its iterative nature. The three steps are identified as the *understanding of the starting conditions*, the *idea generation*, and the *evaluation of visual engagement*. The variables involved include factors shaping the design and types of possible variations in the architectural skin layout. The suggested design methods involve a mix of qualitative research and digital prototyping techniques including parametric simulations, visualisations and VR experiences. The advocated approach, which is the product of the current exploration, may be refined with further research.

9.5 Challenges and Opportunities

9.5.1 Research Journey

The journey of this research began with understanding the difficulty of creating visually interesting architectural skins integrating solar technologies, which originated with previous research and design work by the author and motivated her to undertake the present exploration. This started from a review of literature on visually engaging architectural skins in Chapter 2 and on solar building envelopes in Chapter 3. Such secondary research revealed the lack of an approach,

connecting different disciplines, for conceiving effective solar architectural skins for visual engagement. It also suggested the potential for addressing the issue by exploring how to display attention-grabbing features through static photovoltaic skins that appear dynamic, which was the line of research pursued, while other topics were left aside.

The journey continued with the research of case studies, towards understanding how solar envelopes could be designed for visual engagement. The lack of solar skins with the sought-after characteristics, which emerged from the literature review, led the researcher to consider a broader range of building envelopes. She selected fifteen examples of static architectural skin designs with potential for stimulating visual engagement and for integrating photovoltaic-based technologies. Analysing a variety of cases through primary qualitative research that needed to be conducted onsite posed obstacles in terms of time, resources, and applicability of the methods in real urban settings. Thus, the researcher chose to analyse case studies based on secondary sources, focusing on their design characteristics and deferring the study of people's responses to after proposing a new solar skin concept.

The findings of the secondary research, including the literature review and analysis of case studies, suggested criteria which were condensed into an initial framework that aided the generation of a concept for a solar skin, but with some challenges. While the framework offered a useful range of variables to consider, testing different possibilities in early design was potentially quite time-consuming and expensive. To overcome this and speed up the trial-and-error iterative process to some extent, the researcher chose to rely on digital prototyping techniques enabling quick, interactive design changes. Testing visual effects entailed lengthy visualisation work which combined with the relative lack of realism of the output and with the limited timeframe and resources of the project posed constraints to what could be pursued. Hence, a single design concept was ultimately generated.

The proposed solar skin design was then tested with people's involvement, which showed its capacity for stimulating visual engagement. The evaluative experiment entailed presenting the design within its simulated context through a VR experience which could trigger more realistic reactions than techniques based on physical prototypes and sites. Based on methods employed for media architecture, the evaluation techniques involving behavioural observations followed by interviews were first tested through an informal trial which provided useful insights for the experiment. It allowed the researcher to prevent issues that could compromise the

research, such as bias and inefficient data collection. Yet, the experiment faced a number of other obstacles, besides the time-consuming VR production process with a result which partly lacked realism. People prone to the potential side effects of the simulation could not take part, and the failed experiment with a participant had to be invalidated and repeated. An email invitation was insufficient for recruiting all participants, but the researcher could also invite people in person as she met them in different locations at UCA Epsom Campus, where she conducted the experiment. Limitations of the observational analysis were overcome by collecting participants' written feedback, which could prove their visual engagement with the design. Given the constraints of the experiment, including the small sample of participants, the non-interactive nature of the simulation and the single question asked, the results were only indicative, but they were still useful for improving the previously outlined design framework. This was flexible to use and could be integrated with suggestions for the early design process but could not be fully comprehensive or embed exhaustive information for non-experts. Thus, overall the research journey raised some issues that could be addressed through further work.

9.5.2 The Communicative Potential of Solar Architectural Skins

This research approached the issue of people's visual engagement with solar architectural skins in a rather general way. It may be argued that whether it is appropriate for a building exterior to attract attention depends on the characteristics of the particular project and of its context. For instance, it was noted in Section 2.4 that media facades may not be suitable for all urban environments or buildings. Similarly, it can be suggested that eye-catching solar facades may not be appropriate for historical buildings or may be unsuitable for private properties for which attracting attention can be inconvenient. Therefore, while the current study presents possibilities for enabling people's engagement with building exteriors embedding photovoltaic-based technologies, there needs to be a reflection on the situations in which the suggested solutions can be applicable.

More research can be directed potentially at understanding people's perception of solar building exteriors through the senses. The present study focused on visual engagement only, as vision appears particularly relevant in the experience of building skins from a distance. However, as noted in Section 2.2, other senses contribute to the human experience of spaces. How this affects whether and how solar facades are perceived from different positions relative to the buildings should be investigated further. It also has to be considered that not everyone perceives

spaces the same way, which is exemplified by the fact that the visually impaired experience urban environment by relying more on non-visual senses. Additionally, the potential of solar skins for attracting attention is affected by the presence of other stimuli in the environment, which may act as distractors or reduce people's interest. This limitation emerged in relation to media architecture in Section 2.4, where it was noted that the abundance of visual stimuli can cause what has been called 'display blindness' (Memarovic et al., 2015). As presented in Section 8.3, the VR experiment reported in Chapter 8 showed that participants were often drawn to a prominent visual element in the virtual environment which was competing with the proposed façade design in attracting attention. In real urban settings there are other sensorial stimuli beyond the visual, which may distract people from looking at buildings and may influence visual perception itself. Hence, the issue of engaging people through solar architectural skins can be explored more by considering the role of other senses beyond vision as well as competing stimuli in urban environments.

Approaching the design of solar architectural skins for visual engagement by crossing the boundaries of different disciplines, the present study concentrated on the potential of displaying salient visual features through building-integrated photovoltaic technologies. However, the review of studies on visual attention in Section 2.3 revealed that besides noticeable stimuli, there are subjective influences on the viewers, such as knowledge or tasks to be completed, which may determine what each individual's attention is attracted to. The outcome of the VR experiment described in Chapter 8 showed that including salient features in a solar skin design does not guarantee visual engagement will always be produced. Furthermore, the experience of habitual viewers may be different from that of first-time viewers, which was not assessed as part of this research. Subjective factors and personal habits may impede a solar envelope which displays striking elements from being noticed by every visitor in a particular urban environment. Further research could be directed at understanding better the influences on people's attention to solar building fronts, which could entail conducting primary case study research. This may involve investigating thoroughly the cultural background and the customs of potential users and visitors in specific settings to gain more insights into their possible interests, as well as testing solar façade designs with habitual viewers.

The current exploration ultimately concentrated on how a given visual message can be displayed through a solar architectural skin, but the aspect of *content* itself deserves more consideration. Aiming to uncover ways of translating contents into

solar skin configurations that can trigger interest, the present research did not delve deeply into the matter of the meanings that can be communicated to audiences in the public outdoor spaces of cities. For instance, the possible source of a content to be conveyed was left somewhat undetermined. As suggested in Section 6.2.4 and noticeable from the design presented in Chapter 7, the content or message to be communicated is an influence on the design of a solar architectural skin but is also ultimately embodied in the artefact. The distinction between ‘content’ and ‘interface’, which in Section 2.4 was found to characterise media facades (Halskov & Ebsen, 2013:664), may be less obvious in static solar envelopes. As part of the design example presented in Chapter 7, for which there was no firm brief, the content translated by the researcher into a solar skin design was chosen as a visual reference to the local culture, but in other cases it could be sourced differently, being indicated, for instance, by the client, also for economic purposes. Potentially, the message could even originate from the building’s users or from artists involved in the project. Thus, the concept of *content* itself and its sources could be clarified further to better uncover the expressive potential of solar architecture.

Future research could be directed at exploring more the creation of solar architectural skins as art. Designing solar envelopes with a communicative purpose can be seen as an expression of human creativity in visual form, and therefore can be ascribed to the general definition of art (Oxford University Press, 2019a). In particular, it can be considered ‘public art’, being ‘in the public realm’ (Tate, n. d.). The case studies of visually engaging architectural skins, analysed in Chapter 5, included façade artworks exemplifying compositions which could potentially embed solar technologies. There is more to investigate around solar skins’ capacity for triggering reactions beyond visual engagement and for eliciting specific emotions. As emerged throughout this research, there are constraints to the communicative potential of solar building envelopes, which are posed by other factors beyond the semantic content to be expressed or creative skills. For instance, characteristics of the location, of the building’s outdoor and indoor environments, as well as economic influences and intrinsic limitations of photovoltaic-based technologies affect the functioning of solar façades overall. Hence, while there may be an artistic element to investigate, it emerged from this study that a solar façade’s design cannot disregard the context of the architectural project in a broad sense. Therefore, more research can be directed at exploring the creation of solar architectural skins as a

form of public art that uses solar technologies as media and is shaped by its context as well as by human ability.

The present research implied that attention-grabbing building envelopes incorporating photovoltaic technologies may be based on static visual compositions which produce motion impressions. The case studies of architectural skins examined in Chapter 5 confirmed and expanded the possibilities that emerged from the literature reviewed in Chapter 2. Then in Section 6.3.1 the researcher proposed four general *visual strategies* for inducing motion impressions through non-moving solar envelopes. As noted in Chapter 3, the static nature of building-integrated photovoltaic installations can reduce maintenance-related issues, which is ultimately favourable for their overall performance. Nonetheless, much more research could be conducted on the topic. An extended study of motion illusions and of their potential applications could uncover new strategies for creating seemingly dynamic, solar building skins. At the same time, more research should be directed at assessing the impact on the viewers of displaying such designs in open urban environments. The current study could neither reveal how powerful motion illusions are at attracting attention in comparison to truly kinetic designs, nor investigate the potential for inducing discomfort in the viewers experiencing outdoor public spaces. Hence, the creative possibilities, the benefits and the drawbacks of producing motion impressions through static solar skins should be understood further.

9.5.3 Technologies, Design and Development

Throughout this exploration, it became clear that the research on solar architectural skins for visual engagement can only be open-ended. Currently, solar technologies, and particularly those based on the use of photovoltaics, are still being researched and improved. As emerged in Chapter 3, new semiconductor materials are being tested and techniques for increasing the performance of PVs in various ways have been proposed and developed. These present growing opportunities for the visual composition of attention-grabbing facades, which may even propel the development of novel solar products. Given that, as found in Section 3.3, existing solar modules with aesthetic value tend to be less efficient, there is a need for developing better solar products for building integration, to be also deployed in visually engaging designs. A trade-off between efficient energy generation and an engaging appearance is inevitable, but it can be observed that even a small energy output can contribute to improving the overall building's performance. However, developing

a technology, a product or a design to an advanced stage was not a goal of this research which could neither investigate a single solution in depth nor encompass all solar technologies. Instead, this study suggests an approach towards proposing architectural concepts which can potentially envision new applications of solar technologies including those that are still in development. Hence, further research towards innovating or improving solar products for building integration might be instigated by ideas presented in this study.

Future architectural design projects that may refer to the framework proposed in this research might drive innovation by prompting the development of bespoke solar products, which is not an unprecedented practice. For instance, Simone Giostra's team and Arup developed specifically for the *GreenPix Zero-Energy Media Wall* (see fig. 17.) a façade technology which integrates polycrystalline photovoltaic cells, arranged with varying densities, into a glass curtain wall (Sullivan & Horwitz-Bennett, 2013:59). In Section 3.4, some techniques for improving the performance of photovoltaics, which involve kinetics, were mentioned without being examined in depth or considered further later in the research. They include kirigami-inspired sun-tracking systems (Lamoureux et al., 2015) and the use of planar lightguide concentrators combining passive motion with spectral beam splitting (Tremblay et al., 2012), the deployment of which could be investigated in future studies on photovoltaic solutions for communicative building skins. Therefore, the integration of photovoltaics into visually captivating building exteriors can be explored further by considering additional technologies and potential applications, more of which may be introduced with future research and design.

Ultimately this project focused on possibilities offered by photovoltaic-based systems. However, it emerged in Chapter 3 that there are more solar technologies that could be examined for architectural applications aimed at stimulating visual engagement. While solar thermal systems tend to be less adaptable than photovoltaics for building integration, they may be combined with photovoltaic technologies to facilitate the cooling of solar cells, improving their performance. Furthermore, passive solar thermal systems may be used, which can exploit the natural convection of air or water. Some parts of these systems may not be exposed to sight, thus can have limited or no impact on visual engagement in urban environments. The architectural deployment of kinetic systems based on high-concentration and sun tracking, which were left aside in this study due to the building integration and operational issues they are associated with, may also be considered

more in further research as new techniques are developed. Hence, there is more to research on solar architectural skins for visual engagement, by taking into account different technologies and uses of solar energy in buildings.

The current study ultimately focused on exploring applications of photovoltaic-based systems in the early design of architectural skins for visual engagement. Therefore, the framework which was produced cannot be fully comprehensive about the design of solar building envelopes. Suggested by literature reviewed in Chapter 3, the focus on photovoltaics was justified by the higher compositional flexibility offered by components of such technology. Photovoltaics, and especially thin films, appear easier to integrate into visually captivating building fronts through pixelated configurations which in Section 2.4 were found to be distinctive of media façade interfaces. As demonstrated by the design example presented in Chapter 7, the approach proposed in this research can be successful at providing structure to the creative process thanks to its being open-ended and to the points it offers for consideration. However, the framework does not encompass all solar technologies for building integration, which also continue to be researched, or all aspects involved in the design of architectural envelopes. Other features may emerge from or be tested through further research also exploring later stages of the design process. Furthermore, the offered framework requires that a reader refers to the contents of Chapter 6 for clarifications on the aspects mentioned, and to Chapter 3 for more information specifically on solar technologies. The whole body of interdisciplinary knowledge touched upon in this study could not be condensed in the proposed schematic framework which cannot even eliminate the need for design skills and for case-specific research on solar technologies. At the same time, the framework stays open for improvement which may result from further research; thus, it may be refined in the future in ways that also make it more accessible to designers.

The current project demonstrated some of the obstacles that can be encountered in practice when the proposed approach is applied to conceiving a solar architectural skin. Following the analysis of case studies in Chapter 5, the framework outlined in Chapter 6 presented a range of options for composing solar skin configurations. However, the practical example presented in Chapter 7 showed, particularly in Section 7.3.2, that certain three-dimensional geometries, like some observed in the case studies, did not prove effective in the examined environmental conditions when simulations were run. Hence, while the researcher offered a set of compositional possibilities within this thesis, it will be up to designers approaching new practical

cases to discern, with the support of simulation tools, which features can be appropriate for each particular project.

9.5.4 Design and Research Techniques

This study revealed the challenges involved in generating an idea for a solar building skin that can stimulate visual engagement, showing how they can be overcome with digital prototyping techniques. Chapter 7 illustrated how the creative process can benefit from the use of digital tools including parametric simulations complemented by static and dynamic visualisations. This was found to help the researcher test repeatedly both the solar skin's potential performance in terms of energy generation and the visual effects displayed to the outside space. In the presented example, several gradual adjustments to the design were quickly made until a suitable compromise between energy output and appearance was reached. It may be argued that even if conducted roughly, iteratively run parametric simulations and visualisations can be relatively time-consuming. Yet, they are also timesaving if compared to non-parametric or to traditional analogue prototyping techniques involving model making. The present research gave an example of the simulation methods which can be used, including parametric 3D modelling of geometries, climate-based simulations of insolation levels, and visualisations involving image and video rendering. Reviewed elsewhere, numerous tools are available for the design of building-integrated photovoltaic installations (Jakica, 2018). While this study exemplified how a novel concept for a solar building skin can be generated in the Rhino 3D software environment, it is ultimately up to the designer approaching particular projects to choose the most suitable or preferred methods for each case, potentially experimenting with alternative techniques.

The present research gave a demonstration of how virtual reality can be employed in the early design of a solar architectural skin to evaluate with people's involvement whether a generated idea can produce visual engagement. As explained in Chapter 8, virtual reality was used by the researcher for presenting to people the idea for a photovoltaic façade within its context, which was generated as described in Chapter 7. VR was employed as part of a controlled experiment in which each participant was observed while experiencing the virtual environment containing the proposed design by wearing a headset, to be later asked about what they had noticed the most. The presented example demonstrated that VR simulations in combination with observations and interviews constitute a useful mix of methods for evaluating people's visual engagement with a newly created concept for a solar skin. As

anticipated in Section 4.4.3 and reaffirmed in Chapter 8, the VR-based experiment allowed the researcher to simulate the visual experience of the proposed design within its setting with the likelihood to trigger realistic reactions in the viewers. It appeared more effective and inexpensive compared to methods based on physical prototyping, thus suitable for resource-constrained projects. Using VR instead of AR allowed the off-site testing of the concept, while the chosen non-interactive type of VR simulation showed to facilitate participatory design by requiring limited resources, including movable equipment. Hence, future research and practice may continue exploring similar uses of VR in early design, which could be beneficial potentially to test the visual impact of integrating other new technologies in architectural and urban environments.

Besides the above advantages, the application of VR exemplified in this research also revealed some shortcomings of employing this technique in the early design of solar building skins for visual engagement. As emerged in Chapter 8, the VR visualisation process can be relatively time-consuming, as it involves reproducing the existing site quite accurately through high-resolution rendering. Thus, multiple weather and lighting conditions could not be tested through VR as part of the presented design example. Intrinsic limitations of VR technology and of its deployment also compromise the naturalness of the simulated experience. A controlled experiment for which participants have to wear a headset after being selected and prepared, so that bias and discomfort can be prevented, reduce the realism and the inclusivity of the research process. This can be exacerbated by the deliberate or inadvertent omission of elements which exist in the real setting from the visualisation. Realism is inherently limited in a non-interactive type of VR simulation which participants can experience with their sight and head movements only. Further weaknesses of the presented VR experiment included the small sample of participants, the difficulty of observing attention, and interviews based on a single question, which provided indicative results. Hence, the model for the evaluation of visual engagement using VR, which is proposed in this research, presents some downsides that may be improved upon in further studies.

Given the above considerations, future projects may use digital prototyping techniques similarly to this study to investigate aspects which could not be pursued as part of this research due to constraints in time and resources. The development of the exemplified design process could be taken further with more accurate levels of analysis, representation, and testing. This would involve more attention to other

functions of the architectural envelope beyond stimulating visual engagement or communication, and careful consideration of the overall environmental impact of building-integrated solar solutions. It would require a more precise calculation of the potential energy output and expertise beyond architectural design for defining details of the solar skin's modules and of interconnections within the system. Continuing research and practice could explore more of the options for producing motion impressions through solar architectural skins, visualising and testing them accordingly. They could also investigate subjective and environmental influences on attention, potentially with onsite investigations involving local participants, the use of AR, as well as the study of people's habits and of competing sensorial stimuli in the same setting. Other projects might also use interactive VR simulations in the design of solar architectural skins and assess more human responses beyond what is suggestive of visual engagement. While the current research offered a range of possible design variations and of design methods, it will be up to designers and researchers engaged in future related work to choose what is suitable for each particular project, and to refine or expand the proposed framework.

9.6 Conclusions

This chapter discussed the findings of the present research, responding to the research questions which led this exploration but also pointing at further results and at issues that remain unanswered.

The current study proposed an innovative perspective for designing solar architectural skins with communicative potential, focusing on their capacity for attracting attention and interest, while considering the need for efficient energy generation and usage. Crossing multiple disciplines, from vision science to media architecture and solar technologies, the approach draws from research on the design of both media facades and solar building envelopes. The research proposed a framework which invites consideration of multiple aspects in the design of solar architectural skins for visual engagement and offers a model of design process. The suggested approach can facilitate the creation of new captivating concepts for architectural skins that can generate energy from the sun, ultimately focusing on potential applications of photovoltaics and leaving room for more substantial work in this field of research and practice.

This study revealed that more can be explored around the expressive possibilities of solar building skins and their design. This may involve investigating further

aspects of communication, design development, emerging solar technologies and evolving digital prototyping techniques, as discussed further in the next chapter.

Chapter 10: Research Conclusion

10.1 Chapter Overview

The final chapter draws the conclusions of this research in a way to show how the main argument of the thesis was constructed.

The second section presents an overview of the research undertaken, as a series of discretised tasks addressing particular objectives, presented as chapters. It puts a particular emphasis on its approach and structure.

The third section condenses the outcomes of the inquiry in relation to its aim by proposing an approach which can help to conceive new designs of solar architectural skins for visual engagement.

The fourth section outlines the original contribution to knowledge made by this research which adds to the study of the potential for integrating solar solutions in architecture in a novel way that considers the energy implications.

The fifth section presents briefly other notable findings of the study, considering its limitations and suggesting opportunities for future work.

The sixth section highlights the achievements of this research project and the potential for future related work.

10.2 A Summary of the Research

Highly exploratory in nature and open-ended, this research started to bridge the gap between the design of eminently communicative architecture, featuring power-intensive media façade systems, and that of nearly zero-energy buildings employing renewable energy technologies. It found its context in the study of architectural skins with a distinctly expressive potential and in that of solar technologies for building integration. Seeking ways of facilitating communication through architectural surfaces to improve the quality of public spaces, it examined systems that can supply buildings with energy from the sun rather than depleting non-renewable resources. Thus, the research explored the potential of solar architectural skins for stimulating visual engagement, or in other words, for attracting visual attention and interest, which is essential to conveying messages in urban open spaces. For this reason, it is rooted in the scientific study of human vision, which is relevant to an understanding of visual communication in urban environments. Thus, the inquiry started from recognising the communicative role of architectural skins and from an

overview of research on the psychology and neuroscience of visual perception involving physiological and cognitive aspects, which included examples of applications in the arts. This led to a reflection on media architecture and its drawbacks, followed by an exploration of possibilities for creating visually engaging building skins by employing solar technologies.

The inquiry was guided by the following questions.

1. How can architectural skins produce visual engagement with minimal energy use?
2. How can solar technologies be deployed effectively on architectural skins in ways that produce visual engagement?
3. How can novel concepts of effective solar architectural skins be designed to produce visual engagement?

Due to the nature of the questions, the research was conducted with a predominantly naturalistic paradigmatic stance through a combined strategy which was presented in Chapter 4. With its interdisciplinary foundation, the study is characterised by a holistic perspective and by the use of mixed methods. These completed each other in a form of triangulation strengthening the validity of the research as a whole.

First of all, a broad knowledge base was produced through secondary qualitative research. This involved reviewing literature around the design of visually engaging architectural skins in Chapter 2 and examining studies on the building integration of solar technologies in Chapter 3. After fifteen examples of visually captivating building fronts were analysed in Chapter 5, to seek ideas that could be applied to creating solar envelopes, the findings were combined with those of the literature review. This led to outlining in Chapter 6 a framework for designing architectural skins aimed at producing visual engagement through the deployment of photovoltaic-based technologies.

The framework in Chapter 6 invited consideration of multiple factors and suggested possible design options including strategies, visual features and technologies. It was then tested with primary, practice-based research through its application to the early design of a solar architectural skin for an existing site, which was described in Chapter 7. The generated design concept was then evaluated with a focus on assessing people's visual engagement, as presented in Chapter 8. The

demonstrated design process entailed using digital prototyping techniques ranging from algorithmic modelling including climate-based parametric simulations to static and dynamic visualisations as well as virtual reality. To evaluate whether the generated solar skin concept was capable of stimulating visual engagement, an experiment was conducted using virtual reality and involving participants who were observed during the simulation and interviewed immediately afterwards. Proving the capacity of the produced concept for stimulating visual engagement in most participants, the experiment confirmed that the proposed approach can aid the early design of solar building skins and provided useful insights into the process. Hence, the findings of the research were discussed in Chapter 9 where the previously outlined multi-criteria framework was integrated with suggestions of design methods. Several implications for the research and design of solar architectural skins were unveiled, which are summarised in the following sections.

10.3 Outcomes of the Research in Relation to Its Aims

As anticipated in the statement of its aims, this research produced as its main outcome a framework for designing solar architectural skins that are capable of stimulating visual engagement, or in other words, that can attract people's attention and interest. Based on the outlook that communication is a function of the building envelope, which depends on its capacity for being noticed, the framework absorbs findings from the scientific study of vision according to which the display of salient features may attract people's attention. Therefore, the approach draws ideas from the design of media facades which display features such as motion and images although through generally power-intensive systems. It merges those ideas with suggestions for the integration of solar technologies into architectural skins, so that these can supply buildings with renewable energy generated onsite rather than weighing on their energy balance. Hence, the framework is directed at facilitating the design of visually communicative architectural exteriors that can improve the energy performance of buildings towards nearly zero-energy standards.

The proposed framework is a holistic approach to aiding the creation of novel concepts for engaging, solar architectural skins. It can provide structure to the early design process through a set of variables to consider in decision-making and of suggested methods to employ. Without imposing rigid rules or serving as a substitute for research, knowledge and skills, the framework offers a variety of criteria that designers may refer to when conceiving new ideas for solar building envelopes integrating photovoltaic-based technologies in particular. It may be

applied in different geographic contexts and found useful by architecture practitioners and researchers as well as by students intending to explore the design of visually captivating building exteriors that generate energy through photovoltaics. While recognising the iterative nature of the creative process, the framework views it as effectively composed of three phases. These are indicated as the *understanding of the starting conditions*, the *idea generation*, and the *evaluation of visual engagement*.

The framework invites consideration of factors affecting the design, which include, above all, the *location* of the site with its characteristic conditions from geographic and climatic to socio-cultural, economic and regulatory. Other related elements to ponder concern the building's outdoor and indoor environments and uses, the semantic content to be conveyed to the outside, and economic costs. Design responses to such circumstances, which shape the solar skin's layout, include the overall *visual strategy* as well as features of the *skin morphology*, of surfaces' *visual quality* and of the *solar technology* to be deployed. While several of the indicated aspects are references to media architecture, the framework suggests ways of reducing the operational issues that are typical of media facades, which involve producing motion impressions through static visual compositions.

The approach hints at possibilities for choosing solar technologies that can be incorporated into architectural skins. Focusing on photovoltaic-based systems, it alludes to options regarding the *substrate*, the *absorber*, and ways of improving the generated energy output, which are indicated as *performance enhancement strategies*. These encompass, for instance, solar concentration, spectral conversion, cooling systems and three-dimensional configurations, which may also add visual qualities to the building skin. While the technologies involved are still in development, by encouraging their consideration in the creative design of architectural envelopes the framework can stimulate innovation. It instigates the generation of concepts which envision applications of emerging technologies and so might boost their improvement. Hence, the suggested framework can support the early design of photovoltaic skins aimed at triggering visual engagement by fostering creative, future-oriented thinking, and it remains open to refinement with technological advances.

The proposed approach to designing solar architectural skins that integrate photovoltaic-based technologies also indicates methods that can be employed in the creative process as exemplified in this study. After information is gathered

through research on the site for the design and on its broader context, an idea for a solar skin can be generated and tested through digital prototyping techniques. These include parametric simulations, ranging from the 3D modelling of geometries to climate-based calculations of insolation levels, to visualisations in the form of images, animations and VR experiences. VR simulation, even just of non-interactive type, can be used in combination with observations and interviews to evaluate with people's involvement whether visual engagement is produced by a generated concept for a solar architectural skin. This can facilitate participatory design besides providing feedback on ideas and potentially leading to their refinement. Future research and design on solar building envelopes may refer to the methods suggested in this study to go beyond it and provide further insights into the subject.

This research also produced a secondary outcome which is an example of an early design process for creating a novel concept of a solar architectural skin for visual engagement. This was mostly instrumental in the testing of the design framework. Nonetheless, it is also relevant on its own as it demonstrates how the advocated criteria and the suggested mix of methods can guide the generation and the evaluation of a novel concept for a solar architectural skin that is capable of attracting attention and interest. The created design exemplifies how a photovoltaic façade can be conceived by applying the recommended principles. These include displaying visual content through a modular configuration, creating subtle, seemingly dynamic effects through a static composition, and adopting strategies for reducing performance losses, which can also add visual qualities to the design.

10.4 Contribution to Knowledge

This research proposed a new approach to the study and design of solar building envelopes, which highlights:

- the communicative potential of building-integrated solar technologies as an interdisciplinary topic;
- a possible common ground between designing media facades and solar building envelopes towards nearly zero-energy standards;
- a possible use of VR for participatory research on people's engagement with novel solar façade designs.

Undertaking the exploration of solar architectural skins' communicative potential, this study created new knowledge by connecting scientific, technological and artistic domains. It viewed communication as a function of the solar building envelope, and

visual engagement as what enables its fulfilment. Rather than regarding the appearance of solar skins as a matter of aesthetics, in opposition to functional aspects, or instead of prioritising the quantitative study of energy generation, the present research inquired into the potential of building-integrated solar technologies as media. It looked into how architectural skins can be designed to incorporate photovoltaic-based technologies effectively and attract people's attention to facilitate the conveyance of messages while contributing positively to buildings' energy balance. To do so, the study crossed disciplinary boundaries and merged information from areas of vision science, urban design, architecture, art, media facades, and solar technologies. With a predominantly naturalistic stance, the research pursued its exploratory aim by adopting a methodology which combined secondary research with primary, practice-based research including mixed qualitative and quantitative methods. The approach may serve as a reference for further studies exploring communicative aspects of new architectural technologies.

This research proposed that media architecture can be looked at as a model for new designs that are closer to meeting nearly zero-energy standards. However, this entails making an abstraction of it, by taking its compositional principles and methods to apply them with different technologies and achieve similar results in terms of human responses. Thus, it involves a conceptual operation of transposing elements of media architecture to the design of systems for nearly zero-energy buildings. It instigates the creation of energy-generating alternatives to media facades, which may be visually engaging while having a potentially lower environmental impact. By condensing knowledge into a design framework, the present research hinted at new ideas for creating solar architectural skins that may be attention-grabbing with reduced operational issues and improved energy generation. This involves composing static designs which communicate content by displaying salient features such as images or patterns in a seemingly dynamic way. With modular grids like the 'pixel configuration' of media facades (Halskov & Ebsen, 2013:665), such designs present modules which can be interpreted variably, for instance as non-active or active solar elements and as volumes or voids. Instead of emitting light or producing movement through power-intensive systems, new designs can exploit sunlight both for producing engaging visual effects and for generating electric power with integrated photovoltaic technologies. Previous research pointed out that considering the technical constraints of photovoltaics from the start of a project can limit designers' creativity, unless such constraints can

become design criteria (Moser et al., 2018:318). Solutions for enhancing the performance of photovoltaics may be improved with various strategies including solar concentration, spectral conversion and cooling, which are largely still in development and can add visual qualities to a design. They can compensate to some degree for efficiency losses which may occur due to choices made by the designer in response to priorities of a project. Envisioning applications of emerging solar technologies in early architectural design may potentially stimulate their development.

A further suggestion of this study is that participatory research employing VR may be useful, with relatively limited resources, for evaluating novel concepts of solar architectural skins. Previous research suggested that people's responses linked to perceiving solar installations should be investigated further by using methods 'beyond self-report questionnaires' (Sánchez-Pantoja et al., 2018a:234). The present study showed that evaluating people's reactions to the visual experience of a solar architectural skin at an early stage of its design can help to make it visually engaging. This can involve conducting with people an experiment based on a virtual reality simulation with observations of participants' reactions to it followed by interviews, which indicates whether the proposed design can attract attention and interest. Despite their weaknesses, digital prototyping techniques can ease the creative process considerably. This benefits from combining methods that are essential to the design of solar installations, such as climate-based simulations, with visualisations, virtual reality, observations and interviews. The last two are utilised as evaluation methods in the field of media architecture (Memarovic et al., 2012; Lin et al., 2015:331).

10.5 Reflections, Recommendations and Directions for Further Research

Guided by three 'how can' research questions which reveal its exploratory nature, this inquiry was inherently interdisciplinary. It gave greater importance to forming new knowledge by connecting seemingly disparate fields of research and design rather than to investigating a single realm in depth. It provided an overview of the multiple topics involved, from architectural skins' communicative role to solar technologies for building integration. Focusing on visual aspects, the research was conducted from an architectural design viewpoint and its outcome is mainly directed at architecture practitioners and researchers. Thus, it favoured, for instance, a qualitative exploration of solar technologies over an accurate quantitative investigation of their performance. Furthermore, due to constraints in time and

resources, the scope of the project was narrowed to selected topics, and only one early design example was pursued in practice. Hence, several observations, opportunities and recommendations for future work emerged.

Various aspects around the communicative potential of solar architectural skins could not be pursued in this study and deserve further consideration. The nature of the content to be conveyed through a solar envelope, its source, and the contexts in which stimulating visual engagement may be appropriate could be reflected on. The influences on people's perception and attention in open urban spaces could be explored more, including the impact of other sensorial stimuli as well as individual and environmental circumstances. Thorough research should be conducted on the particular context of a design, considering the local culture and lifestyles, from which predictions may be made on what is likely to attract people's interests, also in relation to economics. The potential of solar building skins as public art shaped by the context as well as by human creativity could be explored further. Additionally, more could be understood around the possibilities for producing motion impressions through static solar architectural skins, by examining design variations, benefits and drawbacks, including any risks of inducing discomfort in the viewers.

The present research could not be fully comprehensive in exploring the potential for deploying solar technologies in novel designs of visually engaging building skins. Further related studies may test more options as well as consider more technologies, including new solutions that may become available, or investigate in depth how to apply particular systems. Other inquiries could look into how to integrate solar thermal installations, high-concentration devices and sun-tracking systems into communicative building skins, also considering innovative techniques that may be introduced. More applications of emerging solar technologies may be envisioned, which could lead potentially to further developments of solar architectural products and designs. This would involve attention to more functions and requirements of the solar building envelope than what this study focused on, as well as conducting precise quantitative analyses, testing refined prototypes, and considering the overall environmental impact of systems.

Designers referring to the model presented in the current study when working on future projects are recommended to go beyond what was exemplified and are invited to refine the suggested open-ended framework accordingly. This could be made more accessible to designers by embedding clarifications and references to expert knowledge in the field of solar technologies. Thorough research should be

conducted on the initial circumstances of particular design cases and should include onsite investigations when possible. More could be explored in each of the identified phases of early design, also through experimentation with alternative design variations, technologies and methods. These may be chosen depending on characteristics of specific projects and may go beyond what was presented in the framework proposed in this research, thus potentially expanding its scope. New designs of solar architectural skins for visual engagement may also be developed beyond early stages with the involvement of multidisciplinary teams.

The present research demonstrated how virtual reality can be employed in early design to test with people's involvement the potential for deploying new solar technologies in architecture with visually engaging results. Thus, the visual impact of further emerging technologies for building integration could be potentially assessed in a similar way. It was shown that a non-interactive VR experience may facilitate the participatory design of innovative building skins with limited resources. Future work may explore the use of alternative techniques, such as interactive VR and AR simulations, depending on particular cases and on the human responses to be evaluated beyond visual engagement. It may overcome drawbacks of VR research that were noted in this study, including the lengthy visualisation work and the relative lack of inclusivity and realism. It may also tackle the difficulty of observing attention as well as limitations of this study related to the small sample of participants involved and the interviews based on a single question.

In summary, thanks to challenges encountered in this study, several avenues for future research and design were identified. Much more could be explored around the communicative potential of solar architectural skins, with more attention to their context and by experimenting with alternative design variations, methods and technologies for creating novel concepts. This may stimulate innovation, leading to the development of solar products and architectural designs beyond early stages. The approach proposed in this study may be refined with future work and may have the potential to be found useful in new projects within related research fields. Hence, the current exploration remains fundamentally open-ended.

10.6 Concluding Remarks

The present research revealed itself as an open exploration into the design of solar architectural skins which have the potential to play a communicative role while also generating energy effectively. It ultimately focused on seeking ways of creating

novel concepts for building envelopes which can attract attention and interest through photovoltaic-based systems.

With its interdisciplinary, mixed-methods approach, combining secondary qualitative and case study research with primary simulation and experimental strategies including quantitative tactics, the present study produced a design framework which may be found useful in future architectural design and research. The framework can aid the formation of novel concepts for solar architectural skins which can produce visual engagement besides generating energy effectively, by offering a set of aspects to consider and of methods that can be employed in the early design stage. Providing structure to the creative process without imposing rigid rules or replacing the role of designers and specialists, the proposed framework may be referred to for guidance by architecture practitioners, researchers and students. It may also influence the development of solar products for building integration and may have the potential to be applied to other related research fields. By implementing its suggested approach, this research also gave an example of an early design process for conceiving a photovoltaic architectural skin that is capable of triggering visual engagement.

A major original contribution to knowledge of this research is its interdisciplinary, holistic perspective which, by recognising the communicative role of the solar building envelope and its energy generating potential, connects seemingly distant areas of knowledge, ranging from the scientific study of vision to media architecture and solar technologies. The study suggests that inspiration may be drawn from media architecture with some degree of abstraction so that new solutions can be introduced for visually engaging building skins with a potentially lower environmental impact. It hints at ideas for reducing operational issues that are typical of media facades and encourages consideration of emerging solar technologies with improved performance which can also add visual qualities to architectural skin designs. It promotes the use of participatory research involving VR simulation, complemented by observations and interviews, for evaluating early designs of solar architectural skins aimed at stimulating visual engagement. This can facilitate an understanding of people's responses to solar skin concepts generated through iterative parametric simulations and visualisations.

Subject to limitations attributable to the availability of time and resources as well as to the perspective adopted, this study identified opportunities for further work in research and design. More is to be explored in relation to the communicative

potential of solar architectural skins, also in relation to economics, by experimenting with and going beyond the ideas suggested through the proposed design framework which is open to refinement. The proposed approach is likely to stimulate innovation and lead potentially to further developments in technology and design.

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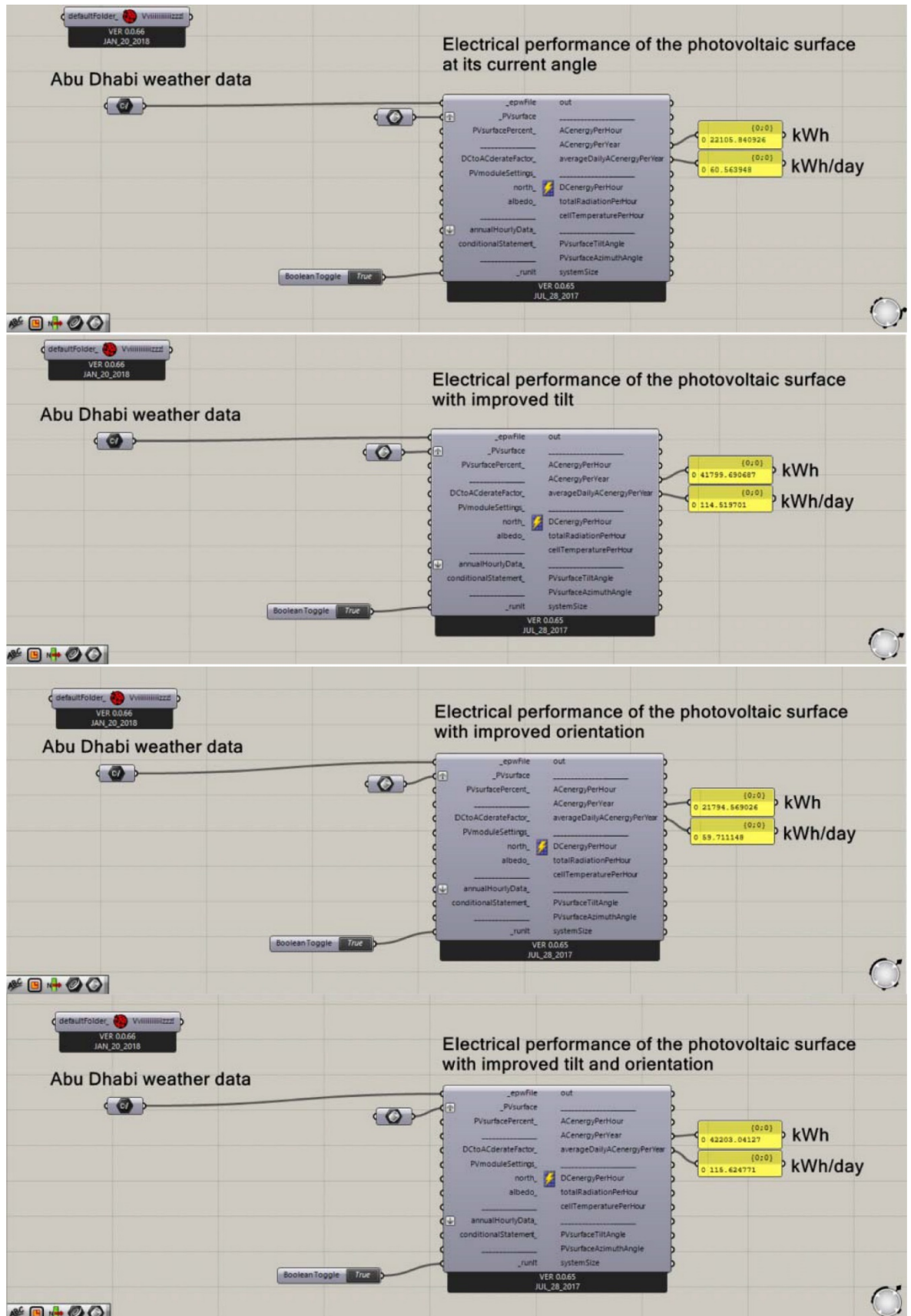
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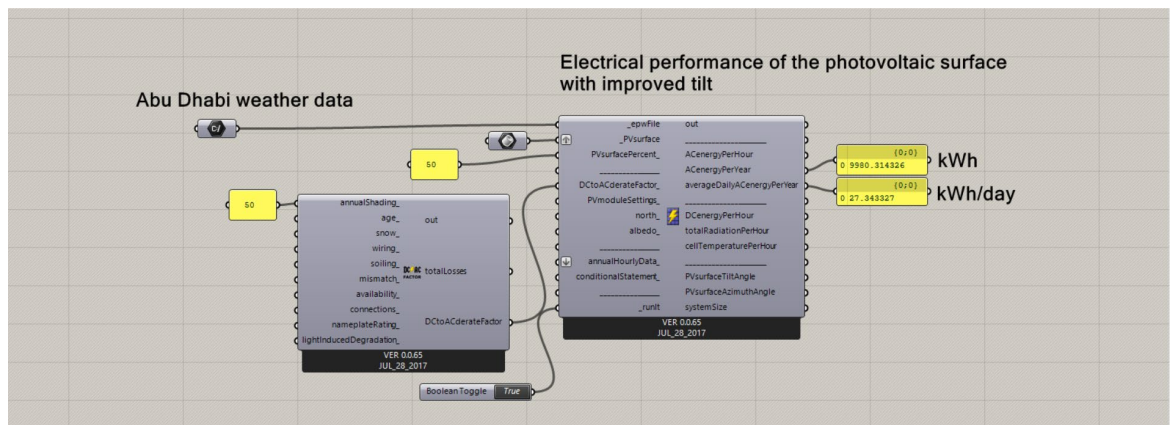
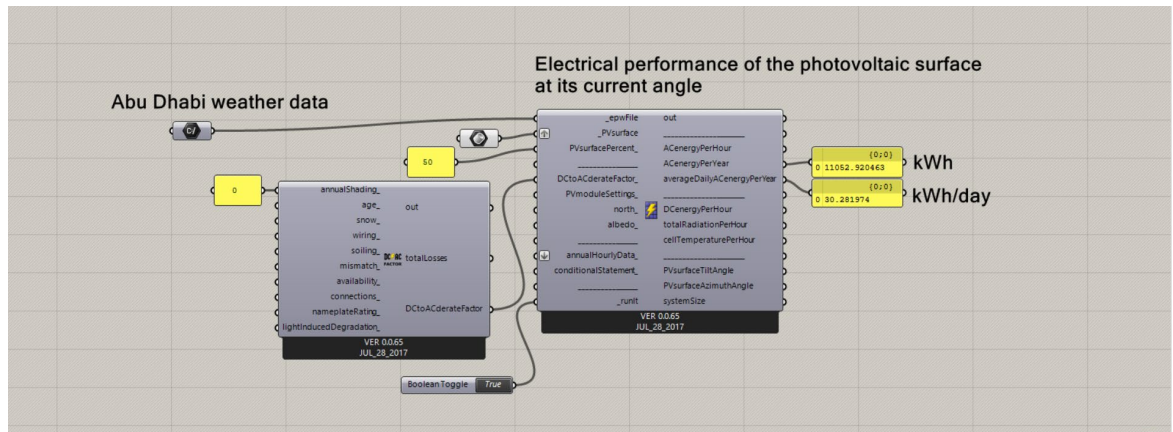
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Appendix 1



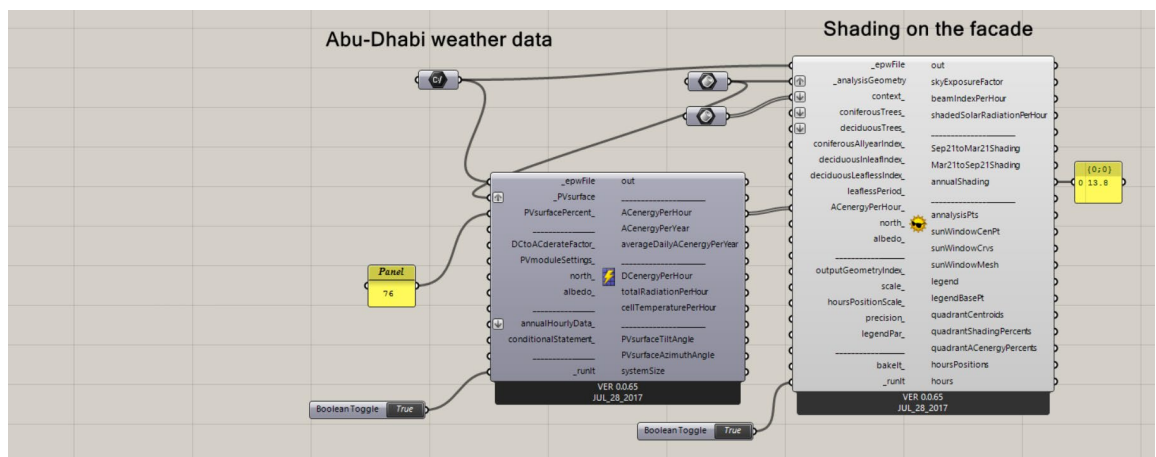
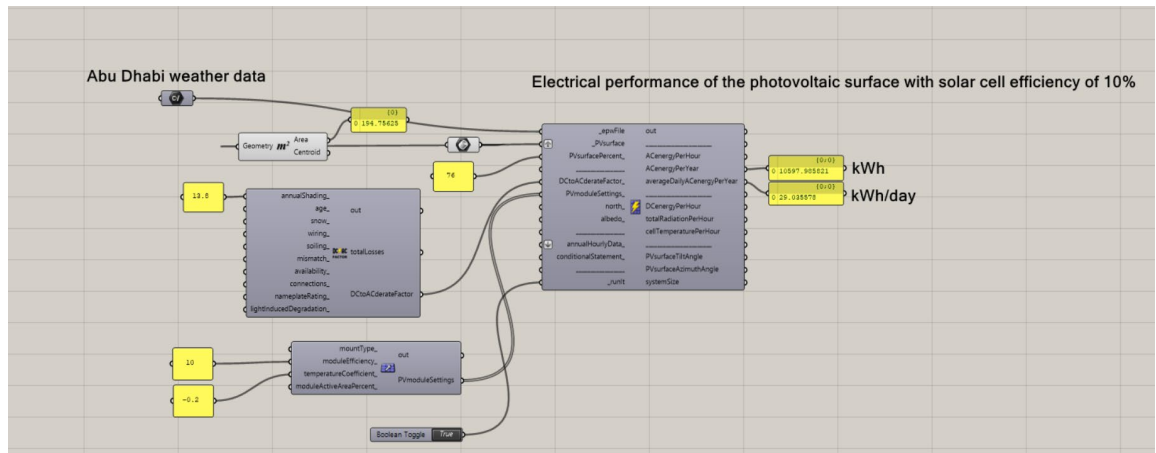
Electrical Performance of a PV Surface for the Chosen Facade at Four Different Angles, Simulated with Ladybug (2018)

Appendix 2



Electrical Performance of a PV Façade with Self-Shading on a Configuration with Tilted Modules, Calculated with Ladybug (2018)

Appendix 3



Electrical Performance of the Designed Solar Skin, Calculated with Ladybug (2018)

Appendix 4

The building with the red ten front to it was where I looked to most. I was also drawn to the tall black building over my right shoulder.	N. 1
The red block - interesting as wasn't quite sure what it was made of!	N. 2
Tower-like structure (checkbox?)	N. 3
The red facade was (to most eye-catching because of its colour and subtle pattern.	N. 4
There was a large red building as I looked around. It stood out because of the colour and the fact that it was different from the other buildings I could see.	N. 5
The first building I saw. With dark glass out side the surface of the building.	N. 6
The building with the red facade was really nice. It reminded me of red windows. But I love to observe also the natural elements in the video like the trees.	N. 7
The taller buildings were more interesting to look at, they had more intrigue to them.	N. 8
There are still in that, RIA can see .	N. 9
Also Maybe a glass fronted building just to the right. Also intrigued by the tower behind me.	N. 10
I remember that there is a to higher building back of me. a little bit black, looks like a chimney. It's very dark because in the shadow...? And I remember another one in front of me. there are white figure on the wall. I think I like the figures more.	N. 11
The building facade with the windows sticks in my mind more than the others as the others seemed bare in comparison.	N. 12
Yes, there was a facade with exotic motives that I found interesting. Maybe because of the red colour plus the motives.	N. 13
For A tower.	N. 14
A red wall building.	N. 15

Participants' Feedback after the VR Simulation