LIVING SKINS
AN ATTRIBUTE FRAMEWORK FOR GREEN FAÇADES

by
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A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF ADVANCED STUDIES IN LANDSCAPE ARCHITECTURE

in

THE FACULTY OF GRADUATE STUDIES

THE UNIVERSITY OF BRITISH COLUMBIA

October 2007
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ABSTRACT. LIVING SKINS An Attribute Framework for Green Façades

The thesis critiques the current practice of green façades in terms of a broader range of opportunities they might realize. It analyses the current practice of green façades as to the different types, construction systems, and relationship with the immediate context. It also identifies a series opportunities related to six areas: human comfort; expressive capacity; air & water quality; indoor-outdoor relationship; urban biodiversity; and carbon neutral architecture. This thesis develops a green façades framework that enables the critique and evaluation of the different existing types of green façades in terms of the extent to which they accomplish such opportunities, facilitating a determination of their appropriateness to different conditions, solar orientations, and user needs. This same framework also intends to improve the current practice of green façades by assisting designers to define a particular green façades.
# LIVING SKINS: An Attribute Framework for Green Façades

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ACKNOWLEDGEMENTS

I would like to thank all of my committee members, and especially my thesis advisor, Ron Kellett, who has been very helpful in leading and guiding the thesis toward its final result, even sometimes understanding the central aims of the proposal better than myself. Without his enormous contribution, this thesis would not have been realized as it is today. And a special thanks also to Ray Cole, whose clarity of ideas and sharp view contributed to the direction of the thesis and helped to focus on the themes that are essential to the topic. And also a remarkable thanks to Doug Paterson, who supported me in uncovering the ethereal meaning of the thesis by paying attention to the poetical dimension that this work demands.

I should like to thank Patrick Mooney, the MASLA program director, who made it possible for me to be at UBC attending the MASLA. I would also like to thank Peter Jolliffe and Douglas Justice who helped me understand how plants work in green façades, their growth, metabolism and evapotranspiration process as well as the carbon cycle within them. Thanks also to Sherry McKay who helped me refine the topic in the beginning phases of the thesis, as well as Daniel Roher whose critical view enriched the quality of the thesis. This thesis is certainly more comprehensible thanks to the editing of Stephanie Bonic. I can not forget to thank all the friends I had the opportunity to meet during these two years of the MASLA program, especially the MLA students, as well as my family back home, my parents Miguel and Gemma, and my sisters and brother, Angela, Nerea and Mikel who have always comforted me and made me feel closer to home.

Finally it would not be fair to finish this moment of gratitude without the biggest THANKS to the person who has always been close to me, always with constructive critiques, adding a full range of positive comments to enhance the thesis, and also to improve my English. A big THANKS to the person who has always been encouraging me, especially in those difficult moments when I was about to leave everything behind. THANK YOU VERY MUCH – MILA ESKER – JONE.
Building façades constitute the line of division between the indoor and the outdoor, participating in the spaces of both sides. Initially, the main role of façades was to provide protection from the climate's inclemencies as well as from other humans or animals. As technology made progress these thick façades became more permeable, allowing air and light to pass through them, leading them to the very thin façades of glazing buildings. Parallel to this, the façades' requirements became more and more complex in order to improve indoor comfort conditions. Today's building façades demand to express the notion of variability and changeability, which introduce the factor of time. This seems to be the main purpose of current green façades.

1.1 Questioning the Current Practice of Green Façades

Contemporary architecture is experiencing an increasing and emerging practice of green façades. More and more architects are experimenting with diverse ways of introducing greenery to building façades, providing a wide spectrum of different types of green façades. This practice, which one might call a boom of green façades, is spreading all around the world as the following recent examples reflect: from Jupilles, France to Reston, US to Tokyo, Japan, to Madrid, Spain [Fig1.1].

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Figure 1.1 Architecture is experiencing a boom of green façades around the world. Houses in Jupilles [France, 1996]; National Wildlife Federation [Reston, 2001]; Prada store basement [Tokyo, 2005]; Gymnastic Pavilion [Madrid 2002].

In this context, leading architects, such as Jean Nouvel and Herzog & de Meuron, seem to find in green façades a natural response to the current accelerated information society, one which demands a changeable architecture, as well as to the emerging need for a carbon neutral architecture, one which demands an environmentally sensible architecture.

Architects are exploring the changeable and expressive capacity of vegetation in the façade, fascinated by its faculty to naturally introduce the notion of time, providing an ephemeral dimension:

"The ephemeral dimension infers a rapport between architecture and ephemeral elements. Vegetation is one of these and is of course very fleeting, very sensitive and very changeable."²

² An interview with Jean Nouvel available on his office website: www.jeannouvel.com
Recent buildings illustrate this. In the case of Nouvel, the green façade of the Quai Branly Museum in Paris [2006], achieves a spectacular explosion of different plant species, transmits the thickness and heaviness of ‘living walls’, and “creates diverse green tapestries rich in texture and tonalities of green, and often punctuated by flowers”\(^3\). In the case of Herzog & de Meuron, the green façade of the basement of the Prada store in Tokyo [2005] uses the same moss-type plant to take different inclinations as if it was “the sponge, grass-covered topography of the yard”\(^4\).

![Figure 1.2 The Green Façades of the Quai Branly Museum in Paris [Nouvel] and the basement of Prada store in Tokyo [Herzog and de Meuron] explore the expressive capacity and plasticity of green façades.](image)

But, do these green façades really realize the full range of opportunities they embody? On a closer look at these two examples, it seems striking, for instance, to find both green façades respond in such a similar way – attached to opaque walls – to the very different conditions they face: Quai Branly Museum’s faces north-west to a main street and the Seine river, while the green façade at the basement of Prada faces south-east and north-east to the “front yard” of the store. At the same time both green façades are still relatively hermetic. Although they express the changeability that occurs naturally by the passing of time, which is a key aspect of green façades, this thesis understands there are many other qualities in green façades that are ignored or underestimated.

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3 L’Atelier Vert www.frenchgardening.com
4 Pedro Arroyo, Prada Tokyo. Architecture is architecture. Website: www.architettura.supereva.com

1. Introduction
This thesis argues that green façades could and should respond in a different manner to different orientations as a means of really understanding the variability of their surroundings. Green façades could and should show different faces according to the movement of the sun. The opacity or transparency of the walls that they are attached to should play a key role in this sense. In addition, this could significantly reduce the energy demand of buildings, refreshing the façade in summer, and allowing for solar energy gain in winter through transparent green façades, or insulating from the cold through opaque green walls. Green façades could also incorporate flexibility and movement to the enclosure skin, by rotating or sliding systems. This would allow the users to create their desired relationship with the outdoor space, by moving these sorts of green lattices.

Green façades can also act as water storage, reducing the runoff, and can even purify the grey water used by the building. In a similar manner they can purify the air of their surroundings by trapping pollutants, such as CO₂. In this sense green façades appear to be the only building material through which the carbon load can be positive considering its life cycle, contributing to carbon neutral architecture. They can significantly improve the urban biodiversity, especially when located in green network edges, enhancing the activity of living organisms. They can even increase the urban agriculture, acting as cultivated green surfaces, where vegetables can grow.

This thesis argues that green façades today are in a rather preliminary stage, given that their designs are relatively intuitive and based more on exploring their expressive capacity than on maximizing the whole range of opportunities they provide. Consequently, designers are often unaware of the larger range of opportunities in green façades. In this sense, this thesis is driven by the following two consecutive questions: Does the current practice of green façades realize the full range of opportunities they embody? If not, what are the attributes that would enable designers to determine the most appropriate green façade for a given context?

* This means that while the rest of building materials always have a “CO₂ load” due to the one created during their fabrication process; for the case of green façades this could be opposed by the CO₂ they trap in their life cycle.
This leads the thesis to develop and propose a framework in order to provide a set of attributes to assist designers in defining the green façades that appropriately satisfy a project's needs. To do so, the thesis:

- Classifies the current types of green façades and undertakes a preliminary critique of these;

- Identifies a broader range of opportunities within green façades; and

- Develops a green façades framework to enable a deeper critique and to evaluate the appropriateness of the current practices of green façades in terms of the accomplishment of the attributes; the aim is to give feedback for and improve on the current practices of building green façades.
1.2 Research Objectives and Contribution to the Body of Knowledge

The main goal of the thesis is to develop a green façades framework to facilitate designers determine the most appropriate green façade for a particular project, through a critique and evaluation in terms of the accomplishment of a broader set of attributes.

The contribution to the body of knowledge consists of bridging the gap between the current practices in building green façades and the accomplishment of the opportunities they embody, in terms of improving human comfort and water & air quality, providing expressivity and changeability to building façades as well as flexibility to the indoor-outdoor relationship, and contributing to urban biodiversity and carbon neutral architecture.

Research objectives

1. To analyse and critique the current practice of green façades in terms of the different types, construction and management systems, and relationship with their immediate context.
2. To identify the opportunities of green façades in six areas: Human Comfort; Expressive Capacity; Air & Water Quality; Indoor-Outdoor Relationship; Urban Biodiversity; and Carbon Neutral Architecture.
3. To develop a green façades framework to facilitate the critique and evaluation of green façades in terms of the accomplishment of the identified attributes; and consequently to suggest better practices in relation to different conditions, orientations, and user needs.
4. To apply the green façades framework to existing case studies in order to identify its usefulness and limitations.
5. To ultimately improve the current practice of green façades.
- Contribution to the body of knowledge

This thesis classifies the current types of green façades into two main categories: attached to opaque walls and attached to transparent walls. It develops a green façades framework, which aims to clarify the broader range of opportunities within the current types of green façades. Within this new framework, a deeper critique and evaluation of green façades is enabled, and hence the framework helps to determine the appropriateness of the different types of green façades to different conditions, orientations, and user needs. Overall, the framework intends to assist designers in the definition of a particular green façade type that better satisfies a project's needs in order to improve the current practices of green façades.

1.3 Methodology

In order to respond to the thesis questions [Figure 1.5], the methodology begins with a preliminary analysis of the current practices of green façades, which reveals a series of deficiencies and the need to identify a broader set of opportunities in green façades. These have been condensed into six areas: human comfort, expressive capacity, water & air quality, indoor-outdoor relationship, urban biodiversity, and carbon neutral architecture. This serves as the basis for the development of a green façades framework, which is then applied to existing case studies in order to reveal its usefulness and limitations.
The Current Practice of Green Façades

This chapter frames the current practice of green façades within the context of a contemporary type of façade that reacts to the stimuli of its immediate environment, which the thesis understands as responsive façades. Green façades represent a natural alternative within this type of façade, they are living skins, which change and react naturally to surrounding stimuli. The chapter then proceeds to identify and classify the different types of current green façades. These are separated into five main types, which are organized into two major categories: those attached to an opaque wall, and those attached to a transparent wall. This analysis detects some preliminary deficiencies in green façades, suggesting the need for a deeper study on the opportunities available in creating green façades.

Green Façades Framework

This chapter identifies the opportunities in green façades condensing them into the following six areas: the improvement in Human Comfort; the exploration of their Expressive Capacity; the influence in Air & Water Quality; the enrichment of the Indoor-Outdoor Relationship; and the contribution to Urban Biodiversity and Carbon Neutral Architecture.
The combination of the two previous findings – the types of green façades on the one hand, and a broader range of opportunities on the other – lays out the foundation for development of the green façades framework. This framework enables the critique and evaluation of the different types of green façades in terms of the extent to which they accomplish the identified opportunities; and, with this, it helps to determine their appropriateness to different conditions in an effort to improve the current practices for building green façades.

- Application of Green Façades Framework

The green façades framework is applied to existing examples of green façades to evaluate their appropriateness to their particular conditions. Five case studies are analysed, corresponding to the previously identified five main types of green façades. The application of the framework reveals its usefulness and limitations in assessing how designers select and define more appropriate types of green façades for specific projects.
Develop the GREEN FAÇADES FRAMEWORK

1. Introduction
2 THE CURRENT PRACTICE OF GREEN FAÇADES.

The following analysis of the current practice of green façades attempts to find some deficiencies or missed opportunities within them. It collects a series of existing examples of green façades undertaking a preliminary critic study, which shows, for instance, current green façades do not consider the different characteristics of the orientation of the façade, since none of them respond to different orientations with different systems. It also shows today's green façades are very static and rigid systems which do not afford any flexibility to the façade. These findings, among others, reveal the need to create a framework to provide a series of attributes that enable to evaluate green façades with better criteria. This is detailed in the next chapter.

This analysis facilitates the classification of the current variety of green façades. All the studied examples suggest that existing green façades can be divided into two major categories: those attached to an opaque wall, and those attached to a transparent wall. In addition, this chapter begins by framing the current practice of green façades within the broader context of building façades. In this sense, green façades present a natural alternative as responsive façades, since they change and react naturally to the stimuli of their immediate context, becoming living skins.
2.1 Green Façades as natural responsive façades

Building façades have always been related to their surrounding environment. As a result many different types of buildings and façades have adapted to the different characteristics of their surroundings as a means of controlling them.

"The problem of controlling his environment and creating conditions favorable to his aims and activities is as old as man himself".

In an accelerated culture and information era, the relationship of buildings to their surroundings has become more complex, demanding more variability and dynamism in building façades. In a desire to introduce the factor of TIME into building façades, leading architects today are exploring and experimenting with different ways in which building façades can change their properties by responding to surrounding stimuli. These perform as responsive interfaces between the indoor and the outdoor, and seek an innovative integration with their surroundings by adapting or reacting to its changes, such as traffic noise, wind, and seasonal changes. These changes may be activated mechanically or naturally.

Different types of façades exist in the category of mechanically activated changes. These include interactive façades, [multi]media façades, switchable façades, and changeable façades, among

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Mechanically activated responsive façades are usually composed of different layers introducing mechanical elements to produce reactions or to adapt to outdoor stimuli. Mechanical elements are usually Light-Emitting Diodes [LED] lighting elements and electrochromic or thermotropic glazing, controlled by computer systems. Electrochromic systems can alter the radiation transmission by applying integrated charges, while thermotropic glazing systems metamorphose from a fully transparent into a milky white skin as temperature rises.

In naturally activated changing façades, the reaction or adaptation to the surrounding stimuli is induced naturally by, for instance, changes in plants through the seasons. These particular types within responsive façades, where vegetation is introduced as a façade material, behave as green façades. In this sense, green façades represent a natural alternative within these types of responsive façades, which respond by changing their properties, such as colour texture and density, to surrounding stimuli. They behave as living skins.

Recent examples of responsive façades

One of the earliest examples of responsive façades in recent architecture is Jean Nouvel's Arab World Institute in Paris, 1988. The façade introduces mechanisms, similar to diaphragms in photographic cameras, within the glazing façade, and reacts differently according to external daylight conditions, opening and closing the incorporated devices in the same way as the diaphragm in a camera [Fig 2.3].

---


2. The Current Practice of Green Façades
The facade of Toyo Ito's Tower of Winds consists of a metallic mesh with a variety of sources of light such as neon tubes and light bulbs. It uses these to respond to different environmental conditions such as traffic, wind, and noise. A computer controls the different light sources [Fig. 2.4]. Another example of mechanically activated responsive facades is those surrounding New York's Times Square, in which screens are continually changing and serving as information transmitters [Fig. 2.5].
According to Jean Nouvel, in his current architecture he tries to create ephemeral building façades: changing and reacting façades. Arguments for the hermetic and static façades of the past are not valid anymore, there is an emerging advocacy for façades that react to the stimuli of the surrounding environment. The more recent version of these responsive façades is achieved by incorporating LED [Light-Emitting Diodes] lighting in building façades. The T-Mobile Headquarters building in Bonn, Germany\(^9\), presents an example of these [Fig 2.6].

![Figure 2.6. T-Mobile Headquarters with LED façade in Bonn, Germany 2006.](image waiting for ® permission)

A particular type of responsive façade, an interactive façade, reacts and interacts with neighbouring movement, such as the passing of people. Aperture façade installations with interactive façade display modes represent a prototype of these interactive façades\(^10\) [Fig 2.7].

![Figure 2.7. Aperture interactive façade. The façade reacts to surrounding movement, such as passers by.](image waiting for ® permission)

\(^9\) An interview to Jean Nouvel available at his office website: www.jeannouvel.com
\(^10\) www.mediaarchitecture.org

\(^{11}\) The information on the Aperture façade can be found at http://www.fredericeyl.de/aperture/index.php?main=2&sub=1
Within the context of the current kinds of responsive façades, and together with an emerging demand for environmentally conscious architecture - carbon neutral architecture, leading architects find in green façades a natural alternative to these responsive façades. Green façades are an innovative type of responsive façade which incorporate vegetation as a means of reacting naturally to surrounding stimuli, by changing their colour and density over time.

Leading architects such as Jean Nouvel and Herzog & de Meuron have been exploring green façades. Both firms have a series of built examples in which green façades play an important role. In the case of J. Nouvel, these are Quai Branly Museum [2006] and the Cartier Foundation [1994], both in Paris. In the case of Herzog & de Meuron, the projects are the CaixaForum Building in Madrid [2007], and the Rue des Suisses apartment complex in Paris [2000].

However, despite this enthusiasm for green façades to participate in such highly particular, responsive and interactive architecture, some of the other aspects that green façades offer are commonly ignored. Green façades are typically treated in a superficial manner, underestimated as living beings with ecological and hydrological needs. The implications of working with a living construction material are being ignored. Therefore, this thesis attempts to present a series of fundamental characteristics of green façades that must be considered in order to design them more thoughtfully in the future.
2.2 Types of Green Façades

One very important aspect for designers of green façades to understand is how green façades are being built. In order to provide a series of different systems for constructing green façades, this chapter studies very diverse examples of existing façades. It identifies and classifies them in different types of systems of construction. This study also provides a preliminarily critique of the current practice of green façades by illustrating deficiencies and missed opportunities in their construction.

Most of the green façades currently being designed belong to one of the two major categories: attached to an opaque wall and attached to a transparent wall. These, in turn, split into the five types described in this section: green façades composed of steel wires, as moss walls, composed of green vertical panels between two transparent layers, and, as a green external layer and a glazed internal layer.

Figure 2.10 Types of Green Façades

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<th>Green Façades composed of steel wires – Green Façade type 1.1</th>
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<td>Green Façades as moss walls – Green Façade type 1.2</td>
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<td>Green Façades composed of green vertical panels – Green Façade type 1.3</td>
</tr>
<tr>
<td>2. Attached to a transparent wall</td>
<td>Green Façades between two transparent layers – Green Façade type 2.1</td>
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<td>Green external layer and glazed internal layer – Green Façade type 2.2</td>
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2. The Current Practice of Green Façades
2.2.1 Green façades attached to an opaque wall.

Most green façades belong to the category of attached to an opaque wall. These range from the typical image of an old house covered by ivy, to more advanced technologies where the plant is guided by steel wires anchored to an opaque wall. The category also comprises metallic or wooden meshes fastened to the wall, with the purpose of guiding the plant. Other innovative systems include those developed by the French botanist Patrick Blanc: a ‘vegetal wall’ inspired by moss walls from the rain forests.

Green façades attached to an opaque wall include three specific types: green façades composed of steel wires, green façades as moss walls, and green façades composed of green vertical panels.

2.2.1.1 Green Façade Type 1.1 Green Façades composed of steel wires

**Description.** The construction system consists of a substructure of steel wires, which are punctually attached to an opaque wall by different types of metallic elements. The substructure creates a metallic grid that guides the plant. The plant grows from the ground close to the opaque wall covering the metallic grid [Fig. 2.11]. It grows in what is considered as a linear plant pot, following the line of the building façade. The irrigation system waters the linear plant pot on the ground by a conventional drip irrigation system.

**Examples.** A representative example of this type of green façade is the Rue des Suisses apartment building designed by Herzog & de Meuron in Paris, 2000. The use of steel wires creates a rhomboidal grid to guide the plants, which grow from the ground [Fig. 2.12].

---

2. The Current Practice of Green Façades
Comment. This type of green façade illustrates a subtle manner in which plants are guided through an almost unnoticeable system of steel wires punctually fastened to blank walls. However, the system makes difficult accessibility for maintenance requirements to many parts of the façade. Furthermore, the height of the green façade is limited by the height of the plant.

CONSTRUCTION SYSTEM

Plants grow from the ground, guided by steel wires punctually attached to the opaque wall.

IRRIGATION SYSTEM

Drip irrigation system placed in the ground.

COMMENT

Unnoticeable steel wire system guides vines subtly forming a rhomboidal shape, which help create an overgrown, unkempt ambience to the landscape areas\(^\text{13}\). Yet, one of the shortcomings is that the vines limit the height of the green façade and the system makes difficult the accessibility for maintenance.

Table 2.1 Green Façade Type 1.1 composed of steel wires attached to an opaque wall

\(^{13}\) Roger Sherwood, Rue des Suisses, www.housingprototypes.org

2. The Current Practice of Green Façades
Manufacturers. The chief company providing this kind of steel wire system worldwide is Jakob AG/SA. It provides the stainless steel wires as well as different options for the fastening system and the shape of the grid, among other things.

Figure 2.13 Stainless steel wires of the Jakob AG/SA Company

The company “greenscreen” provides a similar system, that uses metallic mesh instead of stainless steel. Below are some examples of the system.

Figure 2.14 Some examples of the green façades by the “greenscreen” company [Marketplace at Oviedo, Florida; California State University, Fullerton, California; National Wildlife Federation, Reston Virginia]

14 www.jakobstainlesssteel.com Check the green solutions G1 section.
15 www.greenscreen.com
<table>
<thead>
<tr>
<th>Summary</th>
<th>Green Façade type 1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description:</strong> Green façade composed of steel wires or metallic mesh attached to opaque walls.</td>
<td></td>
</tr>
<tr>
<td><strong>Examples:</strong> Rue des Suisses Apartment complex [Herzog &amp; de Meuron]; Parking buildings in Oviedo, Florida; Fullerton California; and Reston, Virginia.</td>
<td></td>
</tr>
<tr>
<td><strong>Comment:</strong> Unnoticeable steel wires or metallic mesh systems guide vines subtly. However, plants limit the height of the green façade, and the system makes accessibility for maintenance difficult.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.2 Summary of the green façade type 1.1 composed of steel wires attached to opaque walls.

2. The Current Practice of Green Façades
2.2.1.2 Green Façade Type 1.2 Green Façades as moss walls

**Description.** In this particular type of green wall, it is worth mentioning the work of the French botanist Patrick Blanc. Attempting to recreate the ability of some plants to grow without soil and under humid conditions, which he had observed in tropical and rain forests, Blanc has developed a particular soil-less ‘vertical garden’, which consists of:

“A metallic frame, a PVC layer, and a layer of felt compose the construction system of the vertical garden. The metal frame is hung on a wall or can be self-standing. It provides an air layer acting as a very efficient thermic and phonic isolation system. A 1cm thick PVC sheet is riveted to the metal frame. This layer brings rigidity to the whole structure and makes it waterproof. A felt layer, made of polyamide, is stapled on the PVC. This felt is rootproof and its high capillarity allow an homogeneous water distribution. The roots grow on this felt. Plants are installed on this felt layer as seeds, cuttings or already grown plants. The density is about thirty plants per square meter. The watering is provided from the top. Tap water must be supplemented with nutrients. Watering and fertilisation are automated.”

**Examples.** Patrick Blanc has collaborated with well-known architects, such as Jean Nouvel, Renzo Piano, and Herzog & de Meuron. The following figures show some examples of these collaborations, which include Quai Branly Museum in Paris with Jean Nouvel, and CaixaForum building in Madrid with Herzog and de Meuron, among others.

16 [www.verticalgardenpatrickblanc.com](http://www.verticalgardenpatrickblanc.com)

Figure 2.15 GF Type 1.2
Green façades as moss walls
2. The Current Practice of Green Façades

Figure 2.16 Cartier Foundation, Jean Nouvel with Patrick Blanc. Paris, 1998.


Figure 2.18 Quai Branly Museum J. Nouvel, Paris, 2006.
IRRIGATION SYSTEM
Drip irrigation system placed in the PVC sheet

COMMENT
This green façade provides extreme exuberance contained within geometric boundaries, using high tech elements to make fantasy reality. The system is static [like conventional opaque façades] and accessibility for maintenance is complex.

Table 2.3 Green façade Type 1.2 as moss walls.

17 L’Atelier Vert www.frenchgardening.com

2. The Current Practice of Green Façades
Comment. These green façades achieve spectacular explosion of different plant species, transmit the thickness and heaviness of ‘living walls’, and “create diverse green tapestries rich in texture and tonalities of green, and often punctuated by flowers”\textsuperscript{18}. The façade system is static, like conventional opaque façades, and accessibility for maintenance is difficult.

3 images waiting for © permission

Figure 2.19 La Caixa Forum, Herzog & de Meuron with Blanc. Madrid, 2007; Les Halles, Blanc, Avignon France, 2006; and Reykjavik City Hall, 1992. These examples achieve spectacular diverse green tapestries, but are still very rigid structures.

Manufacturers. A variety of this green façade type is proposed by the company Verdirsystem Inc.\textsuperscript{19} in Vancouver, reinterpreting the environment of plants attached to rocks. It presents two varieties of ‘living walls’ associated with volcanic rock: in the first one, the ‘Verdir volcanic rocks’ are enclosed within a metallic mesh, while in the second one the volcanic rock is self-sustaining [Fig 2.20].

\textsuperscript{18} L’Atelier Vert www.frenchgardening.com

\textsuperscript{19} www.verdirsystems.com
Summary

Green Façade type 1.2

| Description: Green façades as moss walls that grow from the opaque wall. |
| Examples: Quai Branly Museum [Nouvel]; CaixaForum [Herzog & de Meuron]; Les Halles and Reykjavic City Hall [Blanc]. |
| Comment: This green façade provides passionate exuberance contained within geometric boundaries. The system is static [like conventional opaque façades], and accessibility for maintenance is difficult. |

Table 2.4 Summary of the green façade Type 1.2 green façades as moss walls.
2.2.1.3 Green Façades Type 1.3 Green Façades composed of green vertical panels

**Description.** This type of green façade consists of prefabricated green vertical panels composed with a layer of soil for plants to grow, confined by a kind of a cage that encloses the panel. It is usually built as if it were a conventional ventilated stone façade, where the vertical green panels are fastened to a metallic substructure attached to the opaque wall. Green panels of a specific size are fabricated creating a rhythmical green façade.

**Examples.** Gordillo Studio and Seedorf House are some examples of this type of green façade in Madrid. Both examples are composed of prefabricated green vertical panels creating a regular square grid in the façade of 60 by 60cm.

![Figure 2.22. Gordillo Studio extension, 2002 Madrid](image1)

![Figure 2.23. Seedorf house, 2004 Madrid.](image2)

**Comment.** This type of green façade seems to provide more controlled living skins, since they are built within a grid and fabricated as independent modules. Accessibility for maintenance is complex, as in the previous types, although the replacement is easier, with the option of replacing one module at a time. This comment also applies to the following examples.
Architect Duncan Lewis, in collaboration with Hugues Klein and Pierre Baumann, introduces similar green vertical panels for the West School Complex in Obernai, France. In this case, the dimension of the green module is 60 by 120cm, which interacts with the surrounding forest. However, the green façade system is static.

In the 2005 World Exhibition carried out in Aichi, Japan, green vertical panels – which were called bio-lung walls – were exposed. “The name Bio-lung was intended to communicate that this kind of structure can use the power of plants to function like a lung for cities”.

Figure 2.26 Green vertical panels exhibited at Aichi Expo, Japan 2005.

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20 Detail Magazine #1 2006 [Spanish edition]

2. The Current Practice of Green Façades
### Green Façade Type 1.3

**Green Façades composed of Green vertical panels**

<table>
<thead>
<tr>
<th>CONSTRUCTION SYSTEM</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>The model is composed by with a layer of soil for plants to grow, a thermal insulation layer, confined altogether in a cage that encloses it</td>
<td>![Section Diagram]</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IRRIGATION SYSTEM</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drip irrigation system placed within the panel interconnecting all of them</td>
<td>![Section Diagram]</td>
</tr>
</tbody>
</table>

### COMMENT

This type of green façade achieves more controlled greenery, modelling it within a regular grid. The system is static, and, although replacement of the modules is easy, accessibility for maintenance is difficult.

---

Table 2.5 Green façade Type 1.3 green façades composed of Green vertical Panels

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2. The Current Practice of Green Façades
Vancouver’s aquarium includes another variety of green vertical panel façade. Designed by the landscape architect Randall Sharp, the panels are framed in plastic boxes attached to a metallic substructure which is attached to the opaque wall. The system provides local plant diversity and environmental benefits.

![Image of Vancouver's Aquarium green vertical panels](image1)

Figure 2.27. Green vertical panels at Vancouver’s Aquarium, 2006.

In a different way, Herzog & de Meuron’s green panels designed for the façade of the basement of Prada in Tokyo, also constitute another variety of green vertical panels. In this case, the modules are enclosed with a special anti-root cloth, which creates a mosaic that adapts to the different inclinations of the wall.

![Image of Herzog & de Meuron's green vertical panels](image2)

Figure 2.28 Herzog & de Meuron’s green vertical panels at Prada Store. Tokyo 2005.

Manufacturers. The Spanish company Intemper S.A manufactures and installs the green vertical panels described in the case of the Gordillo studio and Seedorf House. The green vertical panels are riveted to the metallic profile, and consist of vertical metallic L profiles attached to an opaque wall. The module of 60x60cm containing the soil, the insulation element, and plants is enclosed by a perforated metallic plate and incorporates the irrigation system [Fig 2.29].

The Company Elevated Landscape Technology Inc [ELT] from Vancouver has developed a similar green vertical panel system, called the Living Wall System. In this case, the module consists of plastic rectangles subdivided by mini-cells where the soil is placed for the growth of plants.

Summary

<table>
<thead>
<tr>
<th>Description: Green vertical panels create a regular grid in the façade.</th>
<th>Comment: Through green vertical panels, façades are modulated in a regular square grid. Although accessibility for maintenance is difficult, it is easier than in previous types due to the possibility of replacement of the modules. The system is static.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Examples: Gordillo Studio extension; Seedorf House; Obernai West School; Learning Centre at Vancouver Aquarium; Prada Store in Tokyo.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.6 Summary of the green façade Type 1.3 composed of green vertical panels.
2.2.2 Green Façades attached to a transparent wall

The major attribute in green façades attached to transparent walls versus those attached to opaque ones is that the greenery is not only perceived from the outdoor space, but also from the indoor space. In this sense, light passes through the green mass creating interesting scenes of lights and shadows as well as different colours. At the same time, the system permits solar energy to pass through the green façade into the indoor space, providing the option to passively heat the building.

Green façades attached to a transparent wall are divided into two main types: in the first one, the greenery is located between two transparent layers, whereas in the second one, the greenery represents the outdoor layer of the system.
2.2.2.1 Green Façade Type 2.1 Green element between two transparent layers

**Description.** This green façade system is composed of three layers: two transparent layers in the extremes [indoor and outdoor] with the green element in the middle. Plants grow from a pot and are guided by metallic wires, meshes, or even by a sort of rope mesh similar to fishing nets. The irrigation system consists of watering each plant pot and connects all plant pots.

**Examples.** In the University of Arts and Human Sciences building of Grenoble, France, [Lacaton & Vassal, 2001], the inner layer is glazing and the external one is polycarbonate. The façade acts as a thin greenhouse, and the ventilation needed by the plants between the two layers is provided by openings in the external polycarbonate layer.

“These greenhouses, like slender transparent blades to north and south, create a filter of plants. They provide an innovative image, at once changing and poetic, matching the building’s purpose and the artistic dimension of the classes held in it” 23

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2 images waiting for © permission

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Figure 2.31 Type 2.1
Green element between two transparent layers

Figure 2.32 Arts and Human Sciences building, Grenoble, 1995 & 2001. Lacaton & Vassal. An example of green façade between two transparent layers: a polycarbonate screen is the external layer, a glazing façade is the internal layer, and plants with their pots grow between the two layers.


2. The Current Practice of Green Façades
Comment. The most remarkable aspect of this type of green façade is the possibility it provides to see through it. Consequently, the greenery is perceived both from the inside and from the outside, and the façade permits light to pass through it, therefore facilitating a solar energy gain.

Another example of this type of green façade is one presented as part of the Casa Barcelona 05 project in the Construmat Fair 2005. The design attempts to condense a greenhouse into a thin, double glazing façade\textsuperscript{24}. The outdoor layer is composed of solid polycarbonate louvers on an aluminium frame. The indoor layer consists of sliding glazing and aluminium panels. The greenery is placed in the intermediate layer, which is also moveable by a sliding system [Fig 2.33] In this case, the different movement options proposed by this green façade of polycarbonate louvers with sliding glazing and green panels, provide the necessary flexibility for the façade to accommodate different climatic conditions and user needs.

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig233.jpg}
\caption{Figure 2.33 Casa Barcelona 05 – Green Façade. F. Pich-Aguilera, Intemper S.A. and Jon Laurenz [Rafael Escola Foundation]. This green façade includes different movement options – polycarbonate louvers, sliding glazing and greenery – providing the necessary flexibility for the façade to adapt to different conditions.}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=0.8\textwidth]{fig234.jpg}
\caption{Figure 2.34 Casa Barcelona 05}
\end{figure}

CONSTRUCTION SYSTEM
Polycarbonate louvers in the external layer; sliding glazing and aluminium panels in the internal layer; and the moveable greenery is placed in the middle.

IRRIGATION SYSTEM
Drip irrigation system included in plant pots, with a water cavity of 8cm below the soil.

COMMENT
The system permits light and sun energy to pass through the façade, and adapts to user needs by introducing the sliding movement. The greenery is not perceived directly, but insinuated through the first glazing layer.

Table 2.7 Green façade Type 2.1 Green element between two transparent layers.
### Summary

<table>
<thead>
<tr>
<th>Description:</th>
<th>Green Façade type 2.1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description:</strong> The greenery is placed between two transparent layers.</td>
<td></td>
</tr>
<tr>
<td><strong>Examples:</strong> Arts and Human Science building, Grenoble [Lacaton &amp; Vassal]; Green Façade project in Casa Barcelona05, Construmat Fair.</td>
<td></td>
</tr>
<tr>
<td><strong>Comment:</strong> The façade permits light and sun energy to pass through it. The greenery is perceived from both the inside and the outside. From the outside it is insinuated through the external transparent layer. Depending on the system, it provides flexibility for the façade to change in tandem with the outdoors.</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.7 Green façade Type 2.1 green element between two transparent layers.
2.2.2.2 Green Façade Type 2.2 Green external layer and glazed internal layer

**Description.** The general composition of this type of green façade consists of a glazed inner layer and a green external layer. The green element is usually guided by metallic mesh, wires, or wooden sticks.

**Examples.** Abalos & Herreros in the Gymnastic pavilion in the Retiro Park, Madrid, [2002] propose metallic mesh to guide the growth of the plant in the external layer. The plant grows from the floor surrounding the building, and the irrigation system is embedded within the soil. The inner layer consists of a translucent polycarbonate panel, which provides the hermetecism for the façade.

![Figure 2.35 GF Type 2.2 green element as the external layer](image)

![Figure 2.36 Gymnastic pavilion Abalos & Herreros, El Retiro Park. Madrid, 2002.](image)

**Comment.** This type of green façade enables light and sun energy to pass through the façade, since they are attached to a transparent layer. The greenery can be seen from both the inside and the outside. However, the system is static, with no flexibility for the user to choose his relationship with the outdoor space, and the height of the green façade is limited by the growth of the plant.
### Green Façade Type 2.2 Green external layer and glazed internal layer

**Construction System**

Metallic mesh guides the plant growth in the external layer, and a translucent polycarbonate panel in the inner layer encloses the green façade.

**Irrigation System**

The drip irrigation system is embedded in the soil.

**Comment**

This type of green façade enables light and sun energy to pass through the façade, and the greenery is seen from both the inside and the outside. It is a static solution with no flexibility for the user and with the height limit due to the plant growth.

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Table 2.9 Green façade Type 2.2 Green external layer and glazed internal layer
The Consorcio Building in Santiago de Chile, designed by Enrique Browne, is an office building with a green façade composed of a glazed inner layer, with metallic blinds in the outdoor layer, and a green element in the intermediate layer. The greenery grows from plant pots located on each floor and is guided by the metallic blinds of the outdoor layer.

In addition to same attributes as the previous example, in this case the green façade height is not limited by the growth of the plant because it is planted on each floor, but it is still a rigid solution.

The Pergola Building and the J&R Building, both designed by Bruno Stagno and located in Costa Rica propose conventional glazing façades with a "green screen" attached as an independent plane. Therefore, there is no flexibility, and its height is still limited by the growth of the plant.
Architects Edouard François and Duncan Lewis propose an innovative construction material within this type of green façade: trees. They collaborated in the projects of the Holiday Houses in Jupilles and in the Thiais School, both in France in 1996. In both projects trees serve as a façade construction material.

In both cases green elements are visible from both sides and the daylight and sun energy pass through the façade. The system is static, and the height is limited by the growth of the trees.

**Manufacturers.** The company Jakob AG/SA manufactures different stainless steel wires or metallic meshes to guide the greenery for this type of green façades.

3 images waiting for permission

Figure 2.44 Projects of green façades with Jakob AG/SA company system

<table>
<thead>
<tr>
<th>Summary</th>
<th>Green Façade type 2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Description:</strong> The greenery is placed in the external layer and the transparent element in the internal layer.</td>
<td><strong>Comment:</strong> The greenery is visible from both the inside and the outside. It enables light and solar energy to pass through it. This system does not provide flexibility for the façade to change its relationship with the outdoors.</td>
</tr>
<tr>
<td><strong>Examples:</strong> Gymnastic Pavilion in Madrid [Abalos &amp; Herreros]; Consorcio Bldg and House in Paul St. in Santiago [Browne]; Pergola Bldg and J&amp;R Bldg in Costa Rica [Stagno]; Holiday Houses and Thiais School in France [Francois and Lewis]</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.10 Green façade Type 2.2 Green external layer and glazed internal layer.

2. The Current Practice of Green Façades
The following table compiles the different types of green façades identified in this chapter, with a preliminary and general analysis of the appropriateness of each type.

<table>
<thead>
<tr>
<th>Summary</th>
<th>Types of Green Façade</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attached to an opaque wall</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
| GF 1.1 with steel wires | **Description:** Green façade composed of steel wires or metallic meshes attached to opaque walls.  
                      | **Examples:** Rues des Suisses Apartment complex [Herzog & de Meuron]; Parking buildings in Oviedo, Florida; Fullerton California; and Reston, Virginia. | Unnoticeable steel wires or metallic mesh systems guide vines subtly. Plants limit the height of the green façade and the system makes difficult the accessibility for maintenance. |
| GF 1.2 as moss walls | **Description:** Green façades as moss walls that grow from the opaque wall.  
                      | **Examples:** Quai Branly Museum [Nouvel]; CaixaForum [Herzog & de Meuron]; Les Halles and Reykjavic City Hall [Blanc]. | This green façade provides passionate exuberance contained within geometric boundaries. The system is static (like conventional opaque façades), and accessibility for maintenance is difficult. |
| GF 1.3 as Green Panels | **Description:** Green vertical panels create a regular grid in the façade.  
                      | **Examples:** Gordillo Studio extension; Seedorf House; Obernai West School; Learning Centre at Vancouver Aquarium; Prada Store in Tokyo. | Through green vertical panels, façades are modulated in a regular grid. Although accessibility for maintenance is difficult, it is easier than in previous types due to the possibility of replacement of the modules. The system is static. |
| Attached to a transparent wall |                                                                                                                                 |
| GF 2.1 Between two layers | **Description:** The greenery is placed between two transparent layers.  
                        | **Examples:** Arts and Human Sciences building, Grenoble [Lacaton & Vassal]; Green Façade project in Casa Barcelona05, Construmat Fair. | The façade permits light and solar energy to pass through it. The greenery is visible from both the inside and the outside. Depending on the system, it provides flexibility for the façade to change its relationship with the outdoors. |
| GF 2.2 Green in external | **Description:** Greenery is placed in the external layer and the transparent element in the internal layer.  
                      | **Examples:** Gymnastic Pavilion in Madrid; Consorcio Bldg and House in Paul St. in Santiago; Pergola Bldg and J&R Bldg in Costa Rica; Holiday Houses and Thiais School in France | The greenery is visible from both the inside and the outside. The façade enables light and solar energy to pass through it. The solutions are often static and do not provide flexibility for the façade to change its relationship with the outdoors. |

Table 2.11 The five major types of green façades.

2. The Current Practice of Green Façades
This analysis of the current practices for building green façades shows part of their potential as well as the classification of the different systems of construction. All of the examples and readings analysed reveal green façades are being built as a surface of expression pretending to participate in the current responsive architecture. However, they are not worried about further implications that might be involved, such as the habitat, hydrology, climate, biodiversity, and user needs.

Thus, in examining this classification of the types of existing green façades, there arises a need for evaluating green façades against a broader range of possibilities they could offer. In this sense the thesis develops a framework in order to incorporate these aspects and to provide a series of attributes to assist designers in defining green façades with a wider knowledge of the subject. These, among other aspects, are studied in the following chapter.
The previous analysis of existing green façades shows the possibilities that they offer, but also their challenges. It detects the need to identify a larger range of opportunities afforded by green façades. These can be approached from many different perspectives such as, economically, biologically, agronomically, ecologically, mechanically, etc. These diverse viewpoints would provide different opportunities such as:

- **Cost benefits.** The reduction in cooling and heating that green façades can provide imply consequences of direct economic savings.
- **Biological benefits.** Green façades could offer the opportunity to enhance the activity of other living organisms. A deeper study could analyse how different plant species enhance other kinds of urban wildlife, as well as how different plants interact with these wildlife.
- **Plants behaviour.** There is also the opportunity to find the most appropriate plant for a particular case. To study the evapotranspiration, water needs, and metabolism, and to relate them to different types of green façades in order to assign them to a particular climate. It could also include the study of how different plants influence the fragrances of the surroundings, or the characteristics of different types of soils, needs of nutrients, etc.
- **Ecological processes.** The influence of green façades in urban hydrology could be another opportunity to be studied. In addition, how the sun exposure affects different plants could also be included.
- **Manufacturing opportunity.** Green façades could mix the conventional manner of fabricating the construction materials of façades, such as lattices and blinds; with the way plants are “fabricated” in the nursery. A manufacturer would look for the most efficient process to create green façades, including the time that plants need to achieve the ideal size required for a project. This would also include the study of the transportation and management on site.
However, this thesis focuses on an architectural perspective, including the scale of landscape architecture and urban space. It identifies a series of opportunities combining the current architectural trend of the responsive architecture, with the trend of an architecture that is sensible to its environment. Together with this, the identification of these opportunities follows an analysis of a series of research studies on the benefits of greenery to the built environment cited in current literature. Due to the limited literature on green façades, the contribution of green façades to their surrounding environment is assumed to be similar to that of other green surfaces such as trees, grass, parks, or green roofs to the built environment. Considering these architectural trends and collaborating with these research studies, this section condenses and identifies the major opportunities afforded by green façades into the following six areas: Human Comfort [HC]; Expressive capacity [EC]; Air and Water Quality [AWQ]; Indoor-Outdoor Relationship [IOR]; Urban Biodiversity [UB]; and Carbon Neutral Architecture [CNA]. Some of the six areas affect both sides of building façades – indoor and outdoor spaces, and some perform differently depending on the orientation of the façade. These will therefore be analysed in consideration of these variables where appropriate.

This identification of the opportunities in green façades, from an architectural perspective, together with the classification of the types of green façades, establishes the basis needed to develop the green façades framework. In evaluating these attributes, the framework reflects clearly the crucial difference between the two main categories of green façades – attached to opaque walls, and attached to transparent walls. The transparent green façades are visible from both the outside and the inside, opening the opportunities in green façades to the indoor space. This means they perform much better than the opaque green façades, in terms of indoor comfort temperature, reduction in energy demand, indoor visual comfort, psychological benefits, etc. On the contrary, opaque green façades can only partially achieve many of these opportunities. In addition, some of the attributes are only evaluated for opaque green walls, such as the acoustic influence, and others are only evaluated for transparent green façades, such as the influence on indoor visual comfort.
The following section explains each of the identified opportunities, as well as the evaluation process followed in each of them.

3.1 Human Comfort [HC]

Recent research suggests the opportunity of green facades to improve human comfort conditions. These improvements fall into five main categories: the influence of green facades in Comfort Temperature and Reduction in Energy Demand, Acoustic insulation, Visual Comfort, Humidity, and Psychological Benefits. These are considered from both the inside as well as the outside of the facade.

3.1.1 Comfort Temperature and Reduction in Energy Demand

The ability of green facades to influence the comfort temperature is the most studied aspect. These research studies focus on the influence on indoor comfort temperature, the direct consequence of which is a contribution to reducing the energy demand in buildings in terms of air conditioning and heating. Regarding the influence on outdoor temperature, the analysis of the role of green surfaces, such as parks and green canopies, to refresh the outdoor temperature, assumes green facades would contribute in a similar manner. The influence on both indoor comfort temperature [from inside], and outdoor comfort temperature [from outside] are specified below.
From inside. Green façades contribute significantly to the reduction of the indoor air temperature in summer, since they reduce the external air temperature of a west orientation up to 4°C on a clear August day in Fukuoka, Japan; [A. Hoyano, 198826] and by 5°C, in summer [D. Holm, 1989] in South Africa27.

![Figure 3.1 Contribution of green façades to indoor Comfort Temperature.](image)

Therefore, green façades refresh and cool the façade in summer contributing to indoor comfort temperature, and if they are attached to transparent walls this means a reduction in air conditioning of up to 45%; and of up to 23% in heating [Laurenz, 2005]28.

---


From outside. Green façades ameliorate cities' urban heat islands by cooling the air temperature of their surroundings. Regarding the measures on temperatures taken in New York's Central Park [C. Rosenzweig & W. Solecki, 200629], as well as in Tokyo's Shinjuku Gyoen Park [Honjo, T 2002]30, both suggest the temperature inside the park was around 2°C lower than it was outside of the park. Moreover, C. Rosenzweig's study suggests Central Park also contributes to reducing its nearby air temperature by between 2-5°C. This thesis extrapolates these findings assuming that green façades, when applied to the buildings of a block or a couple of blocks, could have similar influences as parks, including the surrounding area. This opens up the possibility for considering green façade buildings as the new lungs of the city in the future [Fig 3.2].

Although more accurate research on green façades would be needed to verify this assumption, this section concludes green façades could contribute to reduce nearby temperatures by an average of around 2°C.

---


The albedo* differences of surfaces are also remarkable: “Pavement radiates as much as 50 percent more heat than does grass.” According to the research on different surfaces for energy transmission and absorption [Ciemat, 1994\textsuperscript{32}], vegetation absorbs 80% of the solar radiation – of which 70% is used for plants’ transpiration – and transmits 0%. The mean temperature of leaves is the same as the air temperature. Green façades can significantly reduce the urban heat island effect, by not transmitting heat to other surfaces since their temperature and the air temperature are the same. The following graph [Fig 3.4] compares the temperature that different surfaces would reach, showing the significant contribution of green façades to reducing urban heat islands.

\textsuperscript{*} Albedo is the fraction of solar radiation reflected by a surface or object, often expressed as a percentage. [From IPCC Report. Group I: The Scientific Basis]


3. Green Façades Framework
Evaluation

The framework develops a simple way of measuring the potential of green façades to influence the comfort temperature and the reduction in energy demand. It consists of evaluating the contribution of each type of green façade based on a five point scale of values or percentages, which ranges from the lowest contribution to comfort temperature and the reduction in energy demand [LOW = 0], to 20% contribution [0.2]; 40% contribution [0.4]; and so on, to the highest contribution 100% [HIGH = 1], [Fig 3.6].
It is important to remark how differently the two main categories of green façades [opaque and transparent] perform in their contribution to comfort temperature and reduction in energy demand. This is mainly because transparent green façades allow sun energy to pass through them, while opaque green façades do not, although they insulate thermally more than the transparent ones. In this sense, when evaluating green façades, the framework makes a clear distinction in the performance of these two main categories of green façades. Together with this, the green façades framework makes a series of assumptions to evaluate the influence of the types of green façades to the comfort temperature and to the reduction in energy demand, as follows:

- **Orientation**. The main assumption is related to the orientations of green façades. In this sense, findings from research studies are mostly associated with west-oriented green façades. Based on the solar movement and the behaviour of façades for different orientations, the framework assumes that a green façade performs similarly for east, west, and south orientations, in terms of its influence on comfort temperature and energy demand in buildings. Thus, it proposes two main groups of façade orientations which are: north, and south, east-west.
**North.** Considering the north orientated façades, the assumption is that there are not significant solar gain options through these façades, being more important to thermally insulate the building. Consequently, in general, those green façades attached to opaque walls [green façade category 1] achieve a higher contribution to comfort temperature and reduction of energy demand than those attached to transparent walls [green façade category 2]. Moreover, within the category of green façades attached to opaque walls, those called “moss walls” [type 1.2] and “green panels” [type 1.3] perform better than those “composed of steels wires” [type 1.1], since they provide higher thermal insulation required by north façades.

**South, east-west.** On the contrary, the framework evaluates the types of green façades in a south-east-west orientation just the opposite as in a north orientation. This is due to the assumption that those green façades attached to transparent walls and with deciduous plants allow solar energy gain through the glazing in colder months, helping, consequently, to improve the indoor comfort temperature and to reduce the heating demand by buildings. On the other hand, in summer, the density of plants protects the façade from solar heat, helping to improve the indoor comfort temperature and to reduce the air conditioning demand by buildings. Green façades attached to opaque walls do not provide the option of solar gain passing through them in winter, and thus, do not perform as well in these orientations.
- Scale. The second assumption made by the green façades framework relates to the scale of green façades. The framework is based on research studies on green façades which analyse green surfaces in their full length and width. These include, for instance, a study of a green façade attached to an opaque wall covering a west facing room of the Tsinghua University Library compared to an uncovered wall [Di and Wang, 1999\textsuperscript{34}]. Another example is the comparative behaviour of a veranda with and without a vine sunscreen [A.Hoyano, 1988\textsuperscript{35}]. These research studies obtain data from different sensors located in different points from the exterior greenery to the indoor rooms. Therefore, according to these research studies, the scale that the framework considers when evaluating the contribution of green façades to the comfort temperature and the reduction in energy demand is the behaviour of a green façade that covers a storey completely from floor to ceiling – vertical limit – and the horizontal limit of the indoor room, enclosed by the indoor walls [Fig. 3.7].

Fig 3.7 The scale considered by the framework to evaluate the contribution of green facades to comfort temperature and the reduction in energy demand is limited vertically from the floor to the ceiling of the room – from slab to slab – and horizontally by the horizontal limits of the room.

Thus, the minimum requirements of green facades in order to consider their contribution to comfort temperature and reduction in energy demand are that the facade should cover the room completely from floor to floor vertically and within its wall limits horizontally. If not, green facades would contribute only partially to these aspects but today there is no way to evaluate that. According to this assumption, the contribution of green facades to these aspects could be extrapolated to a larger scale such as those rooms that are completely covered by greenery both horizontally and vertically, as well as the facade of a building completely covered by vegetation.

In this sense, the framework evaluates the contribution of the types of green facades to the comfort temperature and the reduction in energy demand as follows:

3. Green Façades Framework
<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Orientation</th>
<th>Contribution to Comfort Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
</tbody>
</table>

Table 3.1. Contribution of green façades to comfort temperature and the reduction in energy demand depending on the orientation of the façade.

3. Green Façades Framework
These results are represented using a spider-web graphic scale illustrated in figure 3.8. This graph visually describes the suitability of each type of green façade for different orientations, in terms of its contribution to comfort temperature and reduction in energy demand.

![Diagram showing spider-web graphic scale for green façades](image)

**Figure 3.8** This spider-web graph shows the suitability of each type of green façade for different orientations, in terms of its contribution to comfort temperature and reduction in energy demand, reflecting the strengths and weaknesses of the different orientations. In this example, the hypothetical green façade would perform very well for a north orientation, and not very well for the others.

In this sense, the four façade orientations are represented in each of the sides of the cross [N, S, E, and W]. The contribution to comfort temperature and reduction in energy demand is shown in a grey hatch. It is achieved by interpreting that the higher the contribution of the particular green façade, the further away the direction stands from the axis. This scale graph reveals the strengths and weaknesses of each type of green façade highlighting the areas for improvement.

The following chart incorporates this kind of graph for each type of green façade, which summarizes their contribution to comfort temperature and reduction in energy demand. It shows how transparent green façades perform quite well in south east and west orientations, reducing both heating and cooling demand; while opaque green façades perform quite well in north orientations, insulating significantly from the cold.

---

3. Green Façades Framework
<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Orientation</th>
<th>Contribution to Comfort Temperature and Reduction in Energy Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>North</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
<tr>
<td></td>
<td>South-east-west</td>
<td>LOW 0.2 0.4 0.6 0.8 1</td>
</tr>
</tbody>
</table>

Table 3.2. Contribution of green façades to comfort temperature and the reduction in energy demand depending on the orientation of the façade.
In order to visually represent the contribution of the types of green façades to the opportunity to improve comfort temperature and reduction in energy demand, the framework introduces them in the following chart [Fig 3.9], considering them as POOR contributors, if the total range of values is between 0 and 0.33; as MODERATE if it is between 0.33 and 0.66; and as GOOD if it is between 0.66 and 1. The following figure summarizes this [Figure 3.9].

Figure 3.9 Contribution of green façades to comfort temperature and reduction in energy demand

3. Green Façades Framework
3.1.2 Acoustic insulation

A series of research studies suggest that noise reductions due to vegetation are small unless the vegetation belt is wide. For example, compared with grassland, a densely planted belt of trees – 30m thick – was required to reduce noise by 6 dB(A) [Huddart, 1990]. Other research has looked at the relationship between the vegetation screen visibility and noise attenuation [Chih-Fang, Der-Lin, 2003] and also the influence of foliage and leave sizes in noise attenuation for different frequencies [V.Tyagi et. al, 2006]. Overall, the literature consulted suggests wide vegetation bonds are needed to achieve significant acoustic effects.

Figure 3.10 Contribution of green façades to acoustic insulation is unappreciable.

Evaluation

This attribute is only evaluated for opaque green façades, since based on the explained research, transparent green façades would not have any influence on acoustic aspects. The framework evaluates it similarly according to the influence on comfort temperature and reduction in energy demand. It is based on a low-high scale, meaning the influence of the green façade to acoustic comfort is high [good insulation, value: 1] or low [poor insulation, value: 0] [Fig 3.11].

- Acoustic insulation

<table>
<thead>
<tr>
<th>LOW</th>
<th>HIGH</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 3.11 Range of values for the evaluation of the influence to Acoustic insulation

Based on research, the framework acknowledges that green façades are not significant acoustic insulators, but it argues that those green façades as moss walls [type 1.2] and those composed of green vertical panels [type 1.3] contribute much more to acoustic insulation – considering them as HIGH contributors – than those composed of steel wires [type 1.1]– LOW contributors. This is mainly due to their construction system, since both type 1.2 and 1.3 are composed of an inner layer of soil plus the greenery layer in the external layer.

With these considerations, Table 3.3 shows the evaluation of the contribution of opaque green façades to acoustic insulation.
<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to Acoustic Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW 0</td>
</tr>
<tr>
<td></td>
<td>HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW 0</td>
</tr>
<tr>
<td></td>
<td>HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW 0</td>
</tr>
<tr>
<td></td>
<td>HIGH 1</td>
</tr>
</tbody>
</table>

Table 3.3. Contribution of green façades to acoustic insulation
3.1.3 Visual comfort

From inside. In analysing the indoor visual comfort, the framework refers to the brightness created through a window, which is divided into two kinds of brightness: \textit{Indirect brightness} [looking at a table naturally illuminated] and \textit{brightness by adaptation} [looking through a window].

In the case of \textit{indirect brightness}, produced by a surface's reflection, the luminance contrast should not be higher than 1 to 3 to be considered comfortable. Those green façades that allow daylight to pass through them generally create a luminance contrast higher than 3 [Laurenz, 2005], which means it is not visually comfortable.

The \textit{brightness by adaptation} results when the eye adapts to a luminance average from a visual of a very different luminance average. This occurs when the eye has to adapt from an indoor view to a view through a window. In this sense, the framework assumes green façades attached to glazing façades perform as lattices and blinds do [Serra 1998]. Therefore, they contribute to reduce luminance differences helping the eye to adapt to these. Moreover, those green façades that permit the user to manipulate their relationship with the outdoors contribute more to the visual comfort of the user than those which do not.

\footnote{Rafael Serra and Helena Coch. \textit{Arquitectura y energia natural.} UPC, Barcelona, 1995}


From outside. In general, scenes of natural elements contribute to higher levels of personal satisfaction, relaxation, and even creativity. These aspects are further analysed in section 3.1.5 on the opportunities of green façades to contribute to psychological benefits.

**Evaluation**

This attribute will only affect those green façades attached to transparent walls, since opaque green façades are not visible from inside and therefore cannot influence indoor visual comfort. The framework develops a low-high one-point scale of values similar to the evaluation of the influence of green façades to acoustic insulation. It assumes that transparent green façades work similarly to blinds or lattices, and therefore they perform as HIGH contributors [1] to indoor visual comfort [Fig 3.13].
Table 3.4 shows the evaluation of the contribution of the types of green façades to visual comfort. It suggests transparent green façades perform well in contributing to indoor visual comfort, but deeper research considers how they might negatively affect indirect brightness, which would mean an overall moderate contribution to indoor visual comfort, instead of the high contribution initially estimated.

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to Visual Comfort</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 2.1</td>
<td><img src="image1.png" alt="Image" /></td>
</tr>
<tr>
<td>LOW</td>
<td>0</td>
</tr>
<tr>
<td>HIGH</td>
<td>1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>LOW</td>
<td>0</td>
</tr>
<tr>
<td>HIGH</td>
<td>1</td>
</tr>
</tbody>
</table>

Figure 3.13 Range of values for the evaluation of the contribution to Visual Comfort

Table 3.4. Contribution of green façades to visual comfort
3.1.4 Humidity

The literature reviewed shows contradictory data regarding the influence of green façades to increased humidity. On the one hand, research by Akira Hoyano concludes that although a prediction would suggest higher humidity on a green façade compared to the same facade without vegetation, due to the transpiration of leaves, no significant difference in humidity was found from the measurement [Hoyano, 1988][42]. On the other hand, research by Cantuaria reveals that a west-facing vegetated wall, compared to an uncovered wall, raised humidity by 9% [G.A.C. Cantuaria 2000][43].

Despite this relatively contradictory data, the framework assumes vegetation might somehow influence the humidity of the surroundings. Moreover, it makes another distinction between opaque and transparent green façades, considering transparent green façades will also affect the indoor humidity, while opaque green façades will only affect the outdoor humidity. Thus, until further research obtains more accurate data, the framework assumes that transparent green façades perform as HIGH contributors to increased humidity of indoor and outdoor spaces, while opaque green façades perform as MODERATE contributors to increased humidity, since it can only affect the outdoor space. More accurate research is needed in order to specify which type of green façade contributes more to raised humidity than the others.

The following table 3.5 shows the assumption made in evaluating the influence of green façades to humidity.

---


<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to Humidity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW: 0.5, HIGH: 1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW: 0.5, HIGH: 1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW: 0.5, HIGH: 1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW: 0.5, HIGH: 1</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW: 0.5, HIGH: 1</td>
</tr>
</tbody>
</table>

Table 3.5. Contribution of green façades to humidity
3.1.5 Psychological benefits

"People are often aware that nature is important to them. They appreciate having daily contact with it, even if there is only a modest amount of nature nearby...they enjoy them".

The contribution of green façades to psychological benefits is based on a series of studies carried out by Rachel and Stephen Kaplan. The emerging biophilia hypothesis suggested by Edward O. Wilson in 1984 also argues for similar benefits.

According to Kaplan's book 'The Experience of Nature: A psychological perspective', nature always appears as an important element when studying people's preferences for places. In similar terms, people are generally more satisfied with green places, and the influence of nature encourages faster recoveries from illnesses. Based on a series of surveys made from different groups of people in different places, Kaplan observes "the consistent findings of a strong preference for natural settings" and that "having green things nearby is undeniably pleasant". Another interesting finding from these studies suggests "much of the pleasure that people derive from nature comes from such occasions to observe" and that "the view of natural areas has been shown to make a difference with respect to health measures...as well as satisfaction".

Kaplan suggests nearby nature can also increase satisfaction in the work setting, and that workers with a view of natural elements, such as trees and flowers, consider their jobs less stressful and more satisfying, and even enjoyable and relaxing. Furthermore, he argues for the restorative capacities of natural settings, as it has been "demonstrated that the content of the view is important in hospital patients' recovery from surgery, with nature content contributing to faster recovery".

---

The literature suggests that green façades could play an important role in satisfying people’s work and living environments, in enhancing enjoyment, relaxation, and lowering stress levels, and in contributing to faster recoveries. In this context, green façades attached to glazing façades could contribute to both indoor psychological benefits – by looking at natural elements from the inside – as well as outdoor psychological benefits – by viewing nature from the outside. However, more accurate research on green façades in this direction should be done to verify these intuitions, since other aspects of these studies suggest that “unfavored scenes depicted unmanaged areas with heavy undergrowth. Tree density, weeds, and a scrubby appearance contributed to these low ratings”. Thus these aspects should also be considered as a means of controlling the greenery in order to achieve the highest level of satisfaction possible.

Figure 3.14 Contribution of green façades to psychological benefits. From inside. [i.e. relaxation, contemplation]
Stephen Kellert collected a series of studies related to the intrinsic relationship of humans with the natural world in his book *Biophilia Hypothesis*. Biophilia hypothesis proclaims a “human dependence on nature that extends far beyond the simple issues of material and physical sustenance to encompass as well the human craving for aesthetic, intellectual, cognitive, and even spiritual meaning and satisfaction”. This hypothesis, as the author himself admits, is in a very early stage, and attempts to show “the human inclination to affiliate with life and lifelike process”. It presents the general affiliation of humans to the natural world; and it also attempts to demonstrate the “innately emotional affiliation of human beings to other living organisms” by nine valuations of nature, including genetic links.

“The human search for a coherent and fulfilling existence is intimately dependent upon our relationship to nature”

But what is more relevant to this thesis is the specific research in Kellert’s book, which analyzes the need that humans have for nature, showing its influences on our emotional, cognitive, aesthetic, and even spiritual development. In this sense, from the nine valuations on nature proposed by Kellert, the naturalistic and the aesthetic values are the most significant in considering the topic of this thesis. He describes the naturalistic value as a sense of fascination, wonder, and awe derived from an intimate experience of nature’s diversity and complexity. He argues that activities closely linked to nature “have been related to tension release, relaxation, peace of mind, and enhanced creativity derived from the observation of diversity in nature”.


* The term Biophilia was defined by Edward O. Wilson as the ‘innate tendency to focus on life and life-like processes’. [1984]

* The nine fundamental aspects of our basis for valuing and relating to the natural world are: the utilitarian, naturalistic, ecologistic-scientific, aesthetic, symbolic, humanistic, moralistic, dominionistic, and negativistic.

3. Green Façades Framework
Regarding the aesthetic value he suggests that "the physical beauty of nature is certainly among its most powerful appeals to human animal", arguing that "the aesthetic experience of nature could further be associated with derivative feelings of tranquility, peace of mind, and a related sense of psychological well-being and self-confidence".

It is worth mentioning the last of the values, the negative one, which refers to "the negativistic experience of nature which is characterized by sentiments of fear, aversion, and antipathy toward various aspects of the natural world". Some of these examples are nature settings containing snakes or spiders, which can elicit pronounced autonomic responses. Green façades should therefore also consider this property of negativistic value of the natural world since they can contribute for instance to the appearance of spiders and bees, among other small insects.

Figure 3.15 Psychological benefits of green façades, from outside.
Finally, Kellert explains that there are three general types of biophilic responses to unthreatening natural landscapes: liking/approach responses, restoration or stress recovery responses, and enhanced high-order cognitive functioning. The liking approach responses are very similar to the preferences suggested by Rachel and Stephen Kaplan. In this sense, Kellert suggests “preferences should tend to be higher for settings having green or somewhat verdant vegetation”. He concludes with similar data as Kaplan about the restorative capacity of nature as well as its capacity to facilitate creativity. Several studies made in hospitals showed that recuperation from stress is much faster and thorough when people are exposed to natural settings or images of natural settings.

According to this research, the framework believes green façades present an opportunity to satisfy human psychological aspects such as aesthetic, intellectual, cognitive, and even spiritual sensibilities. There is also a restorative capacity of green façades to transmit tranquility, relaxation, and encourage creativity.

Evaluation

Although psychological benefits are difficult to evaluate, the green façades framework considers green façades in general positively affect human psychology. According to the biophilia hypothesis, humans need to be closely related to nature, and green façades offer an opportunity to enhance this. Thus, the framework evaluates those green façades attached to opaque walls as LOW contributors to psychological benefits [0.5], since they can only be perceived from the outside. On the contrary, those green façades attached to transparent walls are considered HIGH contributors [1], as they are perceived from both the outside and the inside.
Table 3.6 summarizes these considerations.

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution Psychological benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW 0 0.5 HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW 0 0.5 HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW 0 0.5 HIGH 1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW 0 0.5 HIGH 1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW 0 0.5 HIGH 1</td>
</tr>
</tbody>
</table>

Table 3.6. Contribution of green façades to psychological benefits

Combining all of the evaluations of the five aspects included within human comfort—comfort temperature and reduction in energy demand, acoustic insulation, visual comfort, humidity; and psychological benefits—the following chart reflects the overall contribution of the different types of green façades to improve human comfort [Table 3.7].

3. Green Façades Framework
### Contribution of green façades to improve human comfort

<table>
<thead>
<tr>
<th>GF 1.1 Composed of steel wires</th>
<th>Comfort temperature &amp; reduction in energy d.</th>
<th>Acoustic Insulation</th>
<th>Low</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF 1.2 As moss walls</td>
<td>Comfort temperature &amp; reduction in energy d.</td>
<td>Acoustic Insulation</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>GF 1.3 Composed of vertical panels</td>
<td>Comfort temperature &amp; reduction in energy d.</td>
<td>Acoustic Insulation</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>GF 2.1 Between 2 transparent layers</td>
<td>Comfort temperature &amp; reduction in energy d.</td>
<td>Acoustic Insulation</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>GF 2.2 Green ext. transparent int.</td>
<td>Comfort temperature &amp; reduction in energy d.</td>
<td>Acoustic Insulation</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

- **Humidity**: Low | 0.5 | High
- **Psychological benefits**: Low | 0.5 | High

Table 3.7. Contribution of green façades to improve human comfort
3.2 Expressive capacity

The expressive capacity is the most explored element, if not the only one explored in green façades. Today’s architects try to express the “unkempt ambience” of a green façade building, as well as the “material which form seems to melt away”.

This thesis explores green façades as fascinating elements that provide a range of possibilities for creating changeable surfaces, playing with different densities, colours and textures, and rethinking their integration within their surroundings. However, although the concept of its expressive capacity is most commonly considered in the design of a green façade, this framework does not look at expressive capacity alone, but rather, considers it as one vital attribute among others. This expressive capacity is understood in three different ways: by its changeable properties, in the wide range of densities, colours and textures it provides, and according to the options to integrate and engage in a dialogue with its surroundings.

In this context, the changeable properties in green façades refer to the opportunity they offer to introduce the dimension of TIME — or the ephemeral dimension, in Jean Nouvel’s terms — to the building. Green façades change their appearance naturally, responding and adapting to the nearby environment’s stimuli, such as the passing of time. In contrast to the traditional hermetic and unchanging character of building façades, green façades introduce a living skin by building external layers in continuous change, which escape even the designer’s control in a free development over time.

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46 Roger Sherwood, Rue des Suisse, www.housingprototypes.org
48 An interview to Jean Nouvel available in his office website: www.jeannouvel.com
Green façades also provide a wide range of densities, colours and textures. The selection of plants from the broad variety of plant species available permits designers to define and play with green façades, taking advantage of these characteristics.

Green façades also open the door to rethinking the integration of buildings within their surroundings. They offer the opportunity to reinterpret the dialogue between a building and its immediate context, as well as to provide new resources for envisioning the current understanding of architecture as geography. In this sense, green façades help us to understand architecture as another layer of ecology or a game of surfaces.

**Evaluation**

In evaluating these aspects, the framework finds that there are a lack of specific references to determine which type of green façade satisfies the criteria for expressive capacity. Although one could argue that those green façades attached to transparent walls contribute more to expressivity because they are visible from the inside and from the outside, the framework considers all five types as GOOD achievers of the expressive capacity of green façades [value: 1], since they are all contributing factors for why we are experiencing this kind of boom in green façades today. However it acknowledges further research would be needed for a more accurate evaluation.

Table 3.8 shows the assumptions made when evaluating the contribution of the different types of green façades to the expressive capacity they offer.

---

### Table 3.8. Contribution of green façades to the expressive capacity

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to the expressive capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW 0 - - - - - - - - - - - - - - - - - HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW 0 - - - - - - - - - - - - - - - - - HIGH 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW 0 - - - - - - - - - - - - - - - - - HIGH 1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW 0 - - - - - - - - - - - - - - - - - HIGH 1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW 0 - - - - - - - - - - - - - - - - - HIGH 1</td>
</tr>
</tbody>
</table>

1. OPAQUE
2. TRANSPARENT
3.3 Air & Water Quality [AWQ]

The opportunity to improve air and water quality lies in the capacity of green façades to perform as purifying filters, eliminating pollutants.

3.3.1 Air Quality

A collection of research on urban forests and green roofs suggests the potential for trees and plants to trap air pollutants. The work of McPherson and Nowak studies the role of urban forests in trapping air pollutants. In Chicago’s Urban Forest Ecosystem project, they show how urban trees “improve air quality removing approximately 0.3-1% to an average air quality, reaching 5-10%” [McPherson and Nowak, 1994][50]. If we apply these findings to green façades, the thesis assumes they work as vertical green filters that trap air pollutants and purify them. Based on the findings from the book *Urban Biodiversity*[^51], the framework divides plant species into three main types: shrubs, climbers, and grasses. It suggests shrubs contribute the most in trapping air pollutants while grasses contribute the least.

---


3.3.2 Water Quality.

From inside. There is a remarkable opportunity to conserve water, which is a result of innovative models of irrigation for green façades. Existing irrigation systems for green façades are generally based on conventional drip irrigation systems with few practices concentrating on water conservation. As water is a scarce resource in many parts of the world, an opportunity exists to rethink irrigation systems based on minimizing the water demands of plants. In this context, the research carried out by the Spanish green roof company, Intemper Española S.A,\textsuperscript{32} suggests that by using their 'ecological roof', water savings up to 47.6\% can be achieved.

\textsuperscript{32} Intemper, ETSAM and ETSIA. \textit{Estudio a escala natural que la azotea ecológica aljibe tiene sobre el ahorro energético de los edificios}. Madrid, 1999.
This irrigation system proposed in their 'ecological roof' is based on a water storage cavity 8cm deep below the green roof, linked to the plants by filter membranes that guide water by capillaries to the plants when they demand it [Figure 3.17]. In the Casa Barcelona05 project\(^{33}\), the green façade prototype transferred this irrigation system to a green façade. [Fig 3.18]

Thus, the selected irrigation system also offers an important opportunity to reduce the water needs of green façades and ultimately to contribute to water conservation.

**From outside.** The green roofs study in Toronto suggests that greenery contributes to reduce runoff volume, stream erosion, and pollutants [City of Toronto 2005]\(^{34}\). Green façades, as green roofs, filter contaminants from rainwater. "Most of the time heavy metals and nutrients that exist in stormwater are bound in the green roof growing substrate instead of being discharged in the runoff" [City of Toronto 1999]\(^{35}\). According to this study, "green roofs are normally able to retain 70 to 90% of the stormwater that falls on them during the summer months, depending on the frequency of rain and drying rates. In winter months, green roofs are predicted to retain 40 - 50% of the stormwater". This is something that depends on different climate conditions as well as on whether or not it is an extensive or an intensive green roof. The thesis assumes green façades would work in a similar manner as green roofs.

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\(^{34}\) The city of Toronto. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto.*


\(^{35}\) City of Toronto. *Report on the Environmental Benefits and Costs of Green Roof Technology for the City of Toronto.*

Evaluation

The framework follows the same ‘one-point’ scale as in the other categories. However, it breaks the overall contribution of green façades down to air and water quality in a similar way as in the contribution to human comfort. In this sense, within the one-point scale of values or percentages, it considers the influence on air and water quality evenly, so that each of them have a highest value of 0.5, and added together provide the overall evaluation, which has a highest value of 1.

Those green façades with a value closer to 0.5 for air quality have a higher influence on trapping air pollutants. This depends on the selected plants. Values range from a low influence in air quality: grassy species [value: 0.15]; to a higher influence: climber plants [0.3]; to the highest influence: shrubby plants [0.5]. Regarding the contribution to water quality there are two more values: those green façades that accommodate water storage within the irrigation system [0.25], and those that also incorporate some kind of grey-water treatment into the building through green façade [0.5]. The overall evaluation is illustrated in Figure 3.19.

The green façades framework evaluates the influence of the types of green façades to air and water quality as follows:

<table>
<thead>
<tr>
<th>Air and Water Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>LOW 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td>Air quality</td>
</tr>
</tbody>
</table>

Figure 3.19 Range of values for the evaluation of the contribution to Air and Water Quality
Air Quality. Depending on the plant species incorporated in the green façades the contribution to the improvement of air quality can be higher or lower. In this sense, according to Urban Biodiversity, the framework assumes that shrubs contribute the most in trapping pollutants [HIGH value = 0.5]; grasses, the least [LOW value = 0.15]; and vines or climbers moderately [0.3]. Moreover, if the green façade is attached to a transparent wall that can be opened, it is then also related to indoor space, contributing to the indoor air quality as a great deal of research at the University of Guelph suggests.

Water Quality. The framework evaluates as HIGH [0.5] those green façades that do allow some water storage within the irrigation system and some grey-water treatment for the building. It evaluates in the middle [0.25] those green façades that incorporate one of the two options; and as LOW [0] those green façades that do not include any of these.

In this sense, the evaluation of green façades in terms of their contribution to air and water quality is summarized in Table 3.9.

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37 http://www.nature.com/library.html
### Table 3.9. Contribution of green façades to air and water quality

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to Air and Water Quality</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>0 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td></td>
<td>□ □ □</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>0 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td></td>
<td>□ □ □</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>0 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td></td>
<td>□ □</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>0 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td></td>
<td>□ □ □</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW</td>
</tr>
<tr>
<td></td>
<td>0 0.15 0.3 0.5 0.75 1</td>
</tr>
<tr>
<td></td>
<td>□ □ □</td>
</tr>
</tbody>
</table>
3.4 Indoor – Outdoor Relationship [IOR]

The potential for green facades to contribute to the relationship between indoor and outdoor spaces is divided into three main aspects: relationship with the immediate context, indoor and outdoor flexible relationship, and maintenance.

3.4.1 The relationship with the immediate context

The relationship of green facades with their immediate context refers to the specificities of the site in terms of how green facades engage with the immediate urban space, and how they are settled within an urban context, a park context, or a narrow street context, for instance. It considers whether or not the role of the green facade is to oppose the nearby concrete hard surfaces, or to compliment a neighbouring park or the trees on the street.

This aspect also refers to the appearance of green facades, whether they appear as an impenetrable barrier, or as a permeable green screen, as well as the different views and grades of opacities created through the green layer.

Figure 3.20 Simulation of natural changes of green facades from inside.

Figure 3.21 Green Facades and the immediate context. Photomontage of a green facade building simulating its natural reaction and change to surroundings stimuli

3. Green Façades Framework
3.4.2 Flexibility and Permeability

The indoor and outdoor relationship is also related to the flexibility and permeability of the green façade system. This relies on the capacity of green façades to provide enough flexibility for users to change their relationship with the outdoor environment and to be manipulated by it. By providing flexibility users have the option to create, when appropriate, dense green barriers with the outdoor space if they are looking for privacy, or to create different grades of openness, transparencies, and permeability by greenery and flexible systems [such as sliding or rotating systems].

Figure 3.22 Green flexible façades is the capacity of green façades to be manipulated by the user to change their relationship with the outdoor environment.
3.4.3 Maintenance

The maintenance is closely related to the accessibility of a green façade. This includes both the accessibility of the construction system and the accessibility of the irrigation system. This is related to the capacity of the system to be replaced or easily accessible for maintenance purposes.

Evaluation

Since it is difficult to evaluate the indoor-outdoor relationship, especially considering the wide variety of urban contexts, the green façades framework focuses on the evaluation of the relationship between the indoor and outdoor of each type of green façade based mainly on the flexibility provided to change this relationship, as well as on its accessibility. The overall one-point scale of values or percentages is organized as follows:

- Indoor – Outdoor Relationship

![figure](image)

Figure 3.23 Range of values for the evaluation of the indoor-outdoor relationship

If the green façade provides options for the users to change their relationship with the outdoors [by movement systems such as sliding, rotating, etc] the framework evaluates it as a high contributor [0.5]; whereas if it does not provide any options [static systems] it evaluates it as low contributor [0]. In terms of maintenance, in a similar manner, if the green façade system is easily accessible for pruning or replacement, the framework evaluates it as a high contributor to maintenance [0.25].

On the contrary, if a green façade system is not easily accessible, making its maintenance difficult, the framework evaluates it with a low value [0].
The framework follows the same reasoning for evaluating the maintenance of the irrigation system. In this sense, it evaluates as low those irrigation systems which have difficult accessibility [0], and evaluates as high those irrigation systems that are accessible, making maintenance easier.

Table 3.10 summarizes the overall evaluation of the five types of green façades in terms of their contribution to the indoor-outdoor relationship.

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Indoor-Outdoor Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW  0.25  0.5  0.75  1</td>
</tr>
<tr>
<td>1 OPAQUE</td>
<td>HIGH</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW  0.25  0.5  0.75  1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW  0.25  0.5  0.75  1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW  0.25  0.5  0.75  1</td>
</tr>
<tr>
<td>2 TRANSPARENT</td>
<td>HIGH</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW  0.25  0.5  0.75  1</td>
</tr>
</tbody>
</table>

Table 3.10. Contribution of green façades to indoor-outdoor relationship
3.5 Urban Biodiversity [UB]

Biodiversity is defined as biological diversity, or the variety of life in an area [Schaefer 2004]58. Today the World is facing the massive loss of biological diversity since the natural environment is disappearing [Kellert 1993]59.

More specifically, in the urban context, urban biodiversity is also faced with serious challenges of habitat loss and disturbances to air, water and soil [Schaefer 2004]54.

In this context, green façades represent an opportunity to contribute to urban biodiversity by creating microhabitats or patches, which enhance urban plant diversity and provide natural places for small animals to rest and live. Green façades can also contribute to linking isolated green spaces of cities, and participate in emerging projects for greenways and green corridors. In this sense, green façades provides a habitat, which could mean safe nesting places for small animals, and even sources of food for humans. Further analysis and research is needed to acknowledge how green façades can contribute to these features, since the current literature only suggests such intuitions.

As many authors such as Ian MacHarg [1969]60 and Michael Hough [1995]61 have already suggested, there is a need to embrace nature in our lives in the city. In this sense, green façades present the opportunity not only to avoid disturbing urban biodiversity but also enhancing it, by incorporating green elements that facilitate life for other living organisms. By doing so, green façades would be a step towards “GREENING GRAYFIELDS” [the city], in contrast with what cities have always been doing: “GRAYING GREENFIELDS”.

Figure 3.25 Greening Grayfields vs Graying Greenfields

Evaluation

To evaluate the contribution of green façades to urban biodiversity, the framework divides the one point scale of values or percentages into four quarters. It suggests that green façades always contribute in some way to urban biodiversity, and therefore the evaluation always starts with a minimum value of 0.25. Above this, the framework considers three aspects: plant biodiversity, location, and covered surface. Figure 3.26 illustrates the evaluation.

3.5.1 Plant diversity

The direct possibility for green façades to contribute to urban biodiversity relies on the recognition of a city's different plant species, and therefore, to the environmental enrichment of the building surroundings. In this sense, for instance, the green façade at the Quai Branly Museum in Paris hosts more than 170 different species of plants in the installation, which includes perennials such as campanulas, geraniums, ferns, ivies, and sages; shrubs such as shrubby veronicas, buddleias, hydrangeas, and honeysuckles; as well as grasses and sedges. In the case of the Aquaquest Learning Building at the Vancouver Aquarium, 20 different species of plants were originally planted in the modules. It is difficult to evaluate this contribution because of the many variables it depends on, such as building scale, green façade dimension, etc. However, the framework evaluates as higher contributors those green façades which have more than 50 different species, and as lower contributors those green façades composed of less than 50 species.

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62 Proefrock Philip. Living Walls. www.ecogeek.org
63 L'Atelier Vert www.frenchgardening.com
3.5.2 Location

In considering the potential for green façades as a place for different living species, such as birds, butterflies, and insects, the framework suggests that the contribution is higher if the façade is located in a city’s green network. In this sense, it evaluates the contribution as low if the building is not placed within a city’s green network [0], and as high if it is [0.25]. More research is needed to determine which green façade contributes more than another to enhance living activity. The thesis speculates green façades associated with a transparent wall might contribute less, since the environment created between the greenery and the transparent wall might not afford the most appropriate spaces for living species. However, more studies are needed to determine how green façades’ density, thickness, variations in the screen, etc. could enhance the diversity of living organisms.

3.5.3 Coverage

The framework takes into account the percentage of the façade surface that is covered by the greenery. Due to the scarce literature on this issue the green façades framework is based on intuition, considering as low contributors to urban biodiversity those green façades where the greenery covers less than 50% of the façade surface [0], and as high contributors those that cover more than 50% [0.25].

Table 3.11 summarizes the estimation of the contribution of the types of green façades to urban biodiversity.
<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to urban biodiversity</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td>LOW 0.25 0.5 0.75 1</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td>LOW 0.25 0.5 0.75 1</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td>LOW 0.25 0.5 0.75 1</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td>LOW 0.25 0.5 0.75 1</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td>LOW 0.25 0.5 0.75 1</td>
</tr>
</tbody>
</table>

Table 3.11. Contribution of green façades to urban biodiversity
3.6 Carbon Neutral Architecture [CNA]

Carbon neutral architecture results in a net zero flow of carbon into the atmosphere in its design, construction, occupancy, and decommissioning phases, each independently [Ahman et. al. 2006]. It also “seeks to minimize the negative environmental impact of buildings by enhancing efficiency and moderation in the use of materials, energy, and development space.” Today many similar concepts are used to refer to carbon neutral architecture such as zero carbon buildings [Webb 2001], zero energy homes [Iqbal, 2004], low energy buildings [Hestnes, 1996], etc. However, this thesis wants to emphasize that the result of a net zero flow of carbon into the atmosphere would not mean it necessarily classifies as carbon neutral architecture, since this should be achieved by both passive and active design, as well as by minimizing its environmental impact.

In this context, the thesis looks at the contribution of green façades to carbon neutral architecture as rooted in three of their functions: first, green façades are a low energy material, since they demand low energy in their fabrication process; second, they reduce the energy demand of buildings, and therefore, their carbon emissions [Laurenz, 2005]; and, last, they sequester CO2 among other air pollutants [McPherson and Nowak 1994].

66 http://en.wikipedia.org/wiki/Sustainable_architecture
A low energy material, which refers to the life cycle – carbon cycle – of the components of a green facade, also includes the study of the fabrication process of green facades. Although very little research has been done on this issue, it would be interesting to manufacture vertical green panels or green modules that could be created in plant nurseries, as a kind of 'prefabricated green facade'. In this context, green facades could be standardized, facilitating the fabrication as well as the construction process, contributing ultimately to low the energy requirements of green facade buildings.

According to previous findings [analysed in section 3.1.1], the influence of green facades to reduce the energy demand of buildings means a reduction in air conditioning of up to 45%, and up to 23% in heating. Consequently, this also contributes to reduce the CO₂ emissions created to generate that energy; which shows the influence of green facades to diminish the negative consequences of high CO₂ concentrations.

Regarding the capacity of greenery to sequester CO₂, consulted literature suggests this sequestration represents a very little proportion of the total CO₂ emitted by a city [removing approximately 0.3-1% to an average air quality; reaching 5-10% - McPherson and Nowak, 1994[72]]. However, this thesis would like to emphasize that green facades appear to be the only building material that could generate a positive carbon load balance, considering their life cycle. This could occur if the total CO₂ emitted to fabricate a green façade was lower than the total CO₂ sequestered by that green façade in its life time.

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Evaluation

The framework only evaluates the first of the three aspects of carbon neutral architecture – low energy material. This is due to the fact that the other two – CO₂ emissions and carbon sequestration – have already been analyzed in previous sections [3.1.1 reduction in energy demand and 3.3.1 air quality]. Therefore, to quantify the contribution of green façades to carbon neutral architecture, the framework considers three values within the one-point scale: 0 - 0.5 - 1.

- Carbon neutral architecture

LOW       HIGH
0          1

Figure 3.27 Range of values of the contribution to carbon neutral architecture

The framework expects that green façades contribute directly to low carbon materials, since the greenery is a natural material with a low carbon fabrication process, contributing, consequently, to carbon neutral architecture. In this sense, the framework estimates that the contribution of a green façade to carbon neutral architecture would never be low [0], 0.5 being the minimum contribution. However, the framework also takes into account the carbon footprint of the rest of the components of the green façade. It considers the contribution as higher if the rest of the components of the construction system, such as the green façade substructure, the plant guiding elements, etc. are nature-friendly or low carbon materials, such as wood, recycled materials, etc.
Table 3.12 illustrates the evaluation of the contribution of the types of green façades to carbon neutral architecture.

<table>
<thead>
<tr>
<th>Type of Green Façade</th>
<th>Contribution to Carbon Neutral Architecture</th>
</tr>
</thead>
<tbody>
<tr>
<td>GF Type 1.1</td>
<td><img src="image1.png" alt="Image" /> [LOW] [0] [0.5] [HIGH] [1]</td>
</tr>
<tr>
<td>GF Type 1.2</td>
<td><img src="image2.png" alt="Image" /> [LOW] [0] [0.5] [HIGH] [1]</td>
</tr>
<tr>
<td>GF Type 1.3</td>
<td><img src="image3.png" alt="Image" /> [LOW] [0] [0.5] [HIGH] [1]</td>
</tr>
<tr>
<td>GF Type 2.1</td>
<td><img src="image4.png" alt="Image" /> [LOW] [0] [0.5] [HIGH] [1]</td>
</tr>
<tr>
<td>GF Type 2.2</td>
<td><img src="image5.png" alt="Image" /> [LOW] [0] [0.5] [HIGH] [1]</td>
</tr>
</tbody>
</table>

Table 3.12. Contribution of green façades to carbon neutral architecture.

3. Green Façades Framework
3.7 Overview of the framework

According to these considerations, the framework concludes that the influence of green façades in comfort temperature and reduction in energy demand [section 3.1.1] is based in technically deeper research studies than any of the others. It is the most studied aspect and consequently the most deeply analysed in this thesis. Hence, it is based in research on the specific topic of green façades, while the rest, such as air and water quality, are based in related research on green roofs and urban forests, and even in extrapolations and assumptions based on empirical data and intuitions, such as the influence of green façades on urban biodiversity, their contribution to the indoor-outdoor relationship, and their contribution to carbon neutral architecture. This reveals the lack of literature and scarce research available on the specific topic of green façades, claiming the need for deeper analysis on this topic.

However, the framework reflects that, regarding the influence of green façades on human comfort, those green façades attached to transparent façades achieve a better fulfilment of the opportunities, especially for east, west and south orientations; whereas those green façades attached to opaque walls achieve a better accomplishment of the opportunities for north orientations. This is true especially for the opportunity to improve comfort temperature and reduction in energy demand, since those green façades attached to transparent walls allow solar energy gain in the indoor space. On the contrary, green façades attached to opaque walls provide higher thermal insulation than those attached to transparent façades, which is an important asset for north façades. Thus, this analysis concludes that, in general and although a deeper analysis on local context would be needed, for east, south and west orientations, those green façades attached to transparent walls perform better in terms of the influence on human comfort than those attached to opaque walls. At the same time, for north orientations, green façades attached to opaque walls perform better than those attached to transparent walls.
The framework also shows some lost opportunities by all five types of green façades in considering those related to air & water quality and the indoor-outdoor relationship. This is mainly due to the lack of any effort to store rainwater for irrigation and grey water treatment in the building. Current green façade systems generally incorporate neither movement nor flexibility in façades, nor any option to be manipulated by its users.

In general, most types of green façades achieve quite good values for their contribution to urban biodiversity and carbon neutral architecture. The first is due to the assumption that green surfaces within the city always improve urban biodiversity, but further research is needed to clarify which would contribute more to urban biodiversity than others. Regarding the relatively high values achieved in terms of carbon neutral architecture, it seems logical since greenery is a natural element with low energy requirements during its fabrication, leaving the most significant determination of carbon neutral value to the rest of components of the green façade, such as wires or meshes to guide plants, plant pots, etc.

Finally, it is striking that within the category of green façade, those facades incorporating opaque walls perform worse in the framework on the whole; yet, it is one of the most common practices, especially the green façade type 1.1. This confirms the suggestion that the current practices for building green façades are more concerned with exploring and developing their expressive capacity than with taking advantage of other opportunities that are available.

Therefore, the framework considers the element of human comfort to be the most meaningful opportunity, especially with respect to the contribution to comfort temperature and reduction in energy demand. While the practice of green façades suggests the expressive capacity is the most commonly considered aspect of green façades, the research studies on the topic suggest human comfort conditions are the most relevant aspects. This thesis, while waiting for further research in the underdeveloped areas of study, acknowledges human comfort as the most determinant factor in green façades.
4 APPLICATION OF GREEN FAÇADES FRAMEWORK

This chapter applies the green façades framework to existing projects that fit the five types of green façades within the two major categories: attached to an opaque wall, and attached to a transparent wall. By doing so, the thesis attempts to, on the one hand, present a better understanding of the framework by applying it to real green façade practices and, on the other hand, enable a critique and evaluation of the suitability of existing green façades.

This section selects the most representative examples of those used in the development of the framework as a case study for each of the five types of green façades. The example selected for a green façade composed of steel wires attached to an opaque wall [green façade type 1.1] is the Rue des Suisses apartment complex designed by Herzog and the Meuron in Paris, in 2000. The example selected for a green façade as a moss wall [green façade type 1.2] is the Quai Branly Museum by Nouvel in Paris, in 2006. For a green façade composed of green vertical panels [green façade type 1.3] the selected case study is Seedorf House, designed by Manuel Perez in Madrid, in 2004. For a green façade between two transparent layers [green façade type 2.1] the selected example is the Arts and Human Sciences building by Lacaton & Vassal in Grenoble, France, 1995-2001. Finally, the selected example for a green façade where the external layer is the greenery and the internal layer is the transparent layer [green façade type 2.2] is the Gymnastic Pavilion designed by Abalos and Herreros in Madrid in 2002. By applying the framework to these existing examples of green façades, a critique about the suitability of each façade is provided.

The application of the framework presents an overall evaluation of each of the selected existing examples summarized in the following charts. These charts visually show the evaluation of a particular case study in the six identified areas [Human Comfort; Expressive capacity; Air & Water Quality; Indoor-Outdoor Relationship; Urban Biodiversity; and Carbon Neutral Architecture], as a means of facilitating the understanding of the suitability of each project to its particular case.
Evaluation of some opportunities is based on specific data, such as comfort temperature and reduction in energy demand, while in others it is based in empirical data or in intuitions and speculations, such as the opportunity for the expressive capacity of green façades and their contribution to carbon neutral architecture. In this sense, this thesis considers the opportunity for green façades to contribute to comfort temperature and reduction of energy demand as the most decisive aspect when determining a green façade. This is mainly due to the lack of scientific data for the rest of the identified factors specifically on the topic of green façades, the measures of which are extrapolated from research and empirical data on urban forests or green roofs, assumptions and intuitions.

This chapter shows the evaluation of each of the selected case studies of green façades, as a means of critiquing them and determining their suitability for each particular case, bringing together the overall performance of the green façade based on each opportunity.

4.1 Case Study of Rue des Suisses apartment complex [Green Façade composed of steel wires]

The selected green façade building composed of steel wires, as a representative example of this type of green façade, is the Rue des Suisses apartment complex designed by Herzog and the Meuron in Paris in 2000. The green façade building is constructed of an interior slab that is 3 floors in height and part of three interconnected apartment elements which infill a long perimeter block. The long narrow block is a free-standing building located in the interior garden of the perimeter block [Fig4.2].
Fig. 4.2 Rue des Suisses apartment complex, the interior long block incorporates wooden blinds (south-east and south-west orientations) and the green façades (north-east and north-west orientations), as a means of integrating and dialoguing with the interior garden, in contrast with the metallic meshes façades of the apartments facing the streets.

In contrast to the metallic mesh in the façades of the two building blocks that face the streets, the interior long narrow block presents wooden blind façades and green façades as a means of softening their appearance, integrating and dialoguing with the interior garden: “Vines grow on a system of metal wires fastened to the blank walls of the garden buildings, help to create an overgrown, unkempt ambience to the landscape areas.”

The application of the green façades framework to the green façade in the Rue des Suisses apartment complex is summarized in Table 4.1, showing the evaluation of its appropriateness in terms of the accomplishment of the six identified opportunities.

73 Roger Sherwood, Rue des Suisses, www.housingprototypes.org
### Rue des Susisses apartments, Paris
Type 1.1 Green façade composed of steel wires attached to an opaque wall

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<tbody>
<tr>
<td>Comfort temperature &amp; reduction in energy d.</td>
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<tr>
<td>Acoustic insulation</td>
<td>LOW 0</td>
<td>HIGH 1</td>
<td>LOW 0</td>
<td>HIGH 1</td>
<td>LOW 0</td>
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<tr>
<td>Visual Comfort</td>
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<tr>
<td>Humidity</td>
<td>LOW 0</td>
<td>0.5</td>
<td>HIGH 1</td>
<td>LOW 0</td>
<td>0.5</td>
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<tr>
<td>Psychological benefits</td>
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</tbody>
</table>

#### Table 4.1 Evaluation of the selected example – Rue des Suisses apartment – for a green façade type 1.1 composed of steel wires attached to an opaque wall

---

4. Application of Green Façades Framework
Table 4.1 represents the accomplishment of each opportunity according to the selected case study for the green façade composed of steel wires attached to an opaque wall. It shows how this particular case fulfils them, in general, quite poorly. The most relevant opportunity for the developed framework is the contribution to comfort temperature and reduction in energy demand, since it is based on scientific data. In this sense, the green façade in the Rue des Suisses apartment complex is a north-east and north-west oriented façade, which would have performed better in terms of contributing to comfort temperature and reduction in energy demand [red lines] had it proposed a solution with higher thermal insulation capacities. For the rest of the opportunities in the Human Comfort category, which are based on empirical data and intuitions, the performance is rather low.

In the Expressive Capacity category of this case study, which seeks a soft integration with the surrounding interior garden by the subtle steel wires system, the framework is evaluated as a high contributor to the expressive capacity offered by this green façade due to its attention to generating a dialogue with the immediate context. In the case of Air Quality, given that it consists of a climber plant [vine], its contribution to air quality is modest [0.3]; while regarding the Water Quality it would have performed better if it had incorporated some kind of rainwater retention system or treatment for the grey water used by the building. For the Indoor-Outdoor relationship, it does not perform well, since many parts of the green façade are not easily accessible and since it offers no flexibility to allow users to change their relationship with the outdoor space. The performance of the façade in terms of the contribution to Urban Biodiversity would have been better had it proposed more than just one plant species [vines]. In terms of the contribution to Carbon Neutral Architecture, the rest of the materials used other than greenery, such as stainless steel wires which are not particularly environmentally friendly, result in a moderate achievement of this opportunity.
4.2 Case Study of Quai Branly Museum [Green Façade as moss wall]

The framework is applied to the green façade of the Quai Branly Museum designed by Jean Nouvel in Paris in 2006, as a representative case of a "green façade as a moss wall". The Museum is located in the left bank of the Seine along the Quai Branly Street. The four storey green façade, from roof to sidewalk, has a north-west orientation to the Left Bank Boulevard [Fig4.4].

![Figure 4.3 Quai Branly Museum facing Left Bank Boulevard.](image)

Fig. 4.4 The green façade of the Quai Branly Museum faces the Left Bank Boulevard integrating with its vegetation.

The green façade of the Museum seems to look for a disappearance within its surroundings, "where material form seems to melt away, giving the impression [of] a sanctuary without walls." Table 4.2 summarizes the application and evaluation of the framework for this green façade.

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74 Joann Gonchar, AIA. Musée du Quai Branly. Architectural Record February issue, New York 2007
### Table 4.2 Evaluation of the selected example – Quai Branly Museum – for a green façade type 1.2 as moss walls attached to an opaque wall

<table>
<thead>
<tr>
<th>Project</th>
<th>Quai Branly Museum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Quai Branly Street, Paris</td>
</tr>
<tr>
<td>Year</td>
<td>2006</td>
</tr>
<tr>
<td>Architect</td>
<td>Jean Nouvel</td>
</tr>
<tr>
<td>Green Façade orientation</td>
<td>North-west</td>
</tr>
</tbody>
</table>

#### 1. Human Comfort
- Comfort temperature & reduction in energy demand
  - Acoustic insulation: LOW, HIGH
  - Humidity: LOW, 0.5, HIGH
  - Visual Comfort: LOW, HIGH
  - Psychological benefits: LOW, HIGH

#### 2. Expressive Capacity
- LOW, HIGH

#### 3. Air and Water Quality
- LOW, 0.15, 0.3, 0.5, 0.75, HIGH

#### 4. Indoor-Outdoor Relationship
- LOW, 0.25, 0.5, 0.75, HIGH

#### 5. Urban Biodiversity
- LOW, 0.25, 0.5, 0.75, HIGH

#### 6. Carbon Neutral Architecture
- LOW, 0.3, HIGH

---

4. Application of Green Façades Framework

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As Table 4.2 shows, the green façade of the Quai Branly Museum performs relatively well in terms of the contribution to comfort temperature and reduction in energy demand, since it is a green façade with high thermal capacities located in a north-west orientation. Most remarkable is perhaps its high performance in the contribution to Urban Biodiversity, since it is placed in one of the green networks of Paris – Left Bank Boulevard – enhancing life for other living organisms, and introducing more than 150 plant species. This case study of a green façade seeks integration with the surrounding boulevard melting into its greenery; hence, the evaluation of the Expressive Capacity as high..

On the contrary, the rest of the opportunities are not fulfilled as highly. Mostly all plant species are "grassy" species which perform at a low level with respect to their contribution to trap air pollutants; and it does not consider any option for incorporating rainwater retention systems or grey water re-use treatments to achieve a better performance in Air and Water Quality. Nor does it fulfil the opportunity to improve the Indoor-Outdoor Relationship since it is not easily accessible and it does not allow any movement within the green façade to provide flexibility to users to establish the desired relationship with the outdoor space through the greenery. With respect to Carbon Neutral Architecture, the performance would have been better had environmentally friendlier components of the façade been considered, which would have meant using low energy materials instead of a PVC substructure.

75 Proefrock Philip. Living Walls. www.ecogeek.org
4.3 Case Study of Seedorf House [Green Façade composed of vertical panels]

The green façade selected for green façades composed of vertical green panels is the Seedorf house in Madrid, a single family weekend home designed by Manuel Perez, Carlos Arroyo and Eleonora Guidotti in 2003. The house is placed in a small wood and reinterprets the trees of that surround it playing with green carpets – green façades – and glazing façades with diverse opacities. [Fig4.6]

Fig. 4.6 The green façade of the Seedorf House is embedded by the trees of its surrounding environment.

The green façade interacts with the wood of its surrounding. These are suspended “like pieces of fruit, from the structural trunk façade” providing “a blanket of vegetation that changes colour with the seasons”.76 The evaluation of this green façade is summarized in Table 4.3.

76 House of Love. www.carlosarroyo.net.
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<tbody>
<tr>
<td>Comfort temperature &amp; reduction in energy d.</td>
<td>LOW 0</td>
<td>LOW 0</td>
<td>LOW 0</td>
<td>LOW 0</td>
<td>LOW 0</td>
</tr>
<tr>
<td>Acoustic insulation</td>
<td>LOW 0</td>
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<td>LOW 0</td>
<td>LOW 0</td>
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<tr>
<td>Humidity</td>
<td>LOW 0</td>
<td>LOW 0.5</td>
<td>LOW 0</td>
<td>LOW 0.5</td>
<td>LOW 0</td>
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<tr>
<td>Psychological benefits</td>
<td>LOW 0</td>
<td>LOW 0.5</td>
<td>LOW 0</td>
<td>LOW 0.5</td>
<td>LOW 0</td>
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</table>

Table 4.3 Evaluation of the selected green façade – Seedorf House – for a green façade type 1.3 composed of green vertical panels

Project
Seedorf House
Location
La Moraleja, Madrid
Year
2003
Architects
M. Perez & C. Arroyo & E. Cuidotti
Green Façade orientation
North, south, east, west
Table 4.3 suggests that the influence of the green façade in Seedorf House in comfort temperature and reduction in energy demand is higher when facing north than when facing other orientations. This is due to the high thermal capacity of this type of green façade. It is therefore striking to see the same proposal of a green façade facing four different orientations, since the greenery reacts quite differently in each of these directions. Still, the façade performs quite well improving the building’s acoustic insulation. This green façade seeks integration with its surrounding woodlands through the combination of greenery and glazing, which achieves a high evaluation in the category of Expressive Capacity.

As for the rest of the categories, the performance is basically modest and could have been considerably better. Similar to the two previous case studies, it could have performed better in terms of improving Air and Water Quality if any options for incorporating rainwater retention systems or grey water re-use treatment had been considered. The Indoor-Outdoor Relationship could have been better had it provided some kind of flexibility to the users to modify the relationship with the outdoor space, and if the accessibility to different parts of the façade had been easier. The substructure of the green façade, made of stainless steel mesh, which is not a low energy material, results in a modest achievement of Carbon Neutral Architecture.
4.4 Case Study of Arts and Human Science Bld [Green Façade between two transparent layers]

The representative example of green façades between two transparent layers to be evaluated by the framework is the Arts and Human Sciences Building of the Pierre Mendès University in Grenoble, France, designed by Lacaton and Vassal, 1995-2000. The complex, built in two stages, 1995 and 2000, is united by the greenhouses placed in the north and south façades of the building. [Fig 4.8]

Figure 4.7 Arts and Human Science Building. Green façades facing north and south

Fig. 4.8 The Arts and Human Science building of the Pierre Mendès University in Grenoble unifies the two pieces of the building by the “thin greenhouses” proposed for the north and south orientations.

The “thin greenhouses” proposed in this building “open the building to the campus and further surroundings” seeking a poetic atmosphere: “the views in and out are filtered by the plants in the conservatories – bougainvillea on the south side and various types of bamboo along the north face”⁷⁷. The framework evaluates this green façade as follows [Table 4.4].

⁷⁷ University Institute in Grenoble. Detail Magazine, # 12, 2002.
### Arts and Human Science building in Grenoble

**Type 2.1 Green façade between two transparent layers**

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#### 1. Human Comfort

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<th>Acoustic insulation</th>
<th>Humidity</th>
<th>Psychological benefits</th>
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<tbody>
<tr>
<td>N</td>
<td>W</td>
<td>E</td>
<td>S</td>
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<tr>
<td>Visual Comfort LOW</td>
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<td>HIGH</td>
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</tbody>
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#### 2. Expressive Capacity

<table>
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#### 3. Air and Water Quality

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<td>0</td>
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#### 4. Indoor-Outdoor Relationship

<table>
<thead>
<tr>
<th>LOW</th>
<th>0.25</th>
<th>0.5</th>
<th>0.75</th>
<th>HIGH</th>
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<tr>
<td>0</td>
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#### 5. Urban Biodiversity

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#### 6. Carbon Neutral Architecture

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<tr>
<th>LOW</th>
<th>0</th>
<th>0.5</th>
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*Project*

Arts and H. Science Bld.

*Location*

UPMF, Grenoble

*Year*

1995 & 2000

*Architects*

Lacaton & Vassal

*Green Façade orientation*

North and south

---

Table 4.4 Evaluation of the selected green façade – Arts and Human Science Bld – for a green façade type 2.1 between two transparent layers

---

4. Application of Green Façades Framework
Focusing on the graph that shows the influence to comfort temperature and reduction in energy demand of the green façade at the Arts and Sciences Building in Grenoble, it is clear how differently the façade performs for the north and south orientations. Since it allows the solar energy to pass through the glazing façade, it performs quite better in the south orientation, while quite poorly for the north orientation, as it has little thermal inertia. Thus, it is striking to observe the same type of green façade for both orientations. The façade, with greenery being visible from both the inside and the outside of the building, performs quite well for visual comfort and psychological benefits. This, on the whole, results in a successful achievement of the opportunity to improve Human Comfort. These thin greenhouses seek a poetic atmosphere, filtering the views by the plants, which means a high performance in the opportunity for the Expressive Capacity.

Regarding the contribution to air quality, it performs as the best of the five selected green façades, since the shrubby plants proposed perform well in this respect; whereas, as in the previous case studies, this green façade performs poorly in its contribution to water quality since it does not consider any options for incorporating rainwater retention systems or treatment for the grey water used by the building, achieving an overall moderate value in its contribution to Air & Water Quality. Regarding the indoor-outdoor relationship, the façade system facilitates maintenance by allowing accessibility on each floor by way of the metallic cantilevers. However, it does not provide flexibility to the users to modify their relationship with the outdoor space. The greatest flaw of this green façade, when compared with the other four case studies, is its poor contribution to Urban Biodiversity. This is due to the fact that the external transparent layer does not facilitate any interaction with other living organisms. In considering the contribution to Carbon Neutral Architecture, the façade system does not utilize environmentally friendly materials other than the greenery.
4.5 Case Study of the Gymnasium in the Retiro Park [Green Façade as the external layer]

The Gymnasium pavilion designed by Abalos & Herreros in the Retiro Park in Madrid, 2002, is the selected example for the last type of green façade, in which the external layer is the greenery and the internal layer is transparent. The façade integrates the building with the park by the disintegration of architecture melting into the surrounding greenery.

Fig. 4.10 The Gymnasium at the Retiro Park reinterpret the use of trellis and plants in old buildings of the park.

The metallic mesh guiding the vegetation encloses the gymnasium seeking a "similar image to the vegetated structures with a long tradition in gardening... Emulating these references the project strives to create a contemporary vision of the pavilion theme in a garden by using an abstract composition with the vegetation outlined with the framework. The construction will thus be a new amalgam of natural and artificial elements."  

Table 4.5 summarizes the evaluation of this green façade according to the framework.

78 www.abalos-herreros.com

4. Application of Green Façades Framework
Gymnastic Pavilion in El Retiro, Madrid

**Type 2.2 Green external layer and glazed internal layer**

### 1. Human Comfort

- **Comfort temperature & reduction in energy d.**
- **Acoustic insulation**
  - Low
  - High
- **Humidity**
  - Low
  - Medium
  - High
- **Visual Comfort**
  - Low
  - High
- **Psychological benefits**
  - Low
  - Medium
  - High

### 2. Expressive Capacity

- **LOW**
- **HIGH**

### 3. Air and Water Quality

- **LOW**
  - 0
  - 0.15
  - 0.3
  - 0.5
  - 0.75
  - 1
- **HIGH**

### 4. Indoor-Outdoor Relationship

- **LOW**
  - 0
  - 0.25
  - 0.5
  - 0.75
  - 1
- **HIGH**

### 5. Urban Biodiversity

- **LOW**
  - 0
  - 0.25
  - 0.5
  - 0.75
  - 1
- **HIGH**

### 6. Carbon Neutral Architecture

- **LOW**
  - 0
  - 0.3
  - 1
- **HIGH**

Table 4.5 Evaluation of the selected green façade – Gymnasium – for a green façade type 2.2 Green external layer and glazed internal layer
Regarding the contribution of this green façade to comfort temperature and reduction in energy demand, the chart in Table 4.5 shows how differently it performs for, on the one hand, east, west, and south orientations, and, on the other, the north orientation. In these terms, the façade solution performs better for the first group, since it allows the solar energy to pass through the glazing façade, and performs poorly for the latter. As a result, it is unfavourable to see the same solution applied to all four orientations. As for the other aspects of the façade that contribute to Human Comfort, the green façade does well to fulfil its opportunities for visual comfort and psychological benefits, since the greenery is visible from both the inside and the outside of the building. This green façade looks for a way of integrating and camouflaging the building within the landscape of the park by melting the architecture into the surrounding greenery, performing highly in its contribution to the Expressive Capacity.

The contribution of the green façade at the Gymnastic Pavilion to Air and Water Quality, is rather low, as it consists of climber plants – parthenocissus quinquefolia, performing in a modest way in its contribution to air quality – and as it does not incorporate any rainwater retention systems or any treatment for the grey water used by the building. In the case of the opportunity to enrich the indoor and outdoor relationship, this green façade system is still quite rigid and does not provide any movement to enable users to manipulate and change their relationship with the outdoor space. In the case of Carbon Neutral Architecture, environmentally friendlier components of the façade should have been considered, such as recycled materials to guide plants instead of the proposed metallic mesh.
4.6 Overview of the Application

The main conclusions of the application of the green façades framework to the five existing case studies in terms of the six proposed opportunities are the following:

Human Comfort
In terms of the contribution of green façades to the improvement of human comfort, the analysis reveals those green façades attached to opaque walls perform better for a north orientation, while those green façades attached to transparent walls perform better for east, west, and south orientations. From this perspective, it is striking to observe the same façade solution proposed for all four orientations, which many of the case studies reveal. The green façades that perform better as acoustic insulators are, within those attached to opaque walls, the Quai Branly Museum and the Seedorf House [types 1.2 and 1.3 – as moss walls and composed by green vertical panels, respectively]. Due to the scarce data on the influence of green façades to humidity, the framework is not able to evaluate it. On the other hand, those that perform better for visual comfort and psychological benefits are those façades where the greenery is visible from both the inside and the outside; these are green façades attached to transparent walls.

Expressive Capacity
The application of the framework reveals the difficulty to objectively evaluate the expressive capacity of green façades. The overall performance that the case studies reveal is rather high, partly due to the fact that they have been selected among the most representative examples within the current international practices of building green façades. At the same time, the generally high achievement of this opportunity, when compared with those of the other six, illustrates how this aspect is something current practice does fairly well, while the others remain, so far, as relatively missed opportunities.
Air & Water Quality
Although the use of different plant species as air filters trapping air pollutants results in different performances, the general contribution to air and water quality by the selected case studies is rather low. This is mainly due to a major flaw: none of them considers the incorporation of rainwater retention or grey water treatment systems. The application of the framework suggests there is a major neglect of this category and further consideration should be taken.

Indoor-Outdoor Relationship
The general performance of this opportunity is also rather low. Those façade solutions which are accessible for maintenance on each floor perform somewhat better than those that do not. However, all the case studies are relatively hermetic and rigid, indicating a need to advance the design of green façade solutions to be more flexible and moveable, which would allow the building users to modify and enhance their relationship to the outside environment.

Urban Biodiversity.
Overall, the contribution to urban biodiversity is fairly high in most cases. It is higher in those façade solutions that incorporate a larger variety of species and that are located in urban greenways [i.e. Quai Branly Museum] and is lower in those solutions where the greenery is kept from contact with the outside [Arts and Human Sciences Building, Grenoble].

Carbon Neutral Architecture
The application of the framework suggests more effort is needed toward including environmentally friendlier materials for the rest of the components of green façades other than the greenery itself. However, the results for the evaluation of the fulfilment of this opportunity may be considered as partial, since, on the one hand, the framework does not consider the CO2 sequestration capacity of different plant species [due to lack of specific data], and on the other, the reduction of emissions by the building is considered in comfort temperature and reduction in energy demand.
Since the most studied opportunity is the influence of green façades to human comfort conditions, and more specifically, to comfort temperature and reduction in energy demand, the framework considers, until there is further research on the other core opportunities, that this aspect is by far the most decisive in defining a green façade. Therefore, the framework considers that passive solar behaviour together with the energy behaviour of green façades are the most crucial aspects when designing and defining green façades. In this sense, Table 4.6 compiles the evaluation of the contribution of each of the case studies to comfort temperature and reduction in energy demand to show the appropriateness of each of them. The spider graphs illustrate this contribution: red lines illustrate specific orientations [in the case of Rue des Suisses apartment the contribution of the north east and north west green façades; in the case of Quai Branly Museum the contribution of the north west oriented façade; and in the case of Arts and Human Sciences Building the contribution of the north and south orientations]. The grey hatched graphs show this contribution of those green façades to the four orientations.

Finally, the application of the framework to the selected case studies provides a first set of criteria to help determine the most appropriate green façade for a specific project and, at the same time, acknowledges the need for further research studies in all of the identified areas.

4. Application of Green Façades Framework
Comparison of the Appropriateness of the five selected examples of green façades, regarding their contribution to comfort temperature and reduction in energy demand

<table>
<thead>
<tr>
<th>Green Façades attached to an opaque wall</th>
<th>Green Façades attached to a transparent wall</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Image 1]</td>
<td>![Image 2]</td>
</tr>
<tr>
<td>![Image 3]</td>
<td>![Image 4]</td>
</tr>
<tr>
<td>![Image 5]</td>
<td>![Image 6]</td>
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</tbody>
</table>

Table 4.6 Overview of the contribution of the five green façade case studies to comfort temperature and reduction in energy demand, showing their appropriateness

4. Application of Green Façades Framework
5 CONCLUSION

5.1 Overview of the thesis

This thesis opens a larger range of questions than those that designers usually ask when designing green facades. From these, this section extracts two main conclusions:

- **Types of green façades.** This thesis provides a relevant classification of green façades belonging to the two main categories: opaque and transparent green façades. This classification is achieved by analysing the current practices for building green façades, studying a series of existing examples, and identifying their systems of construction.

- **Decisive attributes in green façades.** Of all the analysed opportunities the thesis identifies, the most determinant attribute is human comfort, specifically comfort temperature and reduction in energy demand. This is mainly because it is the attribute that more specifically refers to passive architecture, in terms of different façade orientations and options for taking advantage of solar energy. Moreover, among all the analysed attributes, which are based on a series of research studies, the most deeply studied relates to human comfort.

The thesis proposes a framework which combines these two findings, the one extracted from the current practices of green façades and the other extracted from related research. This brings clarity to evaluate the appropriateness of each type of green façade. This is indeed the most relevant contribution of this thesis: to provide an understanding of why a particular type of green façade, such as opaque, performs better in a north orientation, while other types of green façades, such as transparent façades, function better for south, east and west orientations.
This framework also reveals clear differences between the behaviour of the two main categories: opaque green façades and transparent green façades. It shows how opaque green façades can only partially meet many of the identified attributes. This is mainly due to the fact that opaque green façades only affect one side of the façade, the outside, while transparent green façades affect both the inside and the outside. It also reflects the less fulfilled opportunities, which are the enrichment of the indoor and outdoor relationship and the contribution to air and water quality. This is mainly because none of the existing green façades has incorporated any flexible systems nor has the option of retaining rain water or treating the grey water used by the building been considered.

The thesis attempts to combine the current practice of green façades with the current research on green façades. Apparently these two aspects work independently without interacting with one another. The current practices seem to be more concerned with exploring the expressive capacity and research on exploring the influence on human comfort. This thesis, by combining both and evaluating them, intends to provide a deeper study of green façades in order to improve the present status.

Going back to the two questions raised in the beginning of the thesis: Does the current practice of green façades accomplish the full range of opportunities they embody? And, What are the criteria that enable designers determine the most appropriate green façade for a given context?

The analysis made throughout the thesis, first in a preliminary way in the classification of the current types of green façades, and later more thoroughly in the application of the framework, reveals that the current practices for building green façades do not accomplish the full range of opportunities they might embody. The results from the application of the framework suggest that the current practices for building green façades are ignoring or underestimating many of
possibilities, such as the improvement of human comfort, the contribution to air and water quality, and the enhancement of the indoor-outdoor relationship, among others. The framework suggests current architects, when designing green façades, are primarily concerned with the expressive capacity vegetation provides. Although undoubtedly the natural changeability green façades exhibit is a relevant aspect that leading architects today are exploring, it is important to emphasize that an expressive capacity is not the only opportunity green façades offer.

In this sense, and as for the second question, the framework proposes a set of criteria to determine the appropriateness of a green façade based on the fulfillment of a broader set of opportunities beyond the expressive capacity. These criteria enable a critique of the current practice of green façades, provide solid arguments to distinguish the convenience of the existing types of green façades, facilitate a better understanding of the opportunities, their accomplishment, and their role in a specific context, and, ultimately, help define the most appropriate green façade for a particular project.

5.2 Framework Usefulness, Limitations, and Further Research

5.2.1 Framework Usefulness and Limitations

The development and application of the green façades framework has proved useful in bringing clarity about a broader set of opportunities in green façades beyond their expressive capacity. Through a critique in terms of the fulfillment of the identified opportunities, it allows to determine the appropriateness of a green façade for a specific project.
Through the classification of the current types of green façades and the identification of the opportunities, the framework permits designers to distinguish the appropriateness of the different green façades by understanding why and when one particular type of green façade performs better than others in a given context. It therefore intends to work as a comprehensive tool related to the behaviour of the different types of green façades for the six identified areas. This framework is most useful to combine the type of green façade with the orientation, and in understanding the appropriateness of a particular type for a particular orientation.

Nevertheless, it is important to acknowledge the limitations of the framework. First, there are two important aspects when defining a green façade that have been introduced in the framework in a rather general manner. These are the local climate conditions and the local plant species. The framework clearly evaluates and differentiates the behavior of a green façade for the different orientations, but it also contributes to further studies on local climate conditions as a means of determining whether, for instance, it is more important to achieve a higher thermal insulation than to allow solar energy to pass through the façade, or vice versa. In the case of local plant species, the framework divides them quite generally into three main groups – shrubby, grassy, and climber plants. There is a need for further research on the suitability of different plant species to enhance local species and on their behavior and maintenance to inform different construction systems.

Another major limitation of the framework is that much of the research on which it is based on is not research focused specifically on green façades. Rather, the framework extracts and extrapolates data from related research studies on Urban Forests and Green Roofs. This suggests a major need and opens the door for future research in all of the identified areas of the framework.
5.2.2 Further research

The proposed framework and its limitations demonstrate the need for further green façade-related research in all areas identified in the framework: Human Comfort, Expressive capacity, Air and Water Quality, Indoor-Outdoor relationship, Urban Biodiversity, and Carbon Neutral Architecture. This would help improve the framework, adjusting its usefulness, and providing a better understanding of the behaviour of green façades. Further research themes and extrapolations are detailed below.

- Human Comfort

The different aspects within Human Comfort are the most studied with specific reference to green façades, especially the influence of green façades on comfort temperature. However, these research studies are usually focused on analysing the behaviour of west oriented green façades attached to an opaque wall [A. Hoyano, 198879 and Di and Wang, 199980]. This suggests a need for more research on the influence in comfort temperature and reduction in energy demand for north, south, and east orientations, and for all the different types of green façades.

Moreover, the rest of the aspects affecting human comfort, such as acoustic influence, visual comfort, and psychological benefits require more specific research, since the data used have been extracted and emulated to the behaviour of the influence of a dense tree belt [Huddart, 199081], of blinds in windows [Serra and Coch 199582], and natural scenes [Kellert and Wilson]83 respectively.

82 Rafael Serra and Helena Coch. Arquitectura y energia natural. UPC , Barcelona, 1995
The influence of green façades on increasing humidity in the environment is in need of more research to clarify the results observed in two contradictory studies [A. Hoyano, 1988\(^{84}\) and G.A.C. Cantuaria 2000\(^{85}\)].

- **Expressive capacity**

Although this thesis argues that the expressive capacity that relies on green façades is the main reason for the current use of green façades, the framework needs to be able to evaluate more factors to explain whether one green façade integrates better than others within its surroundings; whether it answers more effectively to a specific urban context than others; and whether the textures and different grades of openness and closeness they provide perform better in some situations than others. Therefore, the framework demands further analysis in this area acknowledging the lack of criteria for evaluating green façades.

- **Air and Water Quality**

There is a need for further research on the specific project of green façades regarding the contribution of green façades to air quality, since the current framework is based on related studies made on Urban Forests [McPherson and Nowak, 1994]\(^{86}\) and Urban Biodiversity [Schaefer 2004]\(^{87}\). In addition, based on the latter study – urban biodiversity – the framework considers the capacity of plants to trap air pollutants dividing them into three main groups.

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\(^{87}\) Valentin Schaefer, Hillary rud, and Jamie Vala. *Urban Biodiversity*. Captus Press, Ontario 2004
[shrubby plants as higher contributors, climber plants as moderate contributors, and grassy
plants as lower contributors]. In this sense, more detailed studies are claimed to differentiate
this contribution, for instance, within the capacity of climber plants to trap pollutants.

In the case of water quality, similar conclusions could be extracted from the capacity of
different plant species to trap and filter water pollutants. But the major need for further
research relates more to the fact that none of the analysed green façade systems incorporates
any way of treating the grey water used by the building, nor of retaining the rainwater for the
watering of the green façade, for example.

- **Indoor – Outdoor relationship**

Together with the opportunity for green façades to contribute to air and water quality, the indoor-
outdoor relationship is the less fulfilled of the opportunities by the current practices for building
green façades. This is mainly due to the general rigidity of current green façades. This fact opens
the door to seek and investigate more flexibility within green façade systems, introducing
movement to the façade, such as sliding or rotating green façades.

- **Urban Biodiversity**

In terms of Urban Biodiversity, further research is needed regarding what types of green façades
contribute more to enhance biodiversity, relating it to the selection of plant species. Another
aspect to be included in urban biodiversity would be the relationship between the scale of the
green façade and its contribution to urban biodiversity. By doing so, it would be interesting to
compile data for the minimum green façade surface required to achieve a minimum level of
biodiversity, and how this relationship would increase by increasing the green coverage. This
would strengthen the intuitive evaluation currently considered by the framework.
There is another emerging concept related to urban biodiversity, which is the contribution of green façades to urban agriculture. Some recent research and architectural projects suggest the possibility of cultivating green façades, known as "vertical farms." In current times where peak oil consumption is said to be approaching and thinking of a world beyond oil is emerging, the notion of reinforcing local products and local food is becoming stronger and stronger. In this context, the option of vegetated and cultivated façades could turn into an important element, becoming a sort of vertical community garden maintained by the community, although this would raise other problems such as the management of the façade, etc. However, it is still a new fascinating way of looking at green façades.

- Carbon Neutral Architecture

In terms of Carbon Neutral Architecture, more research is needed to determine the life cycle of green façades. Not only the consideration of the fabrication process of the greenery, which is likely to be in plant nurseries, but also the life cycle and carbon cycle of the rest of the components of the green façade, such as the materials used to guide the growth of plants - metallic mesh, steel wires, etc - or the materials for plant pots, etc. It would also be interesting to obtain data on the contribution of green façades to sequester carbon. Very little has been researched in this field, most likely because all the related research studies suggest that this contribution would be insignificant.

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