Adaptive Façades

An Integrated Algorithmic Approach

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Thesis to obtain the Master of Science Degree in

Architecture

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Declaration

I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.

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Abstract

The concept of architectural performance comprises an understanding of the interaction between the built and natural environments. Over the past decades, design practices started envisioning the future of façade conception through the use of environmentally reactive components. Covering solutions that vary in terms of materials, components, and systems, adaptive façades provide new aesthetic opportunities by offering the potential to reduce energy demands while enhancing the indoor comfort. However, as traditional simulation tools target the design of static geometries, and adaptive façades encompass an envisioned movement of construction elements, there is a lack of supporting tools and workflows that can correctly evaluate the performance of these systems at an early design stage.

On the other hand, there is a growing potential in Algorithmic Design (AD) strategies, which remains largely unexplored in the architectural context, regarding both early design stages and the modeling of adaptive façades. The presented research aims to develop a unified AD and analysis workflow for the energy performance assessment of adaptive façades. The goal is to further reduce the current gap between form-finding and analytical tasks during project conception, through the adoption of a performance-based design approach. We show that the goal is attainable by integrating the generation of parametric models and the execution of energy simulations into a single algorithmic description, evaluating and using the simulation results to develop optimized control strategies.

Keywords: Building performance simulation, Adaptive façades, Algorithmic design, Energy analysis.

Resumo

O conceito de desempenho arquitectónico parte da observação das interacções entre a natureza e o ambiente construído. Nas últimas décadas, os gabinetes de arquitectura começaram a utilizar componentes reactivos às condições ambientais para o design de fachadas. Abrangendo soluções que variam em termos de materiais, componentes e sistemas, as fachadas adaptativas estabelecem novas alternativas de projecto com o potencial para reduzir gastos energéticos, melhorando o conforto no interior do edifício. No entanto, dado que as ferramentas de simulação tradicionais visam o design de geometrias estáticas e que as fachadas adaptativas abrangem um movimento previsto de elementos de construção, as metodologias de análise existentes não são adequadas para avaliar correctamente o desempenho destes sistemas numa fase preliminar do projecto. Por outro lado, existe um potencial crescente em estratégias de design algorítmico (DA) que permanece, em grande parte, inexplorado no contexto arquitectónico, tanto na sua aplicação em fases iniciais do projecto como na modelação de fachadas adaptativas. Esta dissertação tem como objectivo a diminuição da separação entre tarefas de design e análise, através da adopção de estratégias focadas no desempenho de edifícios. Para tal, propomos uma metodologia que integra DA e análises de desempenho energético para este tipo de fachadas. Mostramos que o objectivo é alcançável ao integrar a geração de modelos paramétricos com a execução de simulação energética numa única descrição algorítmica. Os resultados são avaliados e utilizados para desenvolver estratégias de controlo optimizadas.

Keywords: Simulação de desempenho, Fachadas adaptativas, Design algorítmico, Análise energética.

Contributions

During the development of this master thesis, the following scientific article was published:

- Martinho, H., Leitão, A., Belém, C., Loonen, R., and Gomes, M. (2019). Algorithmic Design and Performance Analysis of Adaptive Facades. In Proceedings of the 24th International Conference of the Association for Computer-Aided Architectural Design Research in Asia (CAADRIA) - Volume 1, Victoria University of Wellington, New Zealand, 685-694.

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INTRODUCTION

The physical environment is composed by several climatic elements tangled into a complex relationship. Man strived to adjust himself to this environment by finding a biological equilibrium: the shelter was the main instrument for fulfilling physiological needs, by filtering, absorbing, or repelling environmental elements according to their beneficial or adverse aspect towards human comfort (Olgyay, 1963). Nowadays, the concept of shelter is further associated with principles of sustainability, not only emphasizing the reduction of operational and utility costs, but also concerning the environmental damage produced by a building's form and materiality.

Architectural design is known for the need of compromise. Adjusting a building to its surroundings comprises an understanding of the energy flows around it, as the interaction between the built and natural environments outlines the concept of architectural performance. The need for more informed decision-making processes propelled the emergence of performance-based design strategies, as a guiding form-finding principle grounded in two aspects: (1) the quantitative aspects of building design (e.g., structure, acoustics, or energy use), and (2) the qualitative factor of design aesthetics and the reaction to hypothetical environmental conditions. However, different performance goals are often conflicting, which calls for creative and effective architectural design solutions (Kolarevic, 2004). Foster and Partner's London City Hall (Figure 0.1), for instance, has an optimized energy performance due to the minimization of solar heat gain. Its façade

Figure 0.1: London City Hall (2002), by Foster and Partners (source: https://www.fosterandpartners.com/projects/city-hall/).

has a 25% smaller surface area than a cube of identical volume, with slim elevations facing East and West to avoid exposure to low sun angles (Figure 0.2). Moreover, the addition of a spiral ramp (Figure 0.3) around the atrium, which separates the offices from the public space, resulted in the leaning of its glazed surface outwards, significantly improving the building's

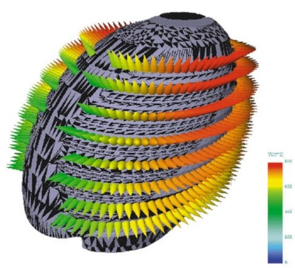


Figure 0.2: Solar diagram for the London City Hall (source: Kolarevic and Malkawi (2005)).

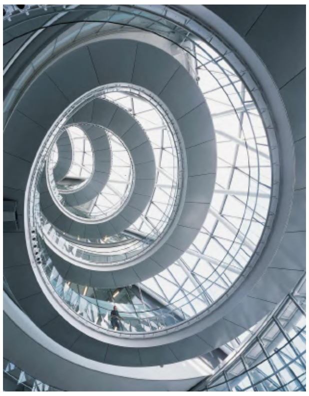


Figure 0.3: Spiral ramp inside the London City Hall (source: https://www.fosterandpartners.com/projects/city-hall/).

acoustic performance (Oxman and Oxman, 2014). These aspects make this building a relevant example in the context of performance-based architectural design.

In an architectural context, weather variations and the fluctuating needs of occupants call for an aptitude of adaptation and change. As the utmost frontier between interior and exterior environments, the façade is a key element to control indoor comfort and energy use. However, while most of the constraints acting upon the façade change over time, architectural design strategies often focus on static solutions, attributing a single geometry as fit for all possible external conditions (Vergauwen et al., 2013). Such results in the need to adjust buildings through their life cycle, in order to address environmental, economic, and operational problems.

Developments in artificial intelligence and new building technologies led to the emergence of an *intelligent architecture* which, through integrated systems and automation, can anticipate and respond to conditions that affect the performance of the building and its occupants (Kroner, 1997). Over the past decades, architectural practices started envisioning the future of façade design through the use of environmentally reactive components. Covering solutions that vary in terms of materials, components, and systems, adaptive façades can repeatedly and reversibly change certain features over time. This aptitude provides new aesthetic opportunities for the reconfiguration of interior spaces, by offering the potential to reduce the energy demand while enhancing the indoor comfort.

As the concept of adaptive façades rises into consideration, it is important to find an efficient way to predict the combined benefits and constraints of specific design propositions. Such requires an understanding of the complex and dynamic interactions between design, performance metrics and local climate variables. When there is no possibility of experimenting a system under particular circumstances, building performance simulation (BPS) can aid to reach some degree of predictability over the effects of external contingencies on buildings. However, modeling and simulation approaches for adaptive façade assessment are still at an early stage of development, with many aspects yet to be explored.

Motivation

The digital engagement of time and movement in architecture was developed around tactics of geometric transformation. When designing a static façade, geometric transformation is a design method. When it comes to adaptive façades, it is a design outcome, as a shifting pattern of geometries in a constant state of motion (Moloney, 2011).

Successfully designing an adaptive façade is a challenging task. This is partly due to the lack of understanding over the risks and benefits of these systems. Existing BPS tools were not originally developed to model non-static geometries and, consequently, give limited guidance in terms of modeling assumptions (Loonen et al., 2017). Thus, there is a need to further improve simulation-based design strategies, aimed towards the development of adaptive façade technologies.

There is a growing potential in Algorithmic Design (AD) strategies which remains largely unexplored in an architectural context, both regarding early-stage design and the modeling of adaptive façades. These strategies rely on the use of algorithms to describe designs, enabling the modeling of complex shapes with little effort. AD is, therefore, grounded in the application of rules, constraints, or a coherent combination of procedures to manipulate variable parameters in building geometries. While not all architects are familiar with custom-written computer code, the integration of AD strategies allows to change geometric and analytic models almost simultaneously, and also to automate the generation of these models. In the past, this methodology was applied to lighting and structural performance analysis (Castelo Branco and Leitão, 2017; Caetano et al., 2018). Our research extends it to also include energy performance simulations, and their application in design strategies for adaptive façades.

Objectives

The presented research aims to develop a unified AD and analysis workflow for the energy performance assessment of buildings with adaptive façades. The goal is to further reduce the current gap between form-finding and analytic tasks during project conception, through the adoption of a performance-based design approach. To that end, we integrate the generation of parametric CAD models and the execution of energy simulation into a single algorithmic description.

We propose an algorithmic strategy that aims to cover the most pertinent stages of an architectural project. This approach is divided into three parts: (1) the generation of a model through an AD tool, describing the geometry of a building with an adaptive façade, (2) the impact assessment of the façade's geometrical variation in the building's energy consumption, and (3) the definition of an optimal adaptive control system, determining the most favorable façade configuration depending on the outside conditions.

Through the proposed approach, the implementation of design changes can be achieved in shorter timespans and with less work from the project team. Moreover, the access to feedback over the performance of multiple design solutions is facilitated, as simulation is executed right after the geometry is generated.

Methodology

To achieve the objectives defined above, this thesis was developed in five stages: (1) literature review, (2) definition of the AD approach, (3) validation of the methodology, (4) application of the methodology to a case study, and (5) evaluation and conclusions.

The literature review, as a first step, outlines an extensive research on the various subjects that motivated the development of the work presented in this thesis. The evolution of sustainability in the built environment is briefly described, from the early application of bioclimatic strategies to the emergence of performance-based design. The potential of AD and BPS is presented, and their application in an architectural environment is discussed. We summarize the main adaptive façade characterization methods, along with a review of current modeling and analysis methods.

Secondly, we introduce and describe an AD strategy which aims to bridge the identified research gaps. The approach is divided into different tasks, which are thoroughly explained so that architects can follow it.

The third stage comprises a validation procedure for the proposed methodology, to assess basic functionalities for energy simulation. For that end, we apply an inter-model comparison technique based on well-known case studies. The simulation results are discussed and evaluated.

After validating the AD approach, we apply it to a second case study which incorporates an adaptive façade. The application of the methodology implies the algorithmic modeling of the design for a CAD application, along with the integration of analysis results in the design process. We explain the modeling and simulation processes of the case study and the advantages found in the use of this methodology.

The last stage of this thesis reviews the presented work, evaluating the advantages and disadvantages of its application in architectural design. We conclude by exposing the final considerations, as well as future prospects and suggestions for further development of this research.

Structure

The first part – **Background** - is divided into three chapters:

1. **Sustainability in the Built Environment |** The first chapter describes the origin of the term 'sustainability'. The concept of bioclimatic architecture is introduced, followed by a brief description of passive building design strategies for heating, cooling, ventilation, and daylight. Energy efficiency and indoor environmental quality aspects are also emphasized, regarding their main trade-offs and sources of uncertainty.

2. **Performance-Based Design |** Following the previous chapter, we illustrate the performative aspect of architecture, from design strategies to building performance simulation. A series of energy analysis tools are presented and compared. We conclude the chapter by assessing the need for integrated design approaches.

3. **The Building Envelope |** Here, we start by describing the main functions of the façade. Inspired by the evolution of natural organisms, we introduce the concept of adaptability in construction. A series of classification systems for adaptive façades is presented, along with illustrative examples. Lastly, we briefly comment on current modeling and simulation strategies for this type of construction.

The second part – **Framework** - is divided into three chapters:

4. **Workflow |** This chapter provides a description of the methodology applied in the present research, which is divided into three stages: (1) Algorithmic Design, (2) Algorithmic Analysis, and (3) Algorithmic Optimization. We conclude by presenting a brief description of the tools considered for this study.

5. **Validation Study |** We assess the proposed workflow through an inter-model comparative approach. This chapter includes a case study from the Building Energy Simulation Test (Judkoff and Neymark, 1995), a well-developed diagnostic method to determine the appropriateness of energy analysis programs.

6. **Case Study: The Arab World Institute |** The final chapter describes the modeling and simulation of a second case study, which incorporates an adaptive façade inspired by Jean Nouvel's Arab World Institute. The application of the workflow described in chapter 4 is further evaluated, based on the analysis and optimization results.

PART I

BACKGROUND

CHAPTER 1

Sustainability in the Built Environment

Architecture is depended on a satisfactory reconciliation of the intuitive with the rational. A building has to be both a poem and a machine. Yet, few buildings achieve such a status. There are those that are sensually stimulating but lack sound construction and those that answer successfully practical needs but fail to generate an emotional charge.

V. A. Metallinou

The dialogue between architecture and nature is as old as architecture itself. By seeking shelter from the elements, humans began constructing from local resources and, with time, perceiving universal laws of proportion in their surroundings. Through *De Architectura Libri Decem*, around I B.C., Vitruvius advocates that an architect should not only show skill in craftsmanship and technology, but also be aware of the environmental constraints of a building, understanding the contextual features of the location site and its climate variations. However, over time, the focus shifted towards the convenience of easily accessing energy and resources.

With the invention of the steam engine, the relation between nature and the built environment faded into a stage where human activity started to strongly impact, possibly irreversibly, several climate systems. The social and environmental burden of industrialization through mid-19th century reflected itself in the architecture of that time, leading John Ruskin to expose a general disillusionment regarding the impersonal, mechanized direction of society. Following this thought, William Morris greatly influenced the *Arts and Crafts* movement, which rose as an effort to reform society's priorities regarding the manufacture of objects. Morris' ideals were associated with a design approach that followed "first, diligent study of nature, and, secondly, intelligent study of the work of the ages of art" (Morris, 1898, p.22). Principles of fitness for purpose and integrity of materials were of fundamental importance, transforming the design task into a democratic instrument and a driver for social change. To these ideals, architects of the Arts and Crafts movement added a sense of response in the application of Morris' philosophies to the design of buildings (Metallinou, 2006).

The core environmental concerns of today were already present in modern architecture, though rarely brought together as comprehensively. A growing population of urban dwellers in the 20^{th} century resulted in a shortage of fuel, energy and materials, as well as problems of health and hygiene. Much of early modern architecture was executed before the possibility to mechanically regulate interior living conditions - such was accomplished through the optimization of building form and orientation, along with the incorporation of layered façades and natural shading (Bone et al., 2014). The embracing of natural surroundings brought forward design strategies that respected the fundamental relationship between architecture and time-varying solar patterns. There was, however, both a passionate concern over certain ecological matters and a complete disregard for others (Rifkind, 2014). One example is Mies van der Rohe's Farnsworth House (Figure 1.1): until the implementation of corrective measures in 1970, the sun-screening was solely provided by the foliage of adjacent trees and there was both a lack of adequate cross-ventilation and passive heating measures. Despite

Figure 1.1: The Farnsworth House, 1950 (source: https://www.archdaily.com/59719).

the architect's desire to bring the building, its occupants and the landscape together into a 'higher unity', the house performed poorly in both mid-winter and mid-summer (Blaser, 1999). Likewise, Le Corbusier promoted the integration of the natural and built environments: however, landscapes were treated as objects of contemplation from, rather than continuous with, their architectural counterparts.

In *The humanization of architecture* (1940), Alvar Aalto critiqued the functionalism of modern architecture for its emphasis on the economic side of construction, leaving aside the harmony between human life and the material world. A more methodical and artistic architectural investigation was pointed out as an aid to combine the technical rationalization with the human and psychological point of view of a project. The concern over the production of pleasing, healthy environments led Aalto, in 1953, to use his summer residence (Figure 1.2) for an experimental study of materiality in construction, observing how changes in aesthetics reacted in a rough climate. Although achieving inconclusive climatic results, the house's courtyard worked as a climatic device to cool the interior spaces[1]. Here, the purpose was to assure a stronger connection between nature, organicity, and the interior-exterior exchanges. But only in the 1980s, after a global energy crisis a decade prior, did the general concern rise over the environmental damage produced by a building's form and materiality. The term 'sustainability' surged as an acknowledgement of the effects of design choices on a building's energy efficiency, bringing forward new methods that strived to reduce the unsustainable excess and consumerism of the society.

Figure 1.2: Muuratsalo experimental house, Alvar Aalto, 1953 (source: https://en.wikiarquitectura.com/building/house-in-muuratsalo).

1.1 Bioclimatic Architecture

Adjusting a building to its natural surroundings comprises an understanding of the energy flows around it. Olgyay (1963) advocated that bioclimatic[2] evaluation was the starting point for any architectural design aiming towards a balanced shelter (Figure 1.3). In other words, architectural expression should be proceeded by the systematic connection of three scientific areas:

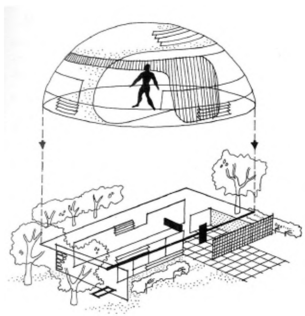


Figure 1.3: Theoretical approach to balanced shelter (source: Olgyay (1963)).

[1] https://melissajbrooks.wordpress.com/2015/04/11

[2] Concerning the relations between climate and living organisms. Source: Collins (2018)

(1) psychology, to establish comfort requirements, (2) climatology, to review existing climate conditions, and (3) engineering, to attain rational design solutions. Bioclimatic architecture, therefore, aims at the construction of buildings that are in harmony with the natural surroundings and local climate, while ensuring comfort conditions for its occupants.

To many architects, it is far from clear how environmental matters translate into action at the level of design strategies and the singularity of an architectural form. Following the rise of concerns over the sustainability of buildings and their construction, Ken Yeang summarized bioclimatic design into three main approaches (Yeang, 1998). The first and of utmost importance was the design for efficient operation costs, considering energy resources, building materials, and space configuration. Secondly, the concern for building first costs[3], aiming for the choice of equipment and assembly plans of low environmental impact. Finally, the architect should consider the building's end use from a reuse and recycle perspective. An illustration on this exercised connection between necessity and conscience is the Solaris building (Figure 1.4, top), in Singapore: designed for a hot and humid climate, the attention was focused on the high average rainfall in the area. Such resulted in the creation of a rainwater recycling system which covers, almost entirely, the watering necessities of the building's plants (Widera, 2014). The study of sun paths aided the reduction of cooling loads through the placement of shading elements, and lighting loads by the addition of a light shaft in the center of the building (Figure 1.4, bottom).

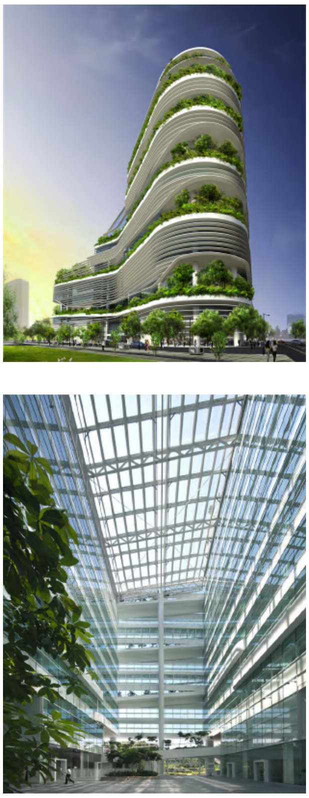
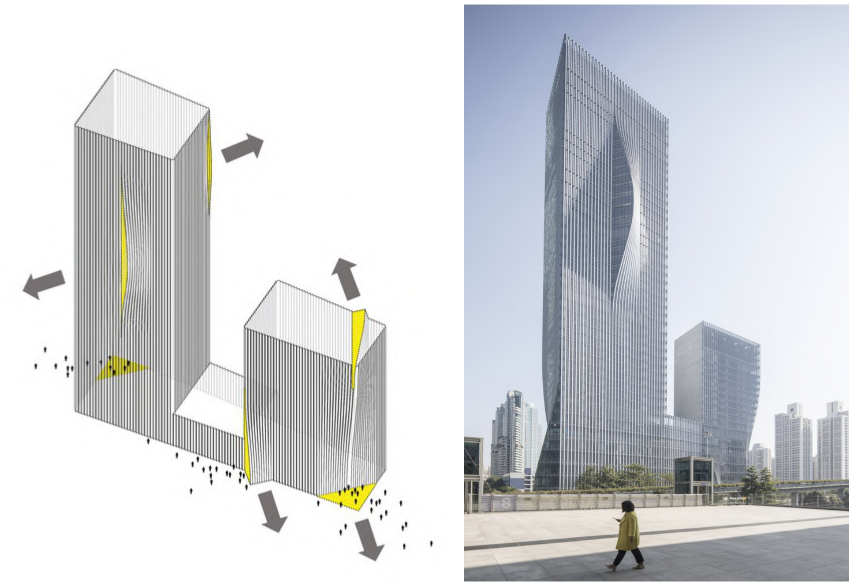


Figure 1.4: Solaris, by TR Hamzah & Yeang. Rendered image (top) and detail of the atrium (bottom) (source: http://blog.cpgcorp.com.sg/?p=2118/).

In a contemporary architectural paradigm, we can identify many examples of bioclimatic form-finding approaches. The Mediterranean architecture of Luis Barragán reflects the site location and climate into both interior and exterior dispositions, with a concern for natural illumination and the use of regional materials (Avila, 2006). On a similar insight, Bjarke Ingels Group (BIG) focuses on maximizing daylight and views while minimizing direct sun exposure and glare. In the Shenzhen Energy Mansion (2018), the subtropical climate of southern China is bypassed through the design of façade extensions that open to North, creating additional viewpoints while also blocking solar radiation from South (Figure 1.5). The inherent design properties give the building a better performance in terms of energy use, projecting a 30% reduction on air conditioning expenses (Ingels, 2015).

Designed in collaboration with Extra Muros SAS d'Architecture, SANAA's winning competition scheme for the Maréchal-Fayolle housing complex (Figure 1.6) comprises over 100 apartments in a mixed space

[3]The sum of the initial expenses involved in capitalizing a property, including transportation, construction, and land acquisition costs. Source: (Dade, 2002).



(a) Diagram of entrances and views. (b) Ground perspective.

Figure 1.5: Shenzhen Energy Mansion, 2018 (source: https://www.archdaily.com/899785).

between nature and urbanity, located in the city of Paris. Instead of being organized into a single block, the living space is separated into four smaller sections for additional natural light, ventilation, and views. As one of the main goals, a pleasant living environment is associated to the curved and generous design of the façades, which fill the interior space with diffused light, as well as to the courtyards, built as extensions of the forests for a stronger connection between the occupants and nature.

(a) View from above. (b) View from the courtyards.

Figure 1.6: Maréchal-Fayolle housing complex, 2009 (source: http://www.pavillon-arsenal.com/en/videos/11200-67-program-100-social-housing.html).

The aforementioned examples result from design strategies that favor a limited use of mechanical or very elaborate systems, which can create higher maintenance costs in the future. Such approaches are put in practice by first looking into the building's general context, to understand how to take advantage of open viewpoints, natural lighting, and small improvements regarding the insulation and air-tightness of building envelope elements. These strategies are highly sensitive to meteorological factors and, therefore, imply a broader understanding of the climatic factors.

1.2 Passive Design Strategies

Bioclimatic design is based on analysis of the climate, including the ambient energy of sun, wind, temperature, and humidity. As a very known present-day challenge, climate change foreshadows an increase in the severity and duration of extreme weather conditions. Weather uncertainty and warming trends should be anticipated in building design, as they result in a very rapid consumption of conventional energy sources. The heating or cooling of a space to maintain thermal comfort accounts for as much as 60–70% of total energy use in non-industrial buildings. Of this, approximately 30–50% is lost through ventilation and air infiltration (Omer, 2008). Passive building design strategies can be of significant help in reducing the building's energy requirements, as they rely on natural resources such as sunlight, wind, and vegetation (Figure 1.7).

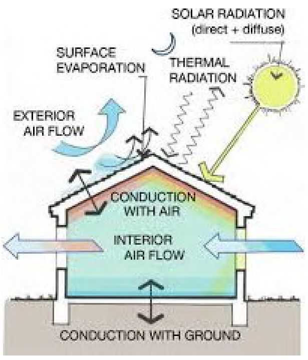


Figure 1.7: Paths of energy exchange at the building microclimate scale (source: Watson and Labs (1983)).

The term *passive design* comprises the use of all possible measures to reduce energy consumption before recurring to any external energy source, thus defining the energy character of the building prior to the consideration of active or mechanized systems (Kibert, 2012). Different strategies are required for the various seasons, as they affect the need to promote or minimize heat loss and solar gains. The main concepts for heating, cooling, ventilation, and daylight passive design techniques are described below.

HEATING

In colder climates, it is important to minimize the surface area through which heat can be transmitted. Reducing the conductive heat flow can be achieved by improving the building's thermal mass: materials with high heat capacity as brick, concrete, and adobe can absorb solar energy during the day and release it in the evening, as temperature begins to decrease. A correct building orientation towards site-specific sun angles allows the use of interior spaces to collect, store, and transfer solar heat. Other passive heating approaches include providing wind breaks to diminish the external air flow, and preventing infiltration caused by uncontrolled air leakage in the building envelope (Watson, 1989).

COOLING

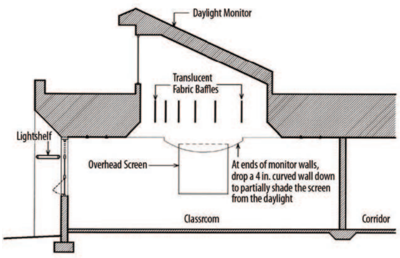
Rather than allowing heat to enter the space, passive cooling approaches target heat gain prevention and endorse heat dissipation. Solutions focus on (1) protecting the building from direct solar radiation, (2) minimizing internal gains caused by occupancy, lighting, and equipment and (3) avoiding external gains from infiltration or conduction. Moreover, (4) natural cooling techniques such as radiant cooling, evaporative cooling, and earth coupling combine the design of building components with the use of natural energy sources, helping to reduce the need to dissipate heat through mechanical systems (Watson, 1989).

VENTILATION

Ventilation is essential for securing good indoor air quality, but it can have a dominating influence on building energy consumption. Active strategies as the use of HVAC rely on mechanical systems to move external air into the building, while at the same time removing an equal amount of internal air to the outside. Passive ventilation, on the other hand, is accomplished through the use of natural forces to move external air into the indoor space, significantly reducing the building's energy demand. Such can be achieved through cross-ventilation, using wind flow to develop a low pressure zone and induce air movement, or stack-effect ventilation, creating a vertical air flow driven by the buoyancy of heated air (Kibert, 2012).

DAYLIGHT

The use of natural light for illumination not only provides psychological benefits to building occupants, but also greatly reduces the expenses from the use of artificial lighting. Climate consideration is paramount for passive daylight design, as it involves a compromise to meet a range of sky conditions expected in the building site. Visual discomfort and glare can be minimized through the introduction of shading elements, while light penetration can be controlled through the design of skylights, courtyards, and atriums. Such strategies aid to balance light levels across the interior space by reflecting, directing, or diffusing the sunlight. The design strategy for Smith Middle School (Figure 1.8), for instance, made use of daylight monitors to capture exterior sunlight, and translucent fabric baffles to diffuse it into the classrooms, achieving a 64% reduction in electric lighting (Nicklas, 2008).



(a) Roof monitor with baffles.

(b) Classroom daylight outcome.

Figure 1.8: Sawtooth-roof daylight strategy for the Smith Middle School, North Carolina (source: Nicklas (2008)).

1.3 Indoor Environmental Quality

The architectural design process refers to the translation of program requirements into graphical plans that can range from the scale of a room to the scale of a city (Kaye, 1975). Considerations regarding building occupant needs and their physical perception of spaces contributed for the emergence of environmental psychology, a research field aiming towards the finding of quantitative indicators for the effect of the built environment in human response (Yalçin, 2015). Although this information can potentially guide design decisions towards more user-centered solutions, the engagement of occupants is often considered only when the formal characters of a building have already been resolved (Altomonte et al., 2015).

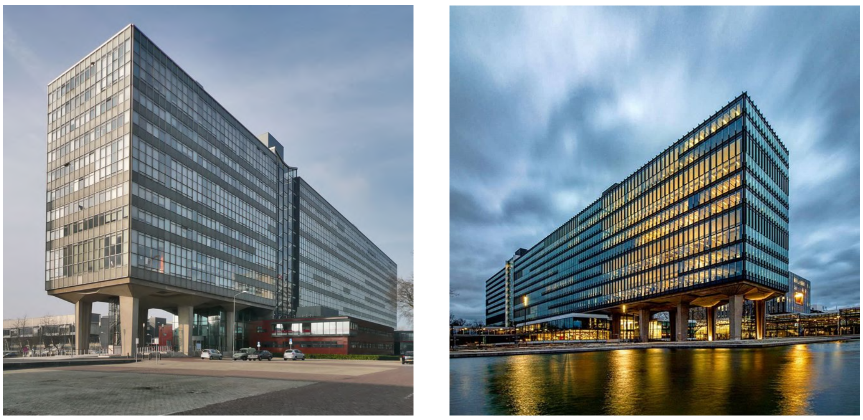
Better performing buildings should not only be sustainable and energy efficient, but also target occupant comfort and well-being. Several human response factors are strongly related to the Indoor Environmental Quality (IEQ) of buildings, commonly referring to design and operation approaches to achieve thermal, lighting, and acoustic comfort, as well as indoor air quality (Brager, 2013). In working environments, for instance, visual comfort strategies as the incorporation of views or the integration of natural elements can result in a higher IEQ, reducing degrees of tension and anxiety while improving health and productivity (Chang and Chen, 2005; Al-Horr et al., 2016). The psychological benefits of daylight are also frequently addressed in literature, specially regarding the design of educational and healthcare spaces (Wu and Ng, 2003; Choi et al., 2012). Moreover, the perception of indoor air quality was found to be related to changes in the thermal conditions of a space, suggesting that lower indoor temperatures can reduce ventilation demands (Fang et al., 1999). Given the complexity of building occupancy, user requirements should be carefully valued and understood by a participatory decision-making approach, bridging gaps between disciplines and resulting in fewer setbacks in the later stages of an architectural project.

1.4 Energy Efficiency

Accounting for approximately 40% of energy consumption and 36% of CO_2 emissions in the EU, buildings nowadays are increasingly expected to meet both energy-efficient and environmentally-friendly design requirements. Towards the minimization of damaging consequences from current consumption and investment activities, it is expected that by 2040, most buildings will need to be either highly efficient or have deep energy retrofits (IEA, 2018). Future policies focus on using renewable energy, enhancing the performance of existing buildings or developing information and decision-making tools for building owners and operators.

In the last few decades, sustainable architecture has grew beyond the concern to reduce utility and operational costs. Principles of social and ecological sustainability have gained presence within the architectural thought, turning the negative environmental impact of buildings into a relevant matter. Passive design strategies progressed towards concepts such as the Net Zero Energy Building (NZEB) and Positive Energy Building (PEB), with various innovative energy-efficient technologies that can be considered for building performance improvement (Kolokotsa et al., 2011). A central notion within NZEB/PEB is that a building can meet its energy requirements from locally available, non-pollutant renewable sources, generating enough energy on site to equal or exceed its annual demand (Cole and Fedoruk, 2015).

As the winner of the 2017 BREEAM[4] award, Team V Architecture's refurbishment of the Atlas building (Figures 1.9 and 1.10) turned a mid-20th century semi-vacant construction into one of the world's most energy-efficient and sustainable buildings. Such is due mainly to the incorporation of intelligent systems and innovative material applications, as the new curtain wall of the façade. The triple-glazed windows have an incorporated heat-reflective coating, providing spaces with natural light while maintaining a healthy environment for its occupants. When night weather conditions are favorable, the windows slide out to cool the building and purify the air. Atlas also retrieves energy from solar panels placed on roofs, which cover most of the building-related power consumption (Eindhoven University of Technology, 2018).



(a) Original construction from 1963. *(b) Refurbished version, 2019.*

Figure 1.9: Atlas Building, Eindhoven University of Technology. Photo credit: (a) Klaas Vermaas; (b) Gordon Thomas Jack.

[4]BREEAM is the world's longest established method of assessing, rating, and certifying the sustainability of buildings. viz. https://www.breeam.com

(a) 1963. (b) 2013. (c) 2019.

Figure 1.10: Evolution of the Atlas Building. Courtesy of the Eindhoven University of Technology and Team V Architecture.

1.5 Trade-offs and Uncertainty

Sustainable architectural design strategies propose a change in the function of the building: the common linear approach of processing natural resources into waste must transition into a paradigm where the building is a self-sufficient unit. The level of complexity of such projects is higher than that of traditional types, given the number of stakeholders involved and the need to balance environmental, economic, and social objectives (Sfakianaki, 2015).

Architectural design is known for the need of compromise, specially in the context of energy criteria. There is still a certain level of disconnection between the concern for a building's energy efficiency and its designed form. Like any concept, passive strategies can be applied improperly to building design: their success is dependent on a careful consideration of building orientation, fenestration, shading, and massing. An ideal building design would consider both passive heating and passive cooling, avoiding commonly associated potential risks as temperature fluctuations, seasonal overheating, poor air quality and unacceptable lighting variation and glare. However, energy consumption and environmental comfort measures are, as well, often in conflict.

Sustainability requirements for contemporary buildings are, to a greater or lesser extent, interrelated. The challenge for architects is, then, to bring together such requirements in innovative ways. The digital revolution offers promise and prospects for new building technologies, although material development and automation are often handled as isolated components which are integrated into otherwise traditional building concepts (Knippers and Speck, 2012). New structural, functional and ecologically efficient buildings may be expected from a more interdisciplinary approach, not only on the level of scientific knowledge, but also on a methodological level within current architectural studios.

CHAPTER 2

Performance-Based Design

I think that in every building, every street, there is something that creates an event, and whatever creates an event is unintelligible. This can also occur in situations or in individual behavior; it's something you don't realize, something you can't program.

J. Baudrillard

Rooted in the mid-20th century, the intellectual movement known as *the performative turn* emerged from the need to conceptualize how human practices relate to their specific context (Hensel, 2013). This movement inspired similar developments in the areas of arts, natural sciences, technology, and economy, ensuing a significant impact in the architectural discourse. Nowadays, there is a very prominent and enduring notion of performance in architecture: but how can we define *performance*?

In recent years, there have been numerous interpretations over the meaning of performance within architectural theory. Kolarevic and Malkawi (2005) defined performance as the manner in which a building acts in a physical, social, and cultural context, regarding its ability to respond to both foreseen and unforeseen changes in external contingencies. In a similar perspective, Leatherbarrow (2008) argued that performance is a matter of technical understanding, tying the operations performed by a building's elements to the appearance and meaning of the overall architectural work. Grobman (2012), on the other hand, proposed a broader definition of the concept, encompassing three performance dimensions:

- Empirical: regarding directly measurable physical data as structural stability, temperature, or illuminance;
- Cognitive: relating to mental functions and processes, focusing on how space can be translated into human cognition and vice-versa;
- Perceptual: regarding the ability of the mind to grasp information through the senses, focusing on how space can be translated into

human perception and vice-versa.

The dichotomy over form and function in architectural design is a recurrent topic of debate. The notion of building program, often maintained as the relation between spaces and activities, is associated with two distinct perspectives: the building is either seen as a fulfillment of formal expectations, where shape, patterning, and ornamentation are of primary importance, or as an assembly of components which serve mainly a technical purpose. Both outlooks lack a full insight over the time- and context-specific variables of a project, which promote continuity between the building and environmental circumstances. Given the material, spacial and temporal connection between a building and its environmental surroundings, a performance-oriented architectural practice requires a balance between a tangible theoretical framework and design strategies and concepts that are adaptable according to context and circumstances (Hensel, 2013).

2.1 Performative Architecture

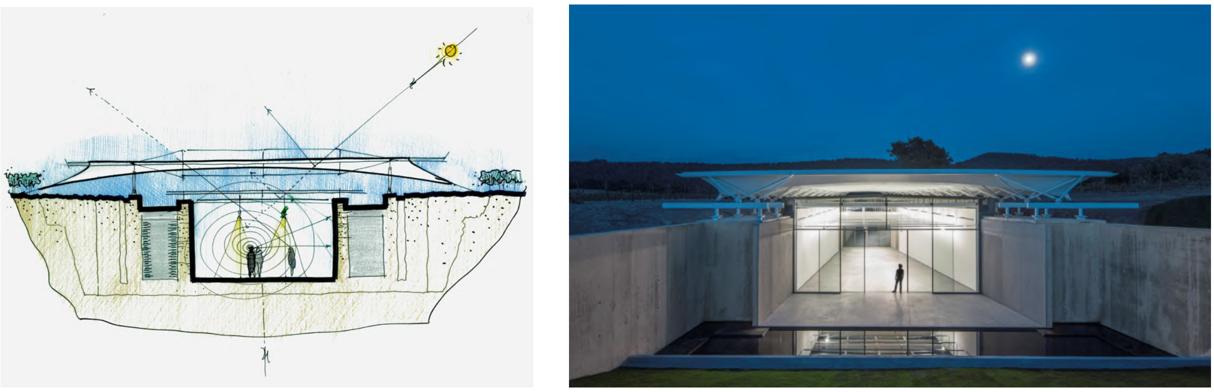
The performative paradigm in architecture is emerging as a guiding design principle, complementing form-finding approaches with a detailed analysis of the interactions between the built and natural environments. Performance-based design strategies are grounded mainly in quantitative aspects of building design (e.g. structure, acoustics or energy use), allied to the qualitative factor of design aesthetics and the reaction to hypothetical environmental conditions. Often, there is a need to reconcile conflicting performance goals in a creative and effective way (Kolarevic, 2004). The following subsections present two examples of contemporary performance-based design practices.

Château La Coste Art Gallery

Figure 2.1: Château La Coste, 2017. (source: http://wearecontents.com/portfolio-items/pavillon-rpbw/).

Located in the vineyards of Aix-en-Provence, the building designed by Renzo Piano was incorporated into the topography through its placement in a six-meter carved valley. Mimicking the graphical layout of grapevines, the metal arches that fasten the roof's sail allow for the remaining exposed geometry to integrate the local surroundings (Figure 2.1). The main gallery, which hosts sculpture and photography exhibitions, is naturally illuminated by the glazed façade, while the roof sail works as a sun-shading system[1] (Figure 2.2). Contrasting to the brightness of this central space, the side galleries are dim-lighted and cold, resulting in optimal conditions for wine preservation.

[1] http://www.rpbw.com/project/chateau-la-coste-art-gallery



(a) Sketch of the project. (b) Finished construction.

Figure 2.2: East elevation of Château La Coste (source: https://architizer.com/projects/chateau-la-coste-art-gallery/).

SUVA House

Dating from the 1950's, the original construction for the SUVA offices in Basel was characterized by a regular arrangement of casement windows and sandstone cladding. Rather than demolishing the existing building, Herzog & de Meuron added a second block for apartments and conference facilities to it (Figure 2.4). To improve the thermal and lighting performance of the spaces, both volumes were covered with a glazed façade, within a one-meter spacing from the original one (Wigginton and Harris, 2002). This enclosure system is composed by operable window panels with different optical and physical qualities, to either allow views, block and diffuse sunlight or improve the building's insulation. The resultant geometry not only provides a unified and coherent urban presence, but also reveals the presence of two separate constructions through the transparency and operation of the façade (Figure 2.3).

Figure 2.3: East elevation of Suva House (source: https://www.herzogdemeuron.com/index/projects/complete-works).

(a) Original construction. (b) Refurbished version.

Figure 2.4: SUVA House (1993), extension and alteration of an apartment and office building. Basel, Switzerland (source: Wigginton and Harris (2002)).

New design practices call for a purposeful use of resources, following a deliberate and systematic paradigm. Performance-based design approaches arose from the development of a critical architectural discourse, along with increasing research by design efforts to respond to current sustainability challenges. As buildings represent complex, interdependent systems affected by external contingencies and growing occupant needs, these form-finding approaches require a quantification of performance criteria. Design decisions can be informed by experiments that simulate the complexity of the real world, making it possible to assess a building's behaviour under specific usage scenarios.

2.2 Representation Methods

The development of Information and Communications Technology (ICT) has radically changed the role of the architect throughout the past decades, progressively replacing the traditional drawing table by the use of computers in design processes. Nowadays, digital design technologies have been adopted almost universally, as the predominant means of production in architectural practices (Kotnik, 2010). ICT had a considerable impact on the design process, improving both the efficiency and the quality of design outcomes, as concepts can be further developed through informed search processes to find enhanced versions of a building's form.

2.2.1 Computer-Aided Design

Starting from the second half of the 20th century, architects and engineers have increasingly discarded traditional drawing and calculation tools. Originally thought to enforce the optimization of vehicle design in the automotive and aviation industries in the 1980s (Figure 2.5), the development of Computer-Aided Design (CAD) has been an evolutionary process which, through the use of increasingly accurate computational methods, allowed the discarding of costly experiments in small-scale models or full scale tests (Czmoch and Pękala, 2014). The first CAD systems served as mere replacements of drawing boards, ultimately growing into a wider acceptance and use in architectural environments. Such can be attributed to the enhancement of 3D modeling capabilities of software, as well as an increasingly larger number of available tools.

Figure 2.5: CATIA software for surface modeling, 1982 (source: https://www.3ds.com/about-3ds/history/).

CAD tools employ a database describing the geometry and other properties of objects, used to visualize and document unbuilt realities during the design process, gradually replacing the manual drafting stage with quicker, more automated processes. Current practices often rely on CAD to solve design and graphic representation problems, aimed to increase design productivity and quality and to simplify documentation procedures. The implementation of Building Information Modeling (BIM) further added a collaborative factor to this paradigm (Figure 2.6), by integrating the conception of building form, system sizing, and construction data management into a single design environment (Eastman et al., 2011).

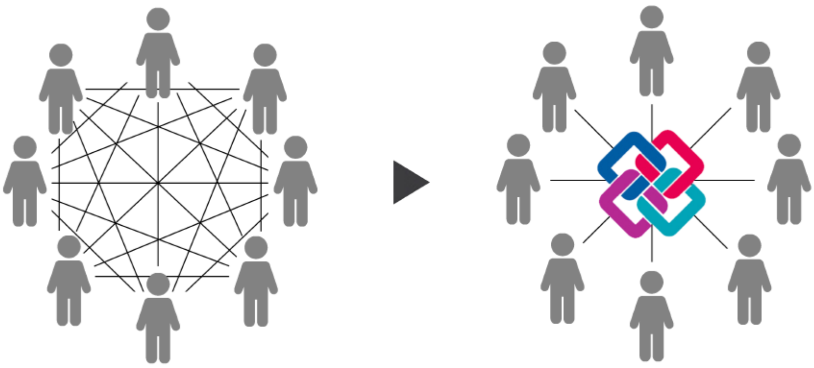
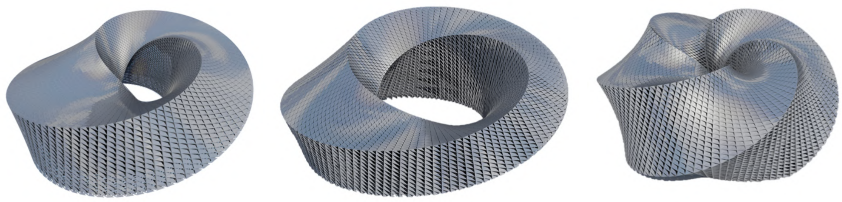


Figure 2.6: Traditional information transfer process (left), and optimized procedure in a BIM project (right) – edited (source: http://www.dds-cad.de/produkte/ihr-mehrwert/open-bim-und-ifc/).

CAD modeling can be addressed as a free-range geometrical exploration, allowing architects to freely create and edit complex geometrical objects (Zboinska, 2015). BIM tools, on the other hand, require a sequential modeling technique, following feasible constructive logic. Given the interdependency of constructive elements, the use of BIM software is still not widely applied to earlier design stages. In architectural practices, a workaround for this limitation might be, for instance, to resort to CAD to produce and compare design variations, transitioning to a BIM paradigm when higher levels of project complexity are reached. However, the differences between the two paradigms difficult tool interoperability, often resulting in the need to rebuild geometrical models to avoid information loss (Castelo Branco and Leitão, 2017).

2.2.2 Algorithmic Design

Modeling a building is an inherently complex problem. Architects must settle a series of physical, social, spatial, and environmental constraints, to encode and clarify the relationship between the design intent and the design outcome. Such constraints, along with other design parameters, link different geometries together while maintaining the design logic. For instance, when a single building element is changed, the rest of the model should be changed accordingly (Figure 2.7). However, 3D modeling approaches like CAD and BIM still rely mainly on the manual insertion of geometric elements, which turn minor changes in large-scale models into lengthy editing processes.



(a) Original model. *(b) Enlarged radius.* *(c) Double twisting.*

Figure 2.7: Model variations of the Astana National Library (source: Castelo Branco and Leitão (2017)).

The possibility of quickly changing a model without disregarding the coherence of its parameters allows for the exploration of design options that, otherwise, would not have been considered. This implies a shift from geometry to logic as the main design concept, which, although not fundamentally adopted by architects, can be achieved through the use of algorithms. An algorithm is a computational procedure for addressing a problem in a finite number of steps: it is the systematic extraction of logical principles in the search for repetitive patterns, interchangeable modules, and inductive links (Terzidis, 2004). In an architectural context, the use of algorithms enables the creation of complex shapes with little effort. Algorithmic Design (AD) consists, therefore, in the description of an architectural shape through algorithms, applying rules, constraints, or a coherent combination of procedures to transform parameters into building geometries.

The application of AD strategies has often raised concerns in architectural practices, given their general association with cutbacks on creative design thinking. The requirement for programming knowledge can also be seen as a setback, as it is less cost-effective and implies considerable time investments for a design team to properly acquire the necessary skills and techniques. However, as projects reach wider scales, this initial cost can be quickly recovered when there is a need to incorporate design changes: by adjusting or adding parameters, the architect can quickly generate a different model that expresses changes in numerical values, geometric shapes, mathematical functions, or even subprograms (Leitão et al., 2013).

2.2.3 Programming Environments: Visual or Textual?

In programming, the choice between visual (VPLs) or textual programming languages (TPLs) comes down to both the scale of the project and the user's required skills. More so than textual approaches, visual scripting can be easily coupled to architectural design processes and, as such, is being embraced by a rapidly expanding group of architects and students. The interactive features of VPLs are more intuitive to non-programmers and beginners, allowing users to create programs by manipulating components and connections, rather than by specifying them textually. However, shortcomings in abstraction mechanisms from VPLs result in a general lack of scalability, compromising the performance and legibility of complex programs. The *Grasshopper*[2] model of the Morpheus Hotel (Figure 2.8), designed by Zaha Hadid Architects, distinctly illustrates such limitations (Figure 2.9). TPLs, despite being more complicated and time-consuming to learn than VPLs, quickly recover the initial investment from the user when the complexity of the problems becomes sufficiently large (Leitão et al., 2012).

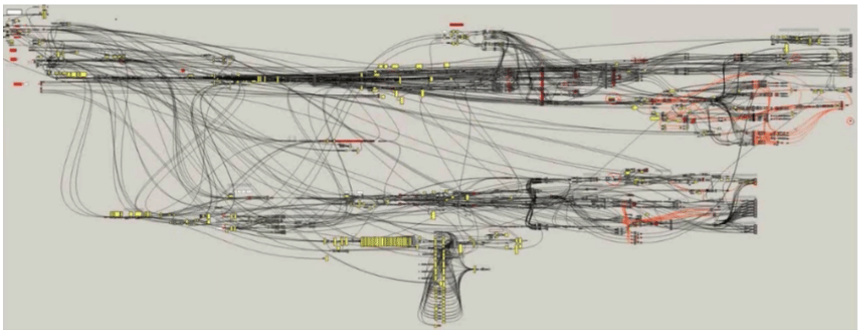


Figure 2.9: Grasshopper model for the Morpheus Hotel (source: Wortmann and Tuncer (2017)).

Figure 2.8: Morpheus Hotel, 2018 (source: https://www.archdaily.com/896433).

VPL-based environments such as *Grasshopper* and *Generative Components*[3] integrate useful AD development and debugging features: (1) traceability, by highlighting selected modeling components in the geometric output, and (2) immediate feedback, to provide real-time visualization of the effects of program changes (Sammer et al., 2019). For that reason, traditional TPLs falling into obsolescence cannot be compared with state-of-

[2]https://www.grasshopper3d.com

[3]https://www.bentley.com/en/products/product-line/modeling-and-visualization-software/generativecomponents

the-art VPLs in a fair manner. Modern TPLs that target generative design domains not only share the features of model traceability and immediate feedback, but can also be significantly easier to learn, use and extend: by extending analytical procedures and abstraction techniques, resulting programs are usually easier to adapt to changing requirements.

2.3 Building Performance Simulation

Reducing the environmental impact of future buildings can be expedited by informed decision-making processes on the basis of performance predictions. When there is no possibility of experimenting on a system under particular circumstances - as is the case of most design solutions under development, since one cannot perform tests on what is yet to be built -, building performance simulation (BPS) can aid to reach some degree of predictability over the effects of external contingencies on buildings. Augenbroe (2011) defined BPS as a three-step process, aiming towards the agreement on (1) performance criteria and (2) techniques of qualification and measurement, as well as a the choice for (3) rational design strategies that consider client preferences and trade-offs between potentially conflicting performance targets, time, and budget limits. As such, it is a field that requires specialized expertise, drawing resources from the several disciplines that compose an architectural project.

To predict the behavior of complex systems, given a particular objective, BPS models need to provide a certain degree of confidence. Model calibration strives for a compromise between simulated and data-driven output, through a wide range of analytical, mathematical and statistical techniques. Due to the large number of required inputs for detailed building energy simulation and the limited number of measured outputs, calibration is an indeterminate problem, where the presence of too many parameters is likely to result in non-unique solutions (Coakley et al., 2014). Moreover, validation techniques determine whether a simulation model can accurately represent the system during an experiment, assuring that a specific approach consistently produces a result that meets pre-determined acceptance criteria.

Complexity can be evaluated by the amount of components of a model, as well as the nature and pattern of their connections. A model that is too simple does not achieve a precise approximation of the system, leading to unrealistic and misleading analysis results due to approximation. A model that is too complex has an increased number of parameter estimates, i.e., the use of sample data when measurement techniques cannot be applied. Consequently, these models have a higher uncertainty level due to (1) the inherent variation associated with the physical environment under consideration and (2) the potential inaccuracy in any phase of the modeling process.

2.3.1 BPS Application

Ideally, building performance assessments should be executed at an early stage of the project, so that the architect continually develops informed design variations while comparing them to the original design intent. However, simulation tools are mostly used during the detailed design stage, when most of the decisions regarding building massing and system types are already made (Brahme et al., 2009). Analysis at the conceptual design stage is often not considered a high priority, although most architectural studios recognize its importance. As a result, decisions regarding building systems and equipment are postponed into later stages of the design process (Figure 2.10). To further integrate BPS into early-stage design, an investment in both tools and training is in order, along with the development of procedural guidelines to allow the collaboration between disciplines (Soebarto et al., 2015). However, the promise of a single piece of software to carry out all design tasks, from building conception to building operation, has yet to become a reality.

Shi and Yang (2013) explored the concept of performance-driven architectural design by integrating multiple performance simulation programs into a parametric CAD context, emphasizing the need to develop architect-friendly interfaces, so that no coding capability is required, into the proposed

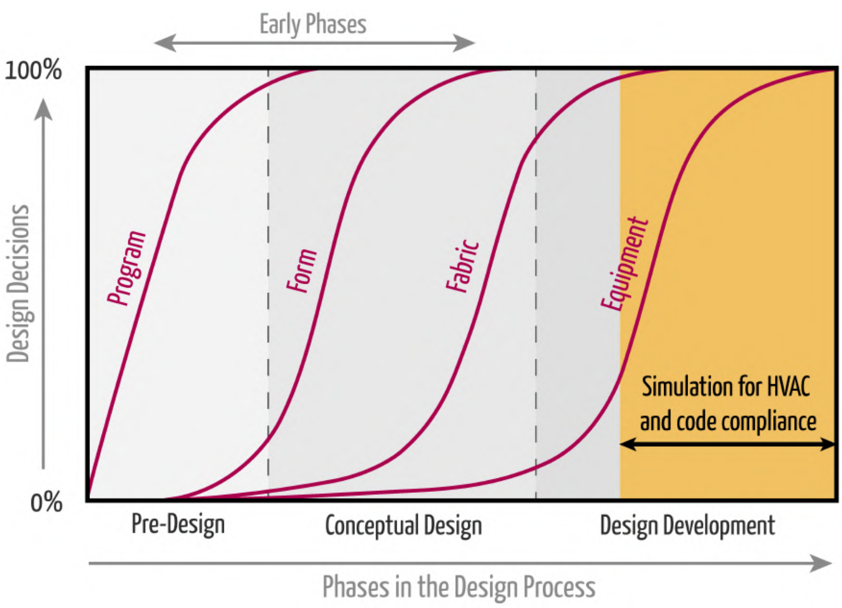


Figure 2.10: Current use of performance simulation in practical building design (source: Torcellini and Ellis (2006)).

workflow. Both Karssies (2017) and Strunge (2017) validated basic modeling features in the interface of parametric analysis plugins for CAD tools, regarding their fitness for early-stage, performance-based design. Although showing a wide parameter flexibility which facilitates form-finding processes, the visual paradigm of plugins that interface BPS tools with CAD programs is limited regarding the modeling of complex and large-scale designs, due to its shortcomings in abstraction and control mechanisms and, in other parts, to the time-consuming metaphor of program construction based on the manipulation of wires and boxes (Leitão et al., 2012).

2.3.2 Analysis Tools

Choosing an analysis tool implies considering the flexibility given to the various BPS tools available, regarding model resolution[4], the applied calculation methods, and the user-friendliness of the graphical user interface. Reviewed literature often compares tool features and characteristics (Crawley et al., 2008; Brahme et al., 2009; Coakley et al., 2014). Surveys led by Attia et al. (2012), for instance, reveal that architects prioritize the integration of an intelligent knowledge-base over the usability of the interface or the accuracy to simulate complex building components. For this reason, it is important to carefully consider the available tools and their adequacy to the project's objectives. The present section offers a brief description of a selection of energy analysis tools which are currently used in design practices.

TRNSYS

TRNSYS is a complete and extensible simulation environment for the transient simulation of systems, including multi-zone buildings. It is used by engineers and researchers around the world to validate energy-related solutions, from simple domestic hot water systems to the design and simulation of buildings and their equipment, including control strategies and occupant behavior. TRNSYS applications include solar systems, low energy buildings and renewable energy use (Solar Energy Laboratory, 2007).

A TRNSYS model (Figure 2.11) is typically setup by connecting components graphically in the Simulation Studio. The user specifies the components that constitute the system, often referred to as *Types*, and the manner in which they are connected, in terms of inputs, outputs, and parameters (Figure 2.12). The tool's library includes many of the components commonly found in thermal and electrical energy systems, as

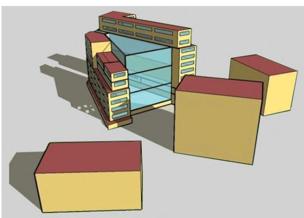
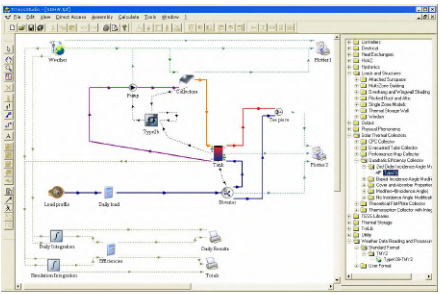


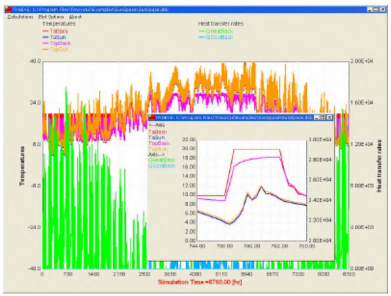
Figure 2.11: Example of a 3D model generated in TRNSYS (source: http://www.trnsys.com).

[4] In a building analysis context, resolution refers to the amount of detail that can be inserted into the description of the building model.

well as component routines to handle input of weather data or other time-dependent functions. One of the key factors that popularized this tool is its modular structure, as models are constructed in such a way that users can modify existing components or write their own, extending the capabilities of the environment to follow specific needs. In addition, TRNSYS can be easily connected to many other applications, for pre- or post-processing or through interactive calls during the simulation (e.g. Microsoft Excel, Matlab).



(a) User interface.



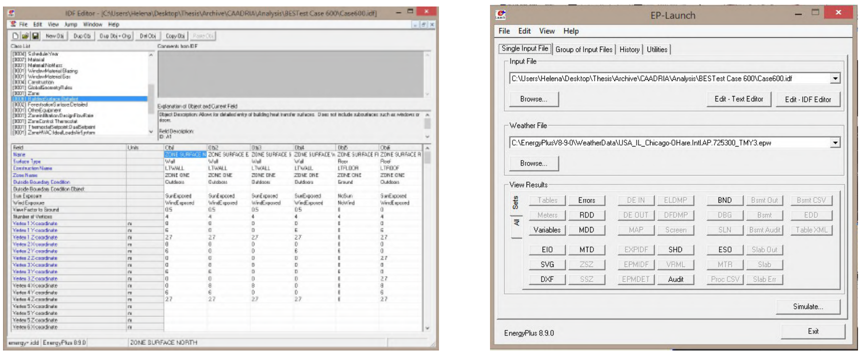
(b) Analysis output example.

Figure 2.12: Screenshots of TRNSYS, a TRaNsient SYstem Simulation program for whole building energy simulation. (source: http://www.trnsys.com/features/).

EnergyPlus

EnergyPlus (EP) is a whole-building simulation engine with an open source software. It forms the analytical basis for energy-efficiency standards such as ASHRAE 90.1, estimating the building's energy consumption considering HVAC systems, radiant, and convective effects. It also conducts the evaluation of illuminance and glare effect, to report visual comfort and drive lighting controls. EnergyPlus receives structured Input Data Files (IDF), which can be edited in any textual programming environment or in the tool's incorporated editor (Figure 2.13a), and are simulated along with a chosen weather file (Figure 2.13b). Simulation outputs are retrieved in unstructured text formats, as CSV and HTML (U.S. Department of Energy, 2019).

Most building energy simulation tools demand considerable expertise on their use, given their requirements and data processing methods. Tools like EP rely on manual data entry processes, which are time-consuming and error-prone. Consequently, despite acknowledging the significance of energy efficiency assessments, not every architectural design studio is prepared to make use of this tool's modeling capabilities. A workaround for this impediment is the use of third-party graphical user interfaces, which support the set-up of basic EP system objects through visual programming languages.



(a) Incorporated model editor.

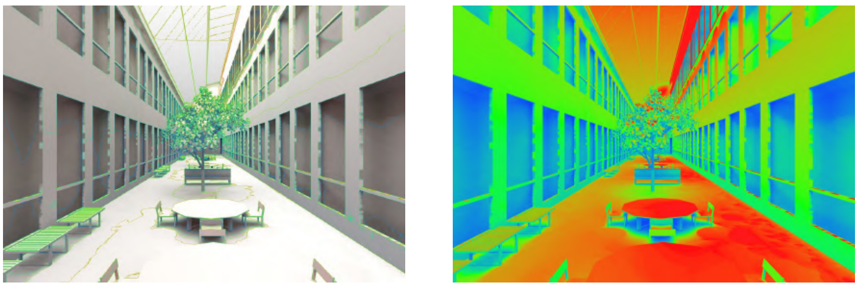
(b) Simulation launch.

Figure 2.13: Screenshots of the user interface of EnergyPlus.

Radiance

Radiance is a computer software package used to analyze and evaluate lighting and visual quality in buildings. It includes programs for modeling and translating scene geometry, luminaire data and material properties, which are used as model input. The lighting simulation is based on ray-tracing techniques, used to compute radiance values (i.e., the quantity of light emitted, reflected, transmitted, or received through a specific point in a specific direction) to assess true lighting conditions in a given space, displaying the results either as color images (Figure 2.14), numeric values, or contour plots[5].

Given its few limitations regarding model geometry, material, or environment descriptions, Radiance is used by architects and engineers to predict the illumination and visual quality of innovative design spaces, and by researchers to evaluate new lighting and daylighting technologies[6]. This tool can be used through textual command interfaces, but it is often accessed through third-party, more user-friendly interfaces.



(a) Lux contour plot.

(b) Falsecolor for lighting analysis.

Figure 2.14: Radiance output (source: https://hiveminer.com/User/PJMsol).

[5]https://www.radiance-online.org/about/detailed-description.html

[6]https://www.buildingenergysoftwaretools.com/software/radiance

Sefaira Architecture

Sefaira Architecture[7] is a collaborative tool that allows design teams to rapidly analyze passive and active construction strategies, aiming to optimize the daylighting, comfort, and energy performance of building designs while potentially reducing operational costs. Validated industry-standard analysis engines can be accessed through a straightforward, easy-to-learn user interface, which allows the simulation of design propositions from an early project stage.

Sefaira provides real-time analysis plugins (for 3D modeling tools such as SketchUp and Revit), which provide constant feedback on energy and daylighting metrics for unlimited design options (Figure 2.15). Moreover, a cloud-based web application can be used for deeper comparative and parametric analysis. Cloud computing enables multiple parallel simulation runs, letting users quickly explore and choose the best performing design solutions.

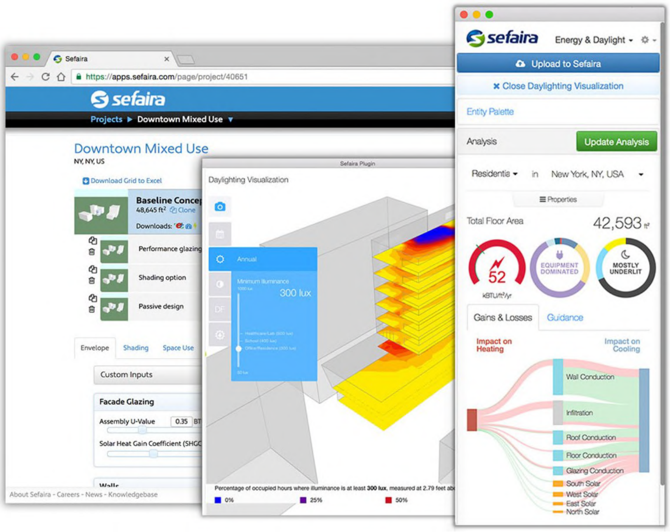


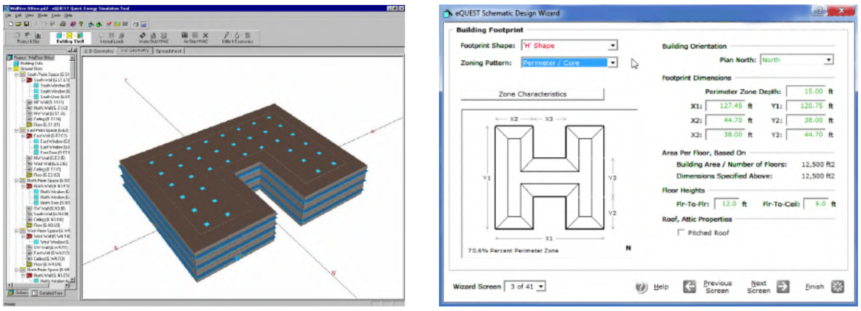
Figure 2.15: Sefaira Architecture's web application, showing the daylight visualization and energy analysis plugins (source: https://sefaira.com/sefaira-architecture/).

eQUEST

eQUEST is a building energy simulation tool, designed to perform detailed analysis of state-of-the-art building design technologies without requiring extensive knowledge on building modeling. The tool's user interface (Figure 2.16a) combines a building creation wizard (Figure 2.16b), an energy efficiency measure (EEM) wizard, and a graphical results display module with an enhanced DOE-2.2-derived building energy use simulation program.

[7] https://sefaira.com/sefaira-architecture/

Within eQUEST, DOE-2.2 performs an hourly simulation of the building based on construction elements, glazing, occupation, plug loads, and ventilation. The alternative results of multiple simulations can be displayed in side-by-side graphics, combining outputs such as energy cost estimation, daylighting and lighting system control, and automatic implementation of energy efficiency measures (James J. Hirsch & Associates, 2004).

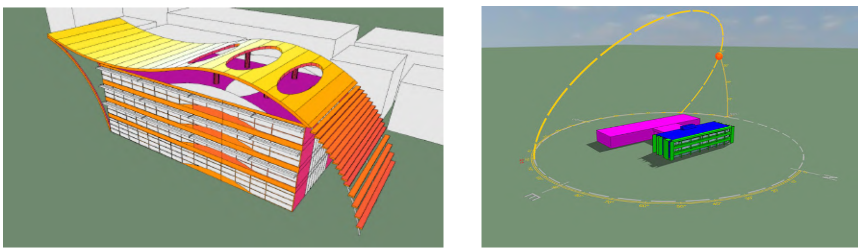


(a) Detailed interface. *(b) Building creation wizard.*

Figure 2.16: Screenshots of the user interface of eQuest (source: James J. Hirsch & Associates (2004)).

IES <VE>

The Integrated Environmental Solutions Virtual Environment (IES <VE>) is a globally-used digital construction tool for architects, engineers and contractors, linking a suite of applications into a common user interface and a single integrated data model. This tool provides an environment for the detailed evaluation of building and system designs, allowing them to be optimized with regard to comfort criteria and energy use. Complex building physics principles and detailed dynamic thermal calculations are comprehensively translated into technical information and visualization (Figure 2.17), through a platform that allows cross-team collaboration from a concept design stage to building operation. IES <VE> supports the modeling of complex buildings, embedding energy and performance assessment across the building's life cycle (IES, 2014).



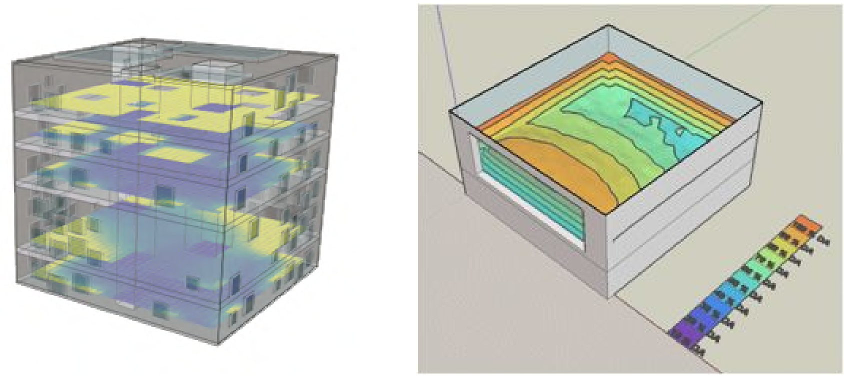
(a) Solar radiation analysis. *(b) Solar path analysis.*

Figure 2.17: Output visualization examples for IES <VE> (source: https://ifsacademy.org/building-energy-performance-analysis-using-ies-ve-software/).

DAYSIM

DAYSIM[8] is a Radiance-based daylighting analysis tool that performs annual illuminance calculations in and around buildings. Simulation outputs cover climate-based daylighting metrics (eg., useful daylight illuminance and daylight autonomy), as well as electric lighting energy use and glare analysis. It is also possible to model hourly schedules for occupancy and dynamic shading, which can be directly coupled with thermal simulation engines as EnergyPlus, eQuest and TRNSYS.

Like Radiance, DAYSIM is directly accessed through a command line interface, which implies a user interaction process that is not common in architectural practices. To make this tool more accessible, a variety of plugins can be used as alternative, easy-to-use interfaces, as Diva for Rhino (Figure 2.18a) or Su2ds for SketchUp (Figure 2.18b).



(a) Diva for Rhino. *(b) Su2ds for SketchUp.*

Figure 2.18: Analysis output in different graphical user interfaces for DAYSIM (source: https://daysim.ning.com).

2.3.3 Tool Comparison

Table 2.1 comprises a summary of basic features and capabilities of the aforementioned building energy simulation tools. We compare the types of analysis that can be performed, along with model resolution, user-friendliness, accessibility, and validity.

Occupant comfort analyses have different simulation targets, depending on the tool in question. TRNSYS, EP, Sefaira, and IES <VE>, for instance, aim towards the attainment of thermal comfort conditions, mostly regarding inner temperatures and ventilation levels. Radiance and DAYSIM, on the other hand, focus on visual comfort, in terms of solar incidence and, consequently, the need for artificial lighting.

[8] https://daysim.ning.com/page/program-structure

		TRNSYS	EnergyPlus	Radiance	Sefaira	eQuest	IES VE	DAYSIM
ANALYSIS TYPE	Energy use	✓	✓		✓	✓	✓	
	Lighting	✓	✓	✓	✓		✓	✓
	Daylighting	✓	✓	✓	✓	✓	✓	✓
	Ventilation	✓	✓		✓		✓	
	Occupant comfort	✓	✓	✓	✓		✓	✓
	Cost evaluation	✓	✓		✓	✓	✓	
EASE OF USE	Interface comprehensiveness	-	- -	- -	+ +	+ +	+	-
	Required expertise	High	High	High	Low	Low	High	High
MODELING FEATURES	Early design stage application	-	- -	-	+ +	+	- -	-
	Interoperability	No	Yes	Yes	No	No	No	Yes
ACCESSIBILITY		Paid	Free	Free	Paid	Free	Paid	Free
VALIDITY		✓	✓	✓			✓	✓

Table 2.1: Comparison of tools.

Sefaira and eQuest provide straightforward and easy-to-learn interfaces, which don't require a high level of expertise to be explored by the users. As such, these tools facilitate the modeling and performance simulation of buildings at an early design stage. Moreover, the cloud-based web application provided by Sefaira promotes a greater level of communication between the several disciplines and teams involved in an architectural project.

Interoperability, in a modeling context, is defined as the ability to exchange information between simulation tools. EP, Radiance, and DAYSIM can be operated through third-party interfaces (e.g. OpenStudio, Design Builder, Ladybug Tools) which allow for a direct visualization of the modeled geometries. These tools show fewer constraints regarding model resolution and, as such, are more frequently adopted in architectural practices.

Another relevant factor towards the selection of analysis tools lies in the accessibility of the software, as it may imply additional costs for building design practices. This is the case of TRNSYS, Sefaira, and IES <VE>, in spite of being among the most complete whole building energy simulation tools currently available.

Finally, validity refers to the reliability of the measurements and calculation methods of a simulation tool. The purpose of tool validation is to assure the user that the analysis output represents the real-world conditions in a credible way. TRNSYS[9], EP[10], Radiance[11], IES <VE>[12], and DAYSIM[13] have undergone several validation studies with positive outcomes.

[9] https://sel.me.wisc.edu/trnsys/validation/index.html
[10] https://energyplus.net/testing
[11] https://www.energy.gov/eere/buildings/downloads/radiance
[12] https://www.iesve.com/software/software-validation
[13] https://daysim.ning.com/page/publications

2.4 Integrating Disciplines

Building form is no longer a sole concern while developing an architectural project. There is a strive to achieve improved performance levels, a justified use of components and materials and decreased production timings and costs. The exploration of sustainable, high-performance design solutions parts from a fundamental engagement of multiple contexts that condition contemporary architecture, which may intertwine spatial, construction, energy and systems logic. Integrated design approaches, therefore, see the building as the product of new social relationships amongst architects, clients, developers, builders, communities, and consultants (Figure 2.19).

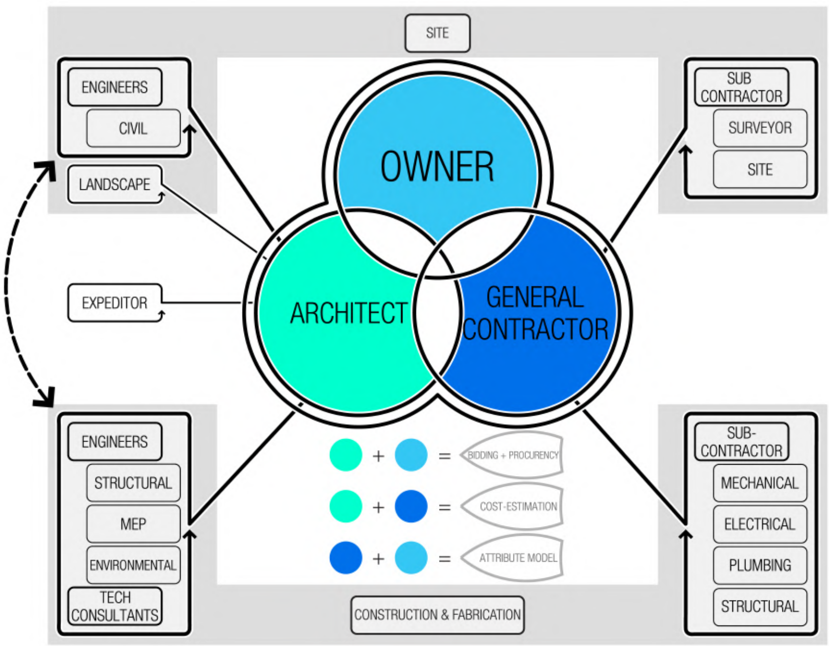


Figure 2.19: Integrated design approach by GRO Architects - edited (source: (Garber, 2014)).

Progress in performance-based design results from the integration of multiple disciplines, from form-finding to analytical processes, into building conception. SANAA's Glass Pavilion at the Toledo Museum of Art (Figures 2.20 and 2.21) is a noteworthy case where the employment of integrated design strongly contributed for the achievement of its emblematic transparency and lightness, with the majority of the building's surfaces being, in some capacity, performative. Guy Nordenson and Associates, along with SAPS/Sasaki and Partners, supported the conception and execution of the structure, which demanded unique solutions for the assembly of solid steel columns (Figure 2.23). Transsolar further contributed for the implementation of energy strategies, dividing the building into three primary zones: (1) an interstitial thermal buffer (Figure 2.22a), separating

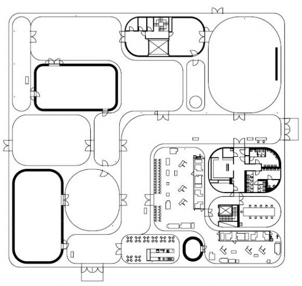


Figure 2.20: Floorplan of the Glass Pavilion, by SANAA (source: Moe (2008)).

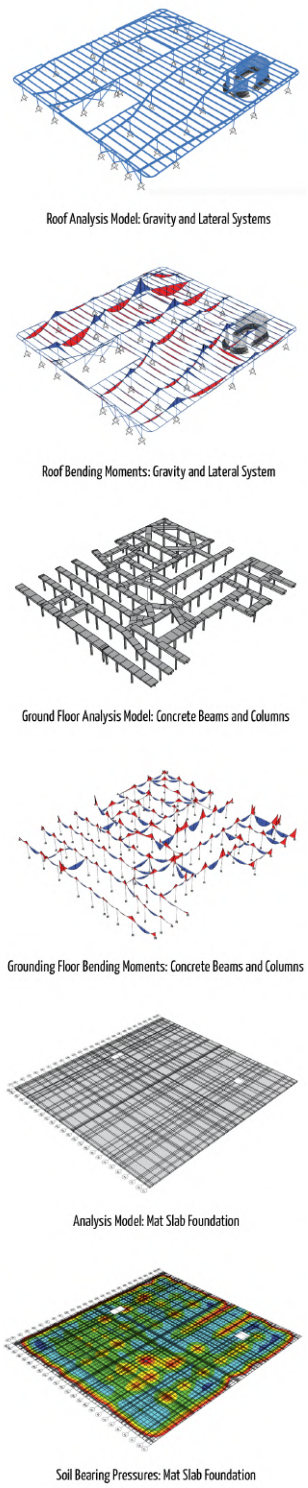
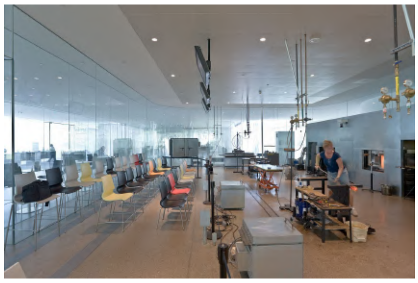


Figure 2.23: Structural diagrams for the Glass Pavilion (source: Moe (2008)).

the exterior glass envelope and the interior zones; (2) a hotshop zone (Figure 2.22b), where the glass production facilities are located; and (3) discrete zones with specific air temperature and humidity requirements, used as galleries for temporary and permanent exhibitions. Thermally active surfaces were strategically employed, to enable the transparency of the building in the cold climate of Ohio. In addition, extensive light studies informed the placement and extent of curtains for various program spaces (Moe, 2008).

Figure 2.21: Exterior view of the Glass Pavilion (source: https://afasiaarchzine.com/2015/10/sanaa-29/).

(a) Interstitial thermal buffer areas.



(b) Hotshop zone.

Figure 2.22: Interior of the Glass Pavilion. (source: https://iwan.com/portfolio/a-sanaa-toledo-glass-pavilion/).

As architectural practices seek greater levels of complexity and detail in building models, performance levels become increasingly more difficult to predict. Moreover, there is still a great ineffectiveness in the interoperability between most 3D architectural models and the models required for energy modeling. AD strategies have the potential to extend the intellectual scope of design, by explicitly representing ideas that are usually treated intuitively (Woodbury, 2010). Adopting and developing new technologies can benefit architectural design practices, either by improving existing workflows or finding fundamentally new solutions to currently intractable problems (Peters, 2018).

CHAPTER 3

The Building Envelope

For physicists, a boundary is not an entity but an action; an active transitional zone where energy transforms from one energy state to another. A boundary is a lively zone of arbitration rather than of delineation.

M. Hensel

As the utmost frontier between the interior and exterior environments, the building envelope (i.e., façade) is directly related to the design, occupation and operation of buildings. Throughout history, principles regarding the symbolism and functionality of the building envelope fluctuated along with architectural styles. With the establishment of the modern movement, the classic picturesqueness of canon metrics and adornment was converted into an extreme formal abstraction, in a paradigm where the outer surface of a building was modeled by the interior spaces and program. This rigorous functionalist thought was later criticized, ultimately restoring the symbolic and expressive façade surface that is present in current architectural practices.

Although visual appearance is often considered as a sole decisive component, the façade is a system that comprises the integration of materials, material properties, and performance design principles. According to Boswell (2013), the façade has four interrelated primary functions:

- Structural: the façade supports its own weight, transfers exterior forces, and spans the necessary distances to support structural elements;
- Weathertighness: as the enclosing membrane separating the exterior elements (e.g., air and water) from the interior spaces and occupants;
- Energy efficiency: considering the local climate, building shape and orientation, as well as material selections, quantity, and placement;
- Accommodating building movements: the façade system must adapt to the movement of the building structural frame.

From a sustainability perspective, the purpose of the façade as a construction element is to provide occupant comfort while using the least possible energy and resources. The location and climate of the building site are, therefore, relevant factors to consider throughout the design process, along with program requirements, material properties, and aesthetic quality (Aksamija, 2013).

New developments in design strategies, performance measurements, materials, systems, and information technology helped designers change the aesthetic and functional characteristics of façades, leading to the emergence of an 'intelligent architecture' which, through integrated systems and automation, can anticipate and respond to conditions that affect the performance of the building and its occupants (Kroner, 1997). Following this concept, the weather-protecting construction elements of a building envelope can perform self-regulated adjustments to their configuration, maintaining comfort with the least use of energy (Wigginton and Harris, 2002).

3.1 Adaptability in Construction

Along the course of evolution, biological organisms responded to changing environmental conditions by constantly readjusting their character, mainly through processes of selection. Nature evolved through constant mutation, by developing multi-functional and self-adaptive solutions towards the compromise between partially conflicting requirements (Knippers and Speck, 2012). Likewise, in an architectural context, weather variations and the fluctuating needs of occupants call for an aptitude of adaptation and change. While most of the constraints acting upon the building envelope change over time, architectural design strategies often focus on static solutions, attributing a single geometry as fit for all possible external conditions (Vergauwen et al., 2013). Often, such causes a need to adjust buildings through their life cycle, in order to address environmental, economic, and operational problems.

Recent technological innovations opened up the development of a new generation of adaptive façade concepts, which promoted new design opportunities for the architectural expression of buildings. Loonen et al. (2013) defined adaptiveness as the façade's "ability to repeatedly and reversibly change some of its functions, features, or behavior over time in response to changing performance requirements and variable boundary conditions, (...) with the aim of improving overall building performance". In this context, adaptive façades allow for a space reconfiguration that follows environmental changes and user needs, focusing primarily on the increase of efficiency and reduction of energy consumption in constructions (Barozzi et al., 2016).

Over the past decades, architectural practices started envisioning the future of façade design through the use of environmentally reactive components. Studios like Ateliers Jean Nouvel (Figure 3.1), Aedas (Figure 3.2), and Ernst Giselbrecht + Partner were among the pioneers on the application of these technologies. The Kiefer Technic Showroom is a pertinent example of the building design versatility provided by the integration of adaptive façade mechanisms in both exhibition and office environments. Answering to the client's request for larger presentation spaces and a more flexible scope for exhibition layouts, Giselbrecht designed the building's façade to move according to general weather conditions. It does so by expanding and contracting a set of individually operated folding panels, providing an aesthetic versatility through an arrangement of load bearing and mobile elements (Figure 3.3). Made of perforated aluminum tiles, the façade panels change their configuration hourly to regulate solar heat gains, with the possibility of being individually adapted to better respond to occupant comfort. Although ensuing a higher operational cost from electricity use, there is the potential to reduce the building's cooling needs while maintaining daylight comfort, as light is allowed to penetrate the interior space even when the façade is closed.

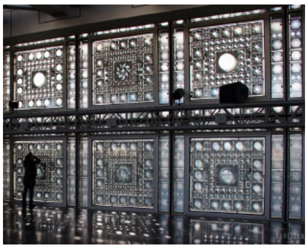


Figure 3.1: Arab World Institute. Jean Nouvel, Paris, 1987 (source: http://www.parisianist.com/public/assets/).

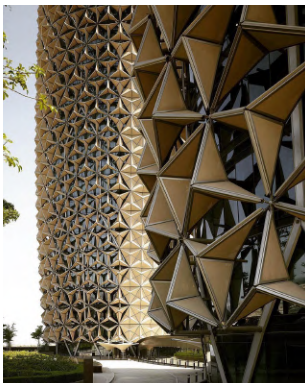


Figure 3.2: Al Bahr Towers. Aedas, Abu Dhabi, 2013 (source: https://www.arch2o.com/al-bahr-towers-aedas/).

Figure 3.3: Different façade configurations for the Kiefer Technic Showroom. Ernst Giselbrecht + Partner, Graz, 2007 (source: https://www.e-architect.co.uk/austria/kiefer-technic-showroom).

In 2008, Hoberman Associates and Buro Happold joined forces to develop technologies that both architects and engineers can engage with in the conception of adaptive façade systems. This collaboration, known as the Adaptive Building Initiative, was dedicated to designing a new generation of buildings that optimize their configuration in real time by responding to environmental changes (Drozdowski, 2011). Later in 2014, the research network COST[1] launched *Action TU1403 - Adaptive Façades Network*, joining the resources, research efforts, and expertise of 27 countries to address the lack of standardized procedures, design support tools, and performance assessment methods for buildings with adaptive façades (Andreas et al., 2018). Initiatives of this sort lead to an increased sharing of knowledge between architecture and engineering research and industry, through the combination of existing technologies and the development of new evaluation tools and design methods.

3.2 Classification of Adaptive Façades

Ever since the development of adaptive façade design and operation came into attention, there have been efforts to classify the different concepts into classes with shared characteristics. In literature, categorization contributed for the development of high-potential, innovative adaptive façade components through the identification of relationships among different adaptive systems.

In *Designing Kinetics for Architectural Façades - State Change*, Moloney (2011) proposed a pattern-based morphological classification to define the aesthetic potential of kinetic façades. In this book, movement patterns are described as "snapshots of form in motion", i.e., the moments created by the transition from one geometric state to another (Figure 3.4). Façade

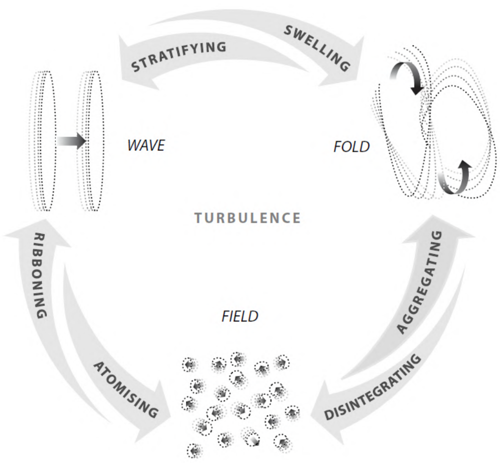


Figure 3.4: State change. Illustration of kinetic pattern as a dynamic morphology through the states of wave, fold and field, along with typical intermediate state transitions (source: Moloney (2011)).

[1] European Cooperation in Science and Technology. More information can be found at https://www.cost.eu/who-we-are/about-cost/

patterning was distinguished in terms of spatial form and temporal behavior, resulting in the identification of three states: (1) **Wave**, a linear or radial ridge of movement with a uniform and consistent dynamic; (2) **Fold**, adjacent patches of movement in a constant reconfiguration of boundaries which define a dynamic of intertwining and expansion; and (3) **Field**, a fragmented movement of singular units through an inconsistent, irregular, and multidirectional dynamic.

Following the *EU COST Action TU1403*, Loonen et al. (2015) identified the requirements and challenges present in existing classification approaches of adaptive building envelope concepts. The collected findings were interpreted in a comprehensive manner to compose a new characterization matrix (Figure 3.5), divided into the following concepts:

- **Purpose/goals** that are expressed through the use of performance indicators, often based on building codes or standards;
- **Responsive functions**, as energy management modules which depend on the building's physical domain;
- **Operation**, defining the types of control strategies for the façade mechanism;
- **Technologies**, in terms of available materials and system types;
- **Response time**, which defines the temporal scale at which the actions of the adaptive façade take place;
- **Spatial scale**, referring to the size of the façade system;
- **Visibility**, regarding the aesthetic quality of the architectural design;
- **Degree of adaptability**, which describes the degree of accommodation of the façade regarding changing boundary conditions.

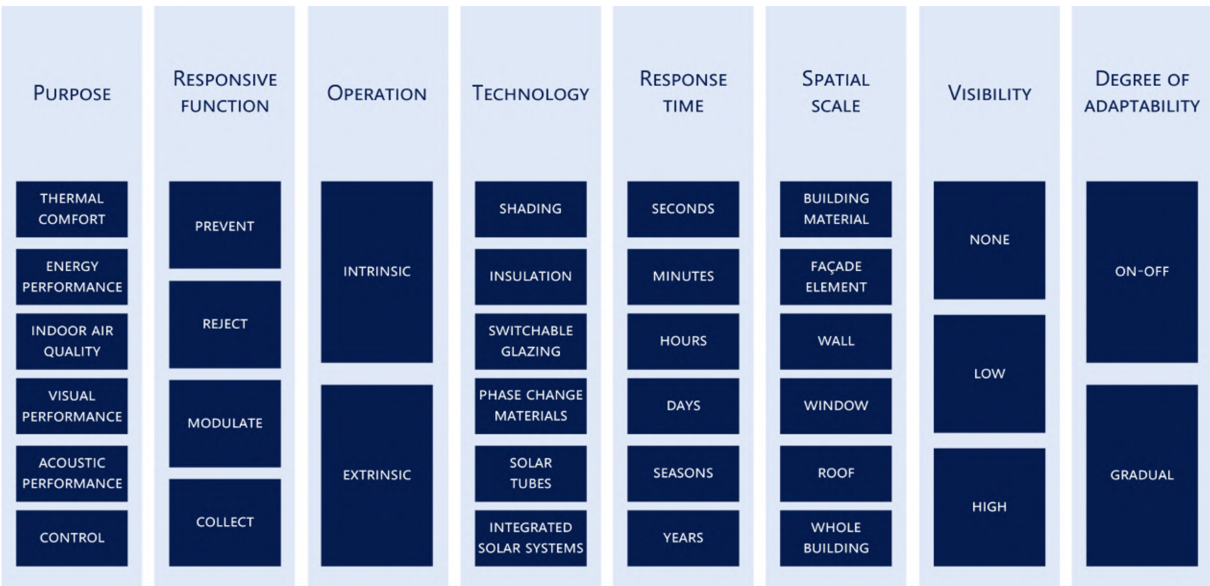


Figure 3.5: Overview of characterization concepts for envelope adaptivity. Adapted from Loonen et al. (2015).

The field of adaptive façade development is rapidly growing, given the current requirements for better environmental building performance and the recent rise in the use of computational tools. To understand how innovative design solutions were developed in terms of reactivity and interactivity, Velasco et al. (2015) assessed the current scope of computationally controlled façades through a literature review and a survey of contemporary projects. This led to the creation of a new classification system for adaptive façade mechanisms, discerning various types of deployable structures and physical transformations based on movement and control. We use this classification as a guideline for the presented thesis, further explaining the subdivision of these categories in the following subsections.

3.2.1 Movement

Patterns of movement in adaptive façades are defined according to the positional displacement of their elements. The degree of variability can be further subdivided, as shown in Figure 3.6.

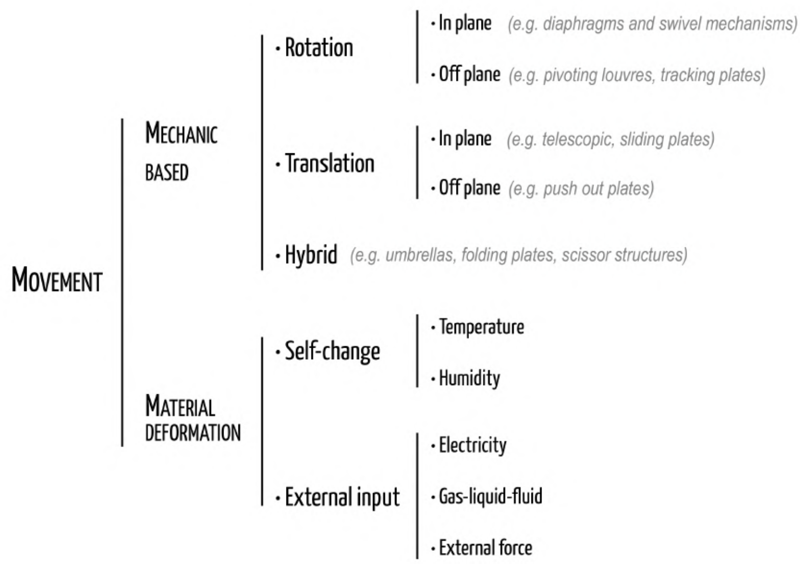


Figure 3.6: Classification of adaptive façade mechanisms based on movement. Adapted from Velasco et al. (2015).

Mechanic-based movement refers to adaptive systems made out of fixed, distinguishable components, transmitting motion by means of dynamic connections. Depending on the type of movement allowed, this classification can be divided into three categories: rotation, translation, and hybrid, the last one referring to mechanisms implying any combination of the first two.

Rotation mechanisms allow the movement of construction elements around a fixed axis, being in-plane when the object is flat and off-plane when otherwise. The façade of the Wyspiański Pavilion (Figure 3.7), designed by

Krzysztof Ingarden, employs a set of rotating bricks organized into a vertical disposition. As the purpose of the building was to provide both transparency and closure, the architect conceived a trapezoidal brick shape to respond to the different lighting needs of spaces with separate functions. The bricks are fixed onto steel rods and can be regulated individually, composing an external movable curtain for the building (Figure 3.8).

Figure 3.8: Rotating tiles of the Wyspiański Pavilion (source: http://www.iea.com.pl/projekt.php?lang=2&pro=22).

Figure 3.7: Wyspiański Pavilion, Krakow, 2007 (source: https://www.e-architect.co.uk/poland/krakow-information-centre).

Translation mechanisms allow the movement of construction elements along an axis, being in plane when the movement is parallel with the axis and off-plane when otherwise. Such can be seen, for instance, in The Shed by Diller Scofidio + Renfro (Figure 3.10). It incorporates an emblematic space for large-scale events and installations, which is formed when the building's outer shell is deployed from the base building and glides along rails (Figure 3.9) onto the adjacent plaza.

Figure 3.10: The Shed, New York, 2019 (source: https://www.archdaily.com/914450/).

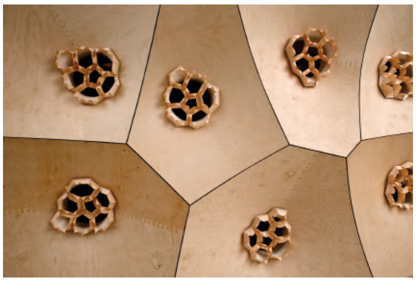
Figure 3.9: Close-up of The Shed's bogie wheels (source: https://artssummary.com/2019/04/05/).

Movement by material deformation is grounded on the physical properties of façade components. Adaptive systems that belong to this class make use of active materials, i.e., materials that can repeatably and reversibly change their shape in reaction to environmental or external stimuli. This classification can, therefore, be separated into two groups: self-changing and external input.

Self-changing façade configurations refer to the use of materials that can translate the energy from surrounding environmental conditions into particular kinds of movement. These material transformations are generally associated to changes on differential humidity or temperature levels. A relevant example is the Hygroskin Pavilion (Figure 3.11), which incorporates a set of climate responsive apertures into a metereosensitive building skin. The plywood sheets that give shape to the apertures respond to relative humidity changes (Figure 3.12), modulating the visual permeability of the building envelope without requiring mechanical control (Correa et al., 2013).

Figure 3.11: Hygroskin Pavilion (source: https://www.archdaily.com/424911/).

(a) High relative humidity (75%).



(b) Low relative humidity (45%).

Figure 3.12: Hygroscopic apertures (source: https://www.archdaily.com/424911).

Exterior input involves the use of artificially-controlled forces to cause material deformation. Such forces can part from electrical current, moving fluids or external sources of movement. This type of technology can be seen in the ShapeShift prototype (Figure 3.13), a project that explores the application of electro-active polymer at an architectural scale. Each

Figure 3.13: Detail of ShapeShift, 2010 (source: http://caad-eap.blogspot.com).

panel is composed by a pre-stressed acrylic film, covered in both sides by a conductive powder paint and a protective silicon layer (Figure 3.14). The panels react to voltage by expanding from a doubly-curved configuration to a flat shape,[2] generating movement that has the potential to create a unique spatial experience.

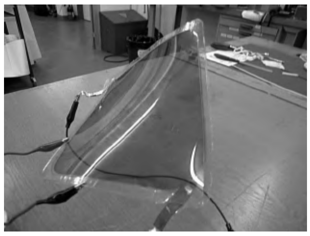


Figure 3.14: Single panel for ShapeShift (source: http://caad-eap.blogspot.com/p/experiments).

3.2.2 Control

While most adaptive façade classifications are focused on the movement or on the structure required for morphological transformation, control is one defining factor that should be more thoroughly considered. Both occupant-operated and reliable automated control mechanisms can be integrated into façade conception, towards the attainment of lower energy requirements while ensuring the environmental quality of interior spaces. Figure 3.15 illustrates the main adaptive control strategies for façade design. In this context, *sensors* are the link between the environmental space and the adaptive system, providing mechanisms with information regarding changes in specific exterior conditions. *Actuators*, in turn, convert the energy into motion and produce a reaction in relation to the stimuli detected by the sensors.

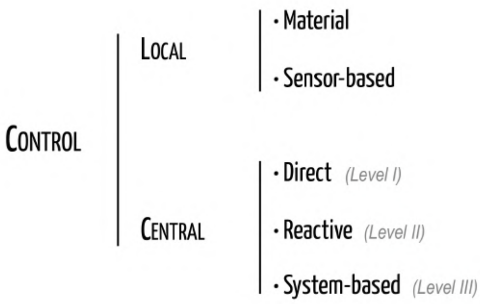


Figure 3.15: Classification of adaptive façade mechanisms based on control. Adapted from Velasco et al. (2015).

Local control strategies are applied at the scale of the component, implying that each actuator is autonomous. This control can either be embedded in anisotropic materials (e.g., the Hygroskin Pavilion), or linked to an exclusive sensor-based scheme. The latter comprises individual control systems for each component, as sensors, actuators, or microprocessors (e.g., the ShapeShift prototype).

Central control strategies, on the other hand, are applied at the scale of the space, implying multiple components being directed by a single unit. Through direct approaches, no input from sensors is requested, as all actions

[2] https://vimeo.com/15368696

are pre-programmed. This is the case, for instance, of the shading panels incorporated in the façade of the Al Bahr Towers (Figure 3.16): each unit is operated by a linear module which opens and closes progressively (Figure 3.17), in response to a pre-defined sequence which has been calculated to avoid direct sunlight from the moment it hits the façade.

Figure 3.17: Shading panels for the Al Bahr Towers (source: https://www.arch2o.com/al-bahr-towers-aedas/).

Figure 3.16: Al Bahr Towers (source: https://www.arch2o.com/al-bahr-towers-aedas/).

Reactive approaches are grounded on deterministic procedures, defining a sensor-based behaviour built on *if-then* conditions to yield decisions at different levels. The Kolding Campus, designed by Henning Larsen for the University of Southern Denmark (Figure 3.18), is an example of the application of this type of control: sensors monitor heat and daylight levels around the building, which is then reflected on the opening and closing of the façade panels (Figure 3.19).

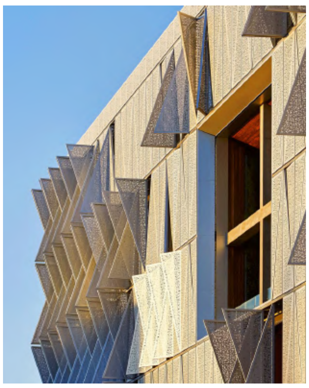


Figure 3.19: Detail of the façade of Kolding Campus (source: http://arcdog.com/portfolio/sdu-university-of-southern-denmark-campus-kolding/).

Figure 3.18: Kolding Campus, 2014 (source: https://www.archdaily.com/590576/).

Finally, system-based approaches are grounded in stochastic procedures, aiming towards the solution of complex problems through substantial data-processing inside the control unit. The Adaptive fa[CA]de prototype conceived by Skavara (2009) explores the computational possibilities and performative aspects of this approach, using Cellular Automata, Genetic Algorithms and Artificial Neural Networks to create a building skin that responds to the light levels of its environment (Figures 3.20 and 3.21). Applied to an architectural scale, this technology allies an appealing aesthetic to the potential for providing optimal light conditions to interior spaces.

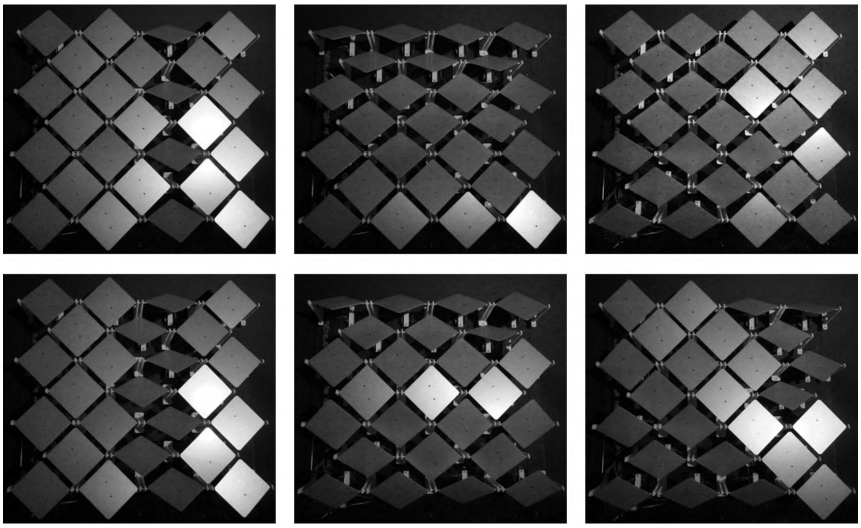


Figure 3.20: Physical kinetic model for the Adaptive fa[CA]de project, 2009 (source: Skavara (2009)).

Figure 3.21: Side view of the Adaptive fa[CA]de prototype (source: Skavara (2009)).

3.3 Modeling and Simulation

The development of responsive architectural elements requires an understanding of the complex and dynamic interactions between design, performance metrics, and local climate variables. As adaptive façade concepts rise into consideration, it is important to find an efficient way to predict the combined benefits and constraints of specific design propositions, which may vary in terms of materials, components, and systems.

Modeling an adaptive façade significantly differs from the process of modeling a static one, as the outcome of the latter defines a geometry that remains constant over time. When it comes to adaptive façades, the design outcome is a shifting pattern of geometries in a constant state of motion (Moloney, 2011). Currently, modeling and simulation approaches for adaptive building envelope assessment are still at an early stage of development, with many aspects yet to be explored (Loonen et al., 2017).

In literature, we can discern trends that focus on combining energy simulation software with dedicated data post-processing, optimization, and control procedures. Goia and Cascone (2014) conceptualized an ideal dynamic Window-to-Wall Ratio (WWR) technology, in which the building's energy performance was calculated by a sum of the minimum energy demands obtained from a series of simulations of the same model with different WWRs. Favoino and Overend (2015), in turn, developed a simulation method to evaluate the energy saving potential of adaptive glazing properties, consisting of three modules: (1) evaluation, to calculate the performance and costs of glazing systems with a predefined control strategy, (2) optimization, to enhance the optical and thermal properties of the model and determine an optimal control strategy, and (3) control, to modify optimization and evaluation settings.

The use of AD tools for performance analysis has also been a widely explored methodology to tackle adaptive façade design. Sharaidin et al. (2012) and Kormaníková et al. (2017) explored the incorporation of performance criteria in a parametric CAD context, to assist the decision-making process at a preliminary design stage. In parallel, Kim et al. (2015) examined a methodology to analyze the performance of buildings with complex dynamic façades by integrating parametric BIM with energy simulation. These approaches open the possibility for architects to run numerous simulations in a short time period, to compare and select the best design alternatives based on pre-determined criteria.

3.4 Overview

Global environmental concerns call for the development of innovative approaches for building envelope design. Several different types of adaptive façade concepts have already been developed and new, innovative solutions are expected to increase in the near future. However, the metrics of current BPS tools provide limited and potentially misleading information about the performance of these systems, due to their intrinsic time-varying features.

Given the number of rules, constraints, and parameters considered for the dynamic behavior of adaptive components, AD approaches can be used to facilitate the decision-making process regarding multiple design solutions. Parametric design tools can be linked with energy simulation software, to further evaluate and improve the performance of adaptive systems in an interactive way. The integration of these tools ensure that the knowledge acquired in building performance analysis tasks is formalized, structured, and incorporated into design practice.

PART II

FRAMEWORK

CHAPTER 4

Workflow

The presented research aims to develop a unified Algorithmic Design (AD) approach for the modeling and simulation of buildings that incorporate adaptive components. The goal is to further reduce the current gap between form-finding and analytic tasks during project conception, bringing architecture closer to performance-based design.

Focusing on the performance of the building from an early project phase emphasizes a comprehensive optimization of various quantifiable performance outcomes. Typically, such assessments are postponed to later stages of the design, serving as verification of compliance with standards. However, by combining design and simulation tasks into an integrated algorithmic approach, it becomes possible to change geometric and analytic models almost simultaneously, and also to automate the generation of these models. In the past, this methodology was applied to lighting and structural performance analysis (Castelo Branco and Leitão, 2017; Aguiar et al., 2017; Caetano et al., 2018). Our research extends it to also include energy performance simulations.

The AD approach we introduce in the following subsections is illustrated in Figure 4.1. It integrates the generation of parametric models for CAD visualization and the execution of energy analysis into a single script, by

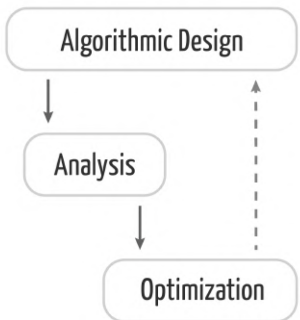


Figure 4.1: Proposed workflow.

including in the same program the description of both the parametric model and the analysis requirements. Since this method relies on an AD approach, the implementation of design changes can be achieved in shorter timespans, potentially reducing the amount of additional work from the project team. Moreover, the access to feedback over the performance of multiple design solutions is facilitated, as simulation is executed right after the geometry is generated.

4.1 Algorithmic Design

Traditional 3D modeling tools are often handled through a direct manipulation of geometry, which can limit exploration and effectively restrict design. Small design changes can imply time-consuming manual rearrangements of building geometry, or even the need to start a model from scratch. As mentioned in Chapter 2, using algorithms as design tools allows for a broader exploration of solutions: rather than modeling unconstrained geometry, the architect builds up the design by establishing and editing relationships between building elements (Woodbury, 2010). These relationships, defined as design parameters, facilitate the adjustment of models to test different design variations which are consistent with the original design intent.

The first step of our workflow comprises the generation of building geometry through an AD tool. The modeled elements have specified design constraints, which can be manipulated throughout the process of design exploration. As the geometric patterns of adaptive façades are time-shifting, we approach the concept of adaptability by creating a series of separate static models, each representing a different stage of the façade's movement. The generated geometries can be visualized in a CAD tool and, almost simultaneously, processed to perform simulation tasks.

4.2 Algorithmic Analysis

Following the AD stage, we assess the impact of the façade's geometrical variation in the building's energy consumption. The geometry defined in the AD tool is imported into an analysis plugin, where material descriptions, internal gains and simulation parameters are added to the initial model. The analysis plugin produces a simulation file based on the introduced input. To simulate the models, we define (1) a file directory to place the generated simulation file and (2) a command that calls a chosen analysis tool to execute the simulation file and produce the requested outputs.

Depending on the objective of the analysis, different design configurations are compared by observing the effect of a combination of external contingencies (e.g., solar incidence, outside temperature, occupation activity) on their performance. We define a sensor to trigger the adaptive system which, for the purpose of this study, is a weather-related variable that is simulated along with the analysis model. The simulated output constitutes a deterministic sampling for the creation of a control strategy for the façade's geometry.

4.3 Optimization

As intrinsically complex systems, the interrelated components of adaptive façades must deal with trade-offs and answer to performance requirements in real-time. Therefore, an optimal adaptive control system is defined by the adoption of the most favorable façade configuration at each simulated moment. To that end, analysis output needs to be processed and sorted according to the project's objectives.

The last phase of our workflow focuses on the interpretation of simulation results to better inform design decisions. To avoid abrupt changes in the façade's geometry, we locate the output values that significantly deviate from the average. Following the post-processing task, the remaining output is assembled into a scatter plot, defining the best performing façade configurations with respect to the sensor's output. Lastly, the scatter plot is interpolated to generate a control surface, which describes the optimal operation strategy for the adaptive façade system.

4.4 Tools

By joining the form-finding and performance assessment stages into an integrated process, the knowledge and experience gained by an analytical consideration of design can be formalized, structured and incorporated into the architectural design practice. There is a wide variety of modeling and simulation tools available, some more complex than others, and requiring different levels of expertise. The present section offers a brief description of the tools considered for this study.

EnergyPlus

As described in Chapter 2, EP is an energy analysis and thermal load simulation program, which reads input from text files (IDF) and writes output to text files. As it lacks a graphical user interface of its own, this tool is intended to be the simulation engine around which a third-party interface (e.g., DesignBuilder, OpenStudio, Honeybee) can be wrapped.

Rhinoceros 3D

Rhinoceros, also known as *Rhino* or *Rhino3D*, is a CAD application based on the NURBS[1] mathematical model. Through an intuitive operational interface, the user can produce 2D drawings and 3D models by generating curves, surfaces, solids, point clouds and polygon meshes (Figure 4.2). Aside from supporting two textual programming languages, *RhinoScript* and *PythonScript*, Rhinoceros features a visual programming tool called Grasshopper, as well as a software development kit that allows for third-party developers to create plugins and add-ons.

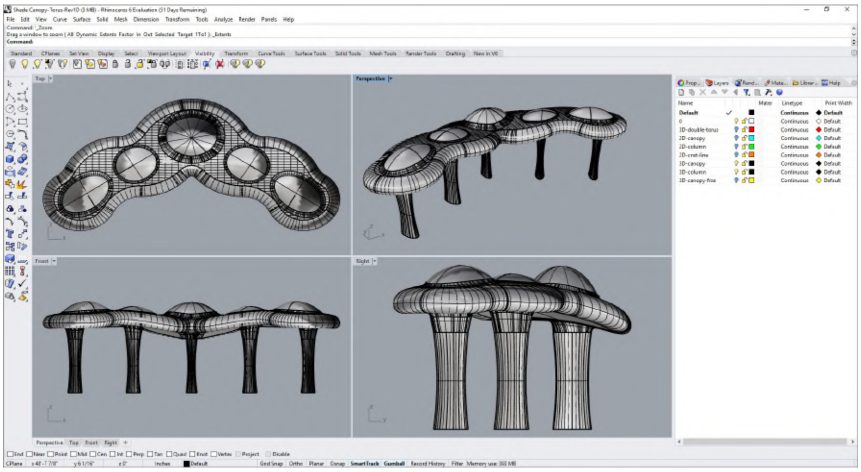


Figure 4.2: Massing model of a canopy design in Rhino (source: http://www.aecbytes.com/tipsandtricks/2018/issue84-rhino.html).

Grasshopper

Grasshopper is a graphical algorithm editor integrated with Rhino's 3D modeling tools. Its flow-based language links multiple components together to form a transformation chain, from input data to generated geometry. Programs are created in a node-based editor, where commands are represented by box-like components which are dragged onto a canvas. Data is transferred from component to component through wires, which always connect an output grip with an input grip. Additional plugins can help complement the built-in command palettes for accomplishing various objectives, from building analysis to model visualization and optimization (Figure 4.3).

[1] Non-Uniform Rational B-Splines (source: https://www.rhino3d.com/nurbs).

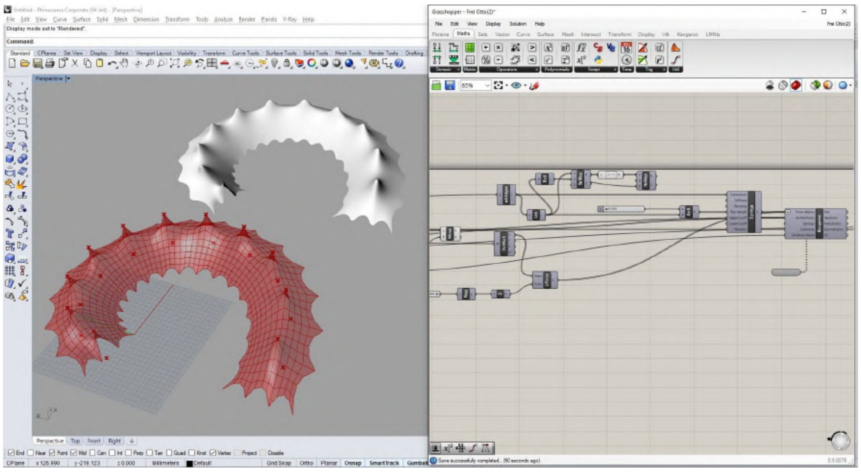


Figure 4.3: Recreation of Frei Otto's German Pavilion using a structural analysis plugin for Grasshopper (source: https://www.youtube.com/watch?v=eE_c40GvRMI).

Honeybee

As part of the *Ladybug Tools*[2] collection, Honeybee is a plugin for Grasshopper that connects it to validated simulation engines such as EP, Radiance, DAYSIM and OpenStudio, for building energy, comfort, daylighting, and lighting simulation. The main purpose of the Honeybee project is to make many of the features of these simulation tools available in a parametric way, and to facilitate the visualization of analysis results (Figure 4.4).

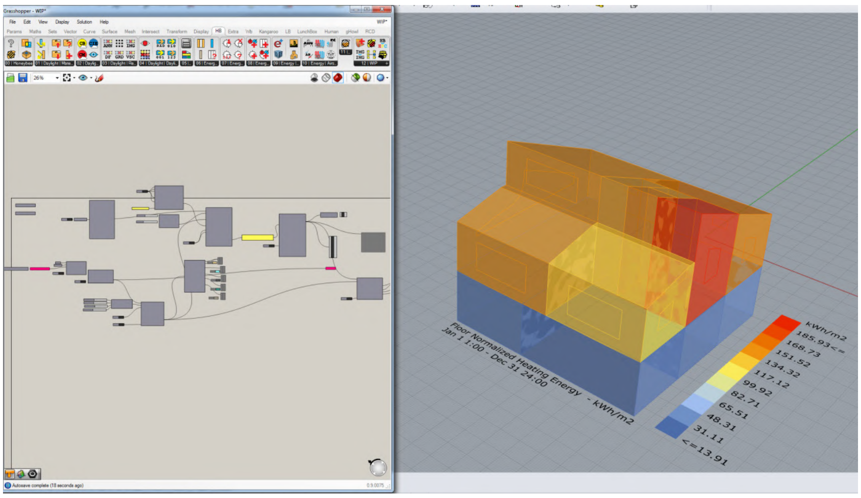


Figure 4.4: Visualization of energy analysis results in Honeybee (source: https://designvisibles.tumblr.com/archive).

[2]https://www.ladybug.tools

Rosetta

The programming environment Rosetta (Lopes and Leitão, 2011) supports several programming languages for the connection of a series of CAD/BIM and analysis tools. Through an abstraction layer, the common operations for geometric modeling are translated into the corresponding operations of each specific tool, commonly known as back-ends, allowing the generation of equivalent models in each tool. Currently, the Rosetta-supported simulation tools include Robot for structural analysis, Radiance and DAYSIM for lighting analysis, and Pathfinder for evacuation analysis (Figure 4.5). To add energy performance simulation into this assembly, a back-end for EP is currently under development.

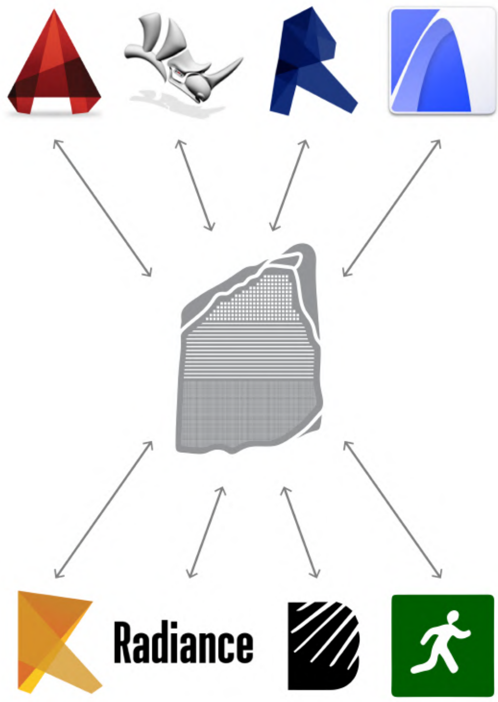


Figure 4.5: Rosetta's back-ends for modeling and analysis.

As different EP graphical user interfaces have different default assumptions and design approaches, their use usually requires developed expertise in the field of energy analysis to assure the quality of the simulation. Notwithstanding the need of a BPS background knowledge, linking Rosetta to EP through a back-end would allow for the whole design process, from the initial concept to parametric optimization, to be fused into a single script, thus eliminating possible data losses that occur when multiple design and analysis tools are used. As a first step towards this objective, we access EP though the Honeybee plugin for Grasshopper. The AD workflow presented in this thesis is further illustrated in Figure 4.6.

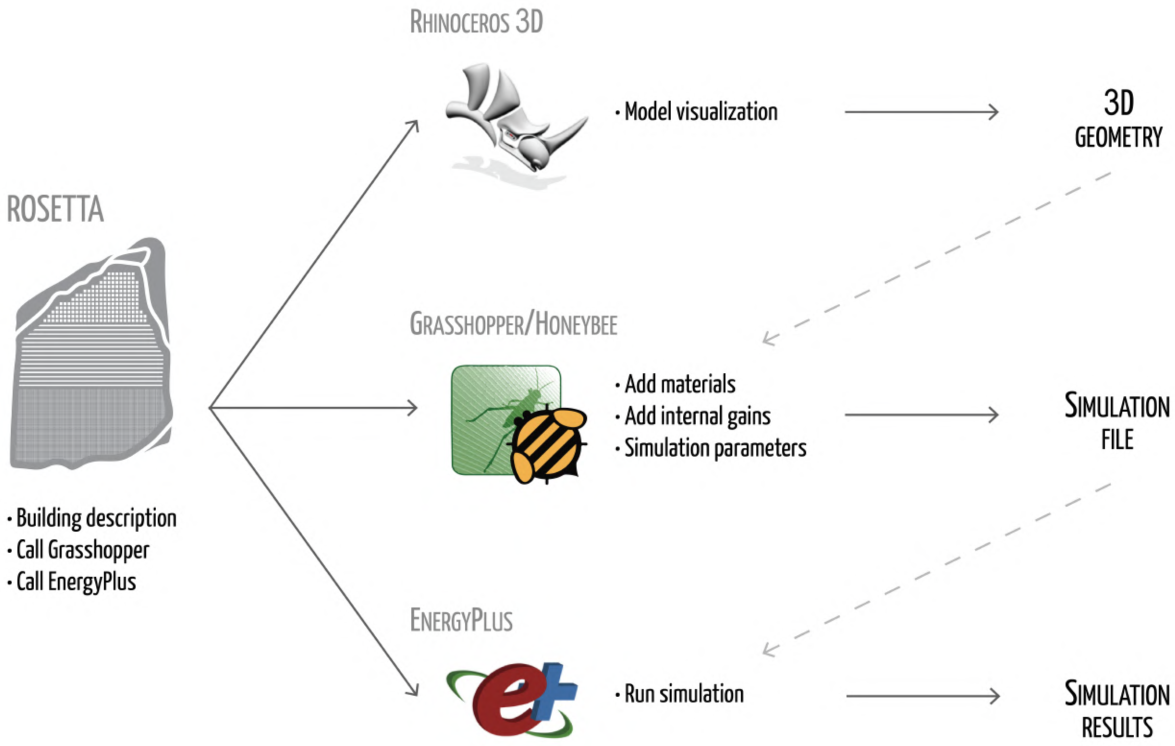


Figure 4.6: Rosetta workflow.

Rosetta is used, in a first instance, to generate a 3D model in Rhinoceros, following a specified geometrical description of the building. Immediately after, the geometry is imported into Grasshopper, where details regarding building materials, internal gains, and simulation parameters are added to the model. This information is promptly gathered by Honeybee into a simulation file, in IDF format, which is placed in a file directory chosen by the user. Lastly, Rosetta retrieves the produced IDF and calls EP to run it, along with a pre-defined *weather file* describing the building's environmental context. The analysis output is displayed in spreadsheet format, to be interpreted and evaluated in a post-processing stage.

CHAPTER 5

Validation Study

Different simulation tools have distinct initial settings and calculation methods that are difficult to control, causing small discrepancies in outputs for the same analytic model. Aside from the required domain knowledge, credibility assurance passes through the exclusion of modeling, simulation or reporting errors. To detect said flaws, Judkoff et al. (1983) proposed a pragmatic approach composed by three primary validation constructs:

- Empirical validation, in which calculated results from a program are compared to monitored data from a real structure or laboratory experiment;
- Analytical verification, in which the output from a program is compared to the result from a known analytical solution;
- Comparative testing, in which a program is compared to itself or to other programs.

Although empirical validation tasks provide an approximated truth standard, the process of gathering data is time-consuming and costly, as well as a possible subject of uncertainty from measurement errors. Analytical assessments have fewer overall costs, but it is hard to ensure the same modeling assumptions, in the sense that the problem description for known solutions is rarely an exact match to the problems they are compared with. Inter-model comparative testing, on the other hand, allows the comparison of any cases that two or more tools can model, having the advantage of not requiring data from a real building. External errors are easily eliminated, granting the user complete control over the accuracy of a model's input. To ensure an efficient workflow, we used an inter-model comparative approach to assess the validity of basic functionalities required for early-stage design.

5.1 Building Energy Simulation Test

Developed by the International Energy Agency[1], the Building Energy Simulation Test (BESTEST) is a well-developed diagnostic method to evaluate energy analysis programs. As input requirements vary from tool to tool, a uniform set of unambiguous test cases is used to perform software-to-software comparisons, allowing the user to produce equivalent models in a variety of detailed and simplified whole-building energy simulation tools (Judkoff and Neymark, 1995). A range of results from a number of detailed public domain models - as *TRNSYS*, *BLAST*, *DOE-2* and *ESP-R* - specify acceptable performance ranges, which can be used as validation and quality control of BPS models.

The BESTEST method is composed by 36 test cases, ranging from case 195 to case 990. While the first represents a very primitive diagnostic case, the latter represents the most thermally-complex model. Series 600 and 900 define the qualification cases, representing a set of lightweight and heavyweight buildings that are relatively realistic with respect to their thermal characteristics. To validate our AD workflow, we used BESTEST cases 600 and 610 as a comparison term. While the first defines the base case test for energy analysis, the second tests the ability of a program to treat shading. The output from validated EP models of these cases[2] was compared to the output of equivalent AD models produced through Rosetta.

5.2 Geometry

Cases 600 and 610 are defined by identical rectangular single zones (8m x 6m x 2.7m) with no interior partitions (Figure 5.1). The South façade has two windows, totalling 12m^2 of glazing area. The construction is lightweight and identical in both geometries. Case 600 has no shading elements, while case 610 has an additional 1m wide horizontal overhang across the South wall (Henninger and Witte, 2015).

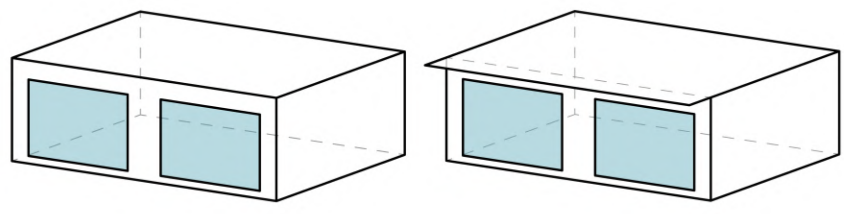


Figure 5.1: BESTEST cases 600 (left) and 610 (right).

[1] https://www.iea.org/about/ourmission/

[2] Available at: http://energyplus.helpserve.com/Knowledgebase/Article/View/128/55/ansiashrae-standard-140----input-files---v80

Both cases were modeled parametrically through Rosetta, in a way that different types of building elements were separated into corresponding layers in Rhinoceros (Figure 5.2). After generating the geometry, the content of each layer was imported into the Grasshopper-Honeybee environment, in which construction materials, internal gains, and simulation parameters were added to the initial model (Figure 5.3). As Honeybee only works with closed geometries, the horizontal overhang of case 610 was modeled as a context shading element, rather than part of the roof construction.

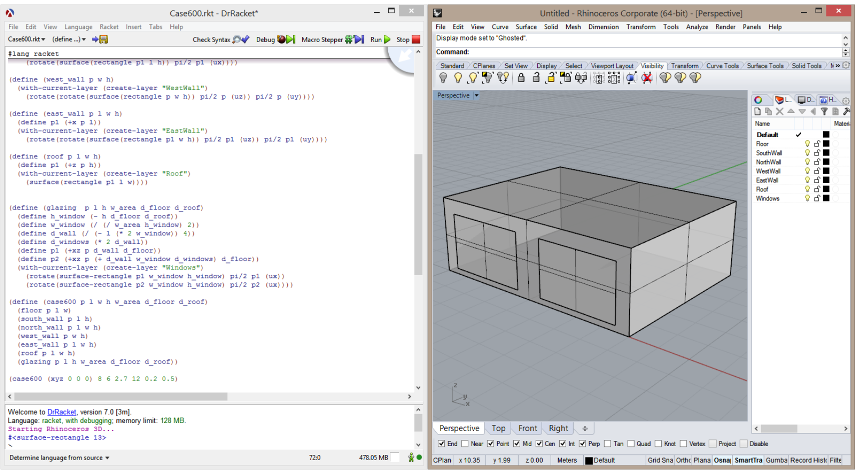


Figure 5.2: Rosetta description (left) and Rhinoceros model (right) of case 600.

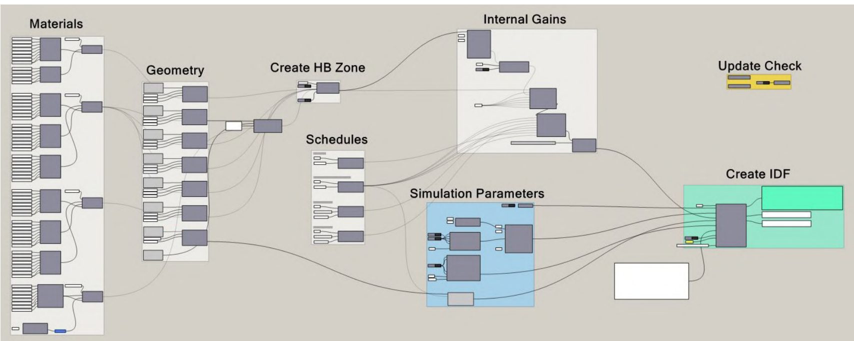


Figure 5.3: Grasshopper-Honeybee description of case 610.

5.3 Internal Gains

The considered BESTEST models comprise the following characteristics:

· Equipment loads are 100% sensible with a 60% radiative fraction, set at a constant consumption of 200W;

· The indoor environment is conditioned by an *Ideal Loads Air System*, with an efficiency of 100% and no capacity limitation;

· The infiltration rate is set at 0.5 air changes/hour, and heating and cooling setpoints are fixed at, respectively, 20ºC and 27ºC;

- No occupancy activity or lighting loads are considered.

5.4 Simulation Parameters

All simulations encompass a year-long analysis period, where a weather file from Denver, U.S.A, characterized by cold clear winters and hot dry summers, is used to define the environmental context of the models. Ground temperatures are constant at 10ºC throughout the year. The solar distribution is defined as *Full Interior and Exterior*, meaning that the solar calculation is performed considering direct solar radiation and its correct distribution in the interior surfaces. Shadow calculations follow a time-step frequency of 4, meaning that, for every hour, four simulations are ran.

The requested outputs include zone mean air temperature, sensible heating and cooling energy, and incident solar radiation on the outside of the building surfaces. After Honeybee gathers the information regarding building geometry and materials, internal gains, and simulation parameters into an IDF, Rosetta calls EP to run it. Simulation results are, then, stored into a previously designated file address.

5.5 Results and Discussion

BESTEST cases 600 and 610 were used as a baseline to validate our AD workflow. To that end, the simulation output of previously validated EP models of these cases were compared to the output of identical AD models. For the purpose of this study, we are assuming an acceptable range up until 10% of variation between results.

Figures 5.4 and 5.5 show the predicted daily average air temperatures over the year. Results are almost identical during warmer seasons, showing a larger discrepancy (up to 8%) with the presence of cold weather. However, this difference is still considered to be within an acceptable range.

Figures 5.6 and 5.7 present the monthly heating and cooling demand for both cases. The output of the AD model varies from the EP output between 0.9 and 2.6% in case 600, and between 0.4 and 7.7% in case 610. Both simulation outputs are within the range presented in the BESTEST study.

It is important to consider that comparative testing is not a certainty over the actual performance of a building performance simulation, but merely an approximation. It exclusively proves that the presented AD workflow is computing solutions that are reasonable when compared to the standalone use of EP for building modeling. With that in mind, we identify enough similarity between the simulation outputs to consider the AD modeling approach valid.

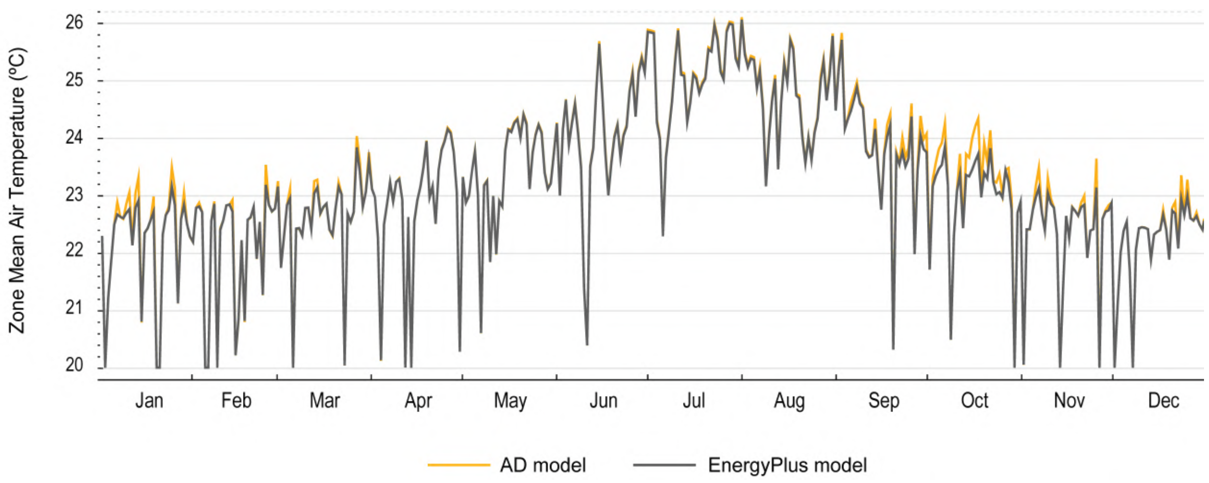


Figure 5.4: BESTEST case 600 daily average temperature plot.

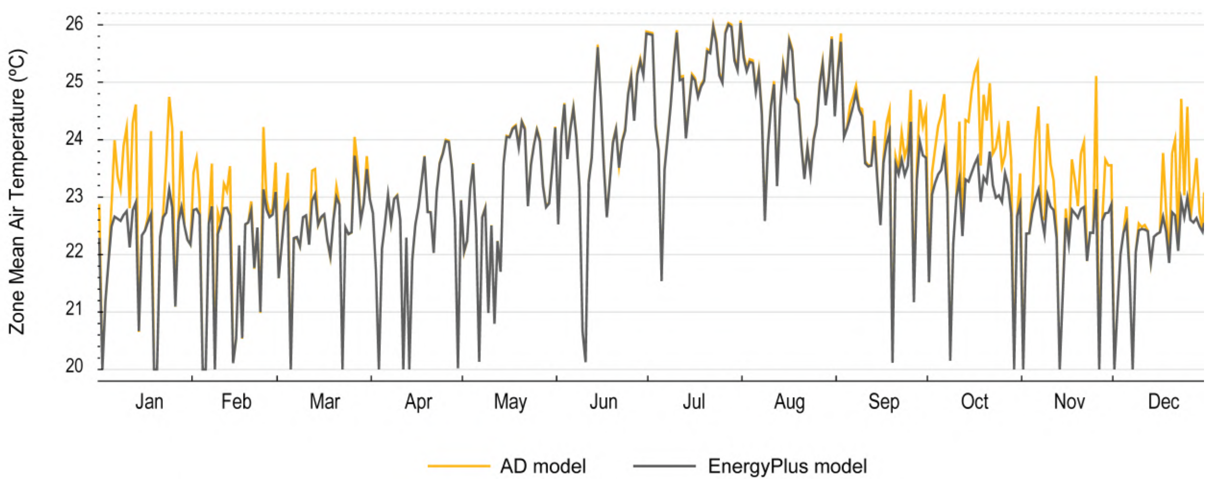


Figure 5.5: BESTEST case 610 daily average temperature plot.

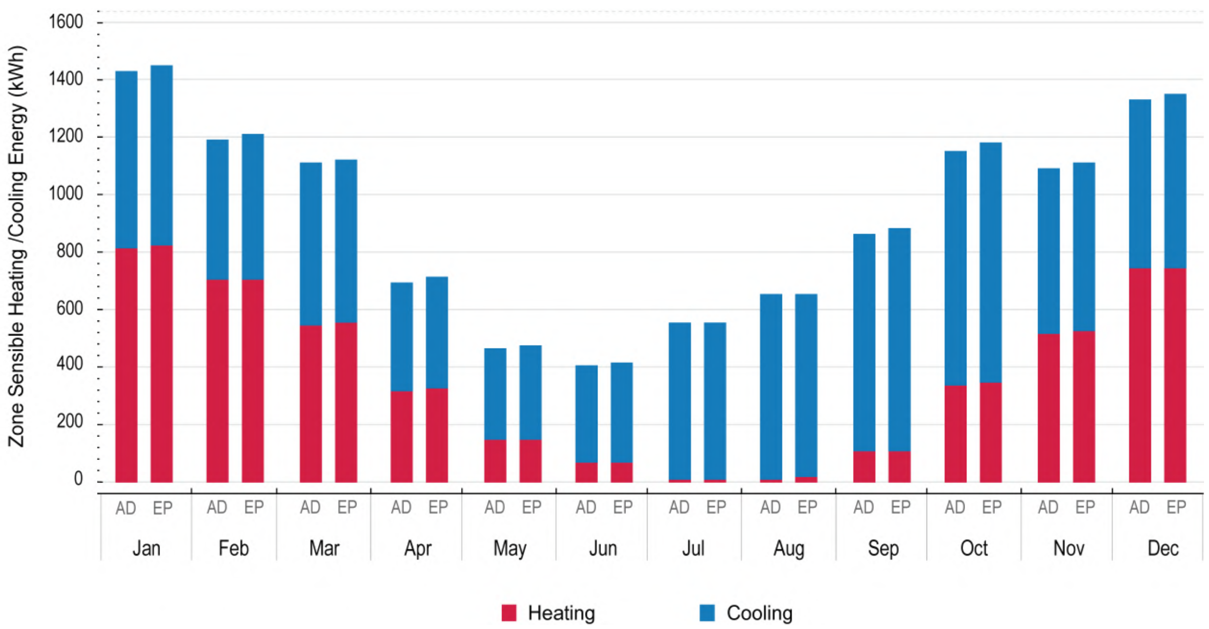


Figure 5.6: BESTEST case 600 heating and cooling demand per month.

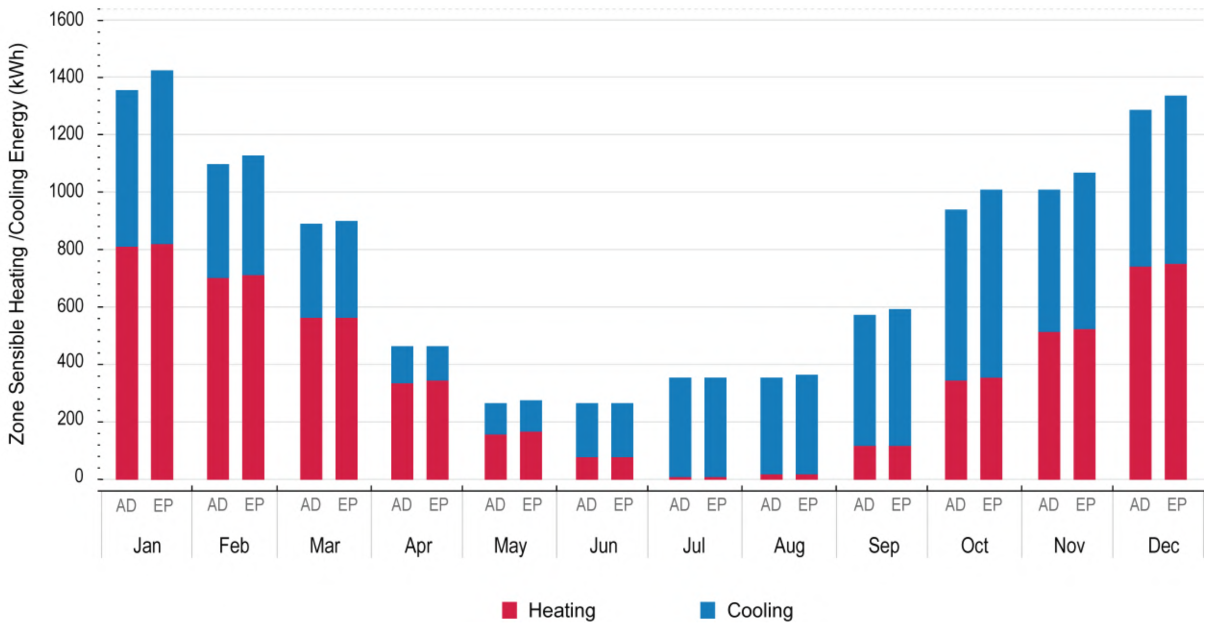


Figure 5.7: BESTEST case 610 heating and cooling demand per month.

CHAPTER 6

Case Study: the Arab World Institute

To evaluate the applicability of the presented AD workflow to an adaptive paradigm, we modeled and simulated a single-zone building which incorporates the façade mechanism of a selected architectural work. The case study is based on the Arab World Institute (Figures 6.1 and 6.2), designed and executed by Jean Nouvel, Architecture-Studio, Pierre Soria, and Gilbert Lèzenes. Built in 1987, it is seen as one of the most distinguished Parisian monuments, articulating the French and Arab histories through its façade. On the North side, linear patterns and markings showcase the western culture by framing the urban landscape across the Seine river. The South side comprises an orthogonal glazed curtain wall, portraying intricate geometric patterns as a contemporary expression of the eastern culture.

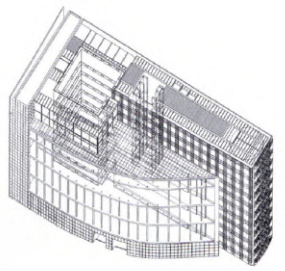


Figure 6.1: Axonometry of the Arab World Institute (source: https://en.wikiarquitectura.com/building/arab-world-institute/).

Figure 6.2: South view of the Arab World Institute. Photo credit: Burçin Yildrim.

Although being recognized as an architectural icon, the Arab World Institute is not sustainable in its entirety. The presence of mechanized components on the Southern façade, which make up the adaptive aspect of the building, can potentially reduce its environmental performance. For this reason, we used this building as a case study, in order to understand the impact of adaptive systems and, consequently, further inform similar design concepts.

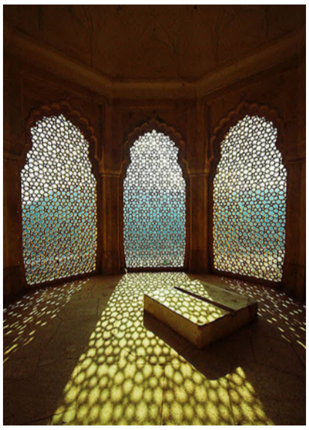


Figure 6.3: Latticed windows in Amer Fort, Jaipur, India. Photo credit: Sean Rutter.

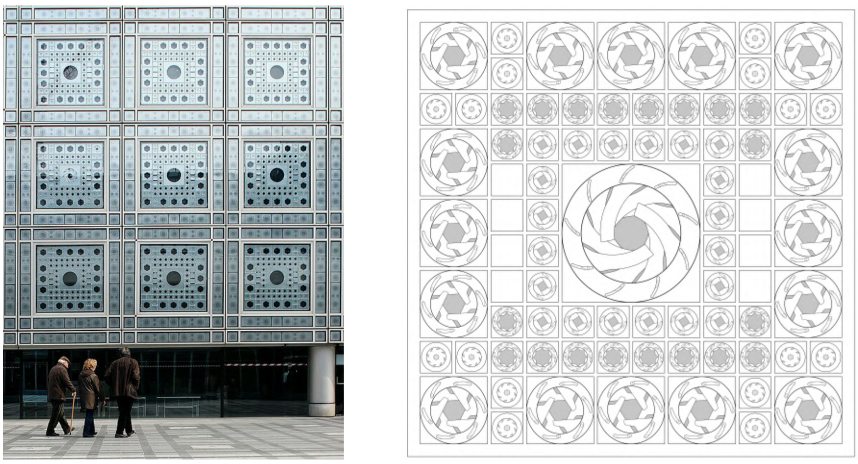
Figure 6.4: House of Suhaymi, Cairo, Egypt. Photo credit: Mohamed Nofalovich.

Figure 6.5: Light effects inside the Arab World Institute (source: http://www.jeannouvel.com/en/projects/institut-du-monde-arabe-ima/).

6.1 Façade System

Often present in the climate-oriented strategies of Islamic architecture, the mashrabiya (Figures 6.3 and 6.4) is a decorative and functional element that merges an aesthetic appeal with daylight control. With the presence of light as main concept, the southern façade of the Arab World Institute holds a kinetic system inspired by these traditional patterns of the Arab geometry. Holding a total of 240 mashrabiyas, the layered configuration of the façade defines the interior space through light and reflections (Figure 6.5) while further integrating the building into its context.

Each façade module has a set of 73 diaphragms, divided into five distinct mobile apertures that mimic the ones of a camera shutter (Figure 6.6). The delicate mechanisms incorporate photoelectric cells, which react to varying solar radiation levels by opening and closing the diaphragms. As such, natural light can be filtered through the façade while the heat gain of the glazed surface is minimized. Acting as a shading element in an otherwise glazed building, the diaphragms grant control over internal temperatures, playing a significant role towards the comfort of occupants.



(a) Detail of the South façade. *(b) Detail of the diaphragms.*

Figure 6.6: Mashrabiyas of the Arab World Institute. (a) Photo credit: Pedro Kok.

6.2 Case Study Model

In order to create an analytical model of the Arab World Institute, we will consider the geometry of BESTEST case 600, shown in Chapter 5. The two original windows are replaced by a set of three mashrabiyas, fully occupying the South wall. In a building analysis context, simulation time increases with the complexity of the model. Hence, we considered simplifying the shape of each diaphragm by reshaping it as a circle with the same area as the original diaphragm, as illustrated in Figure 6.7. The radius for each circle is calculated from the opening area of each diaphragm.

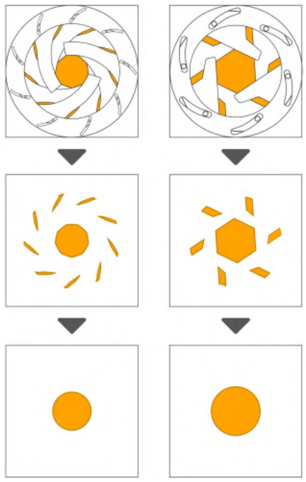


Figure 6.7: Geometric simplification of the aperture mechanisms.

However, circular geometries cannot be processed by EP. To solve this issue, we replace the circular openings with regular polygonal openings with the same area. Ideally, to better approximate the circles, these polygons should have a large number of sides. However, this negatively affects the simulation time. Table 6.1 compares the overall simulation time, along with the annual heating and cooling demands, for year-long analyses using openings of sixteen (Figure 6.10), eight (Figure 6.11), and four sides (Figure 6.12). The latter case shows that the polygon rotation angle is also relevant for reducing simulation time. As the variation in the annual output variables between the four geometries is minor, we opt for the use of axis-aligned squares (Figure 6.13) for the diaphragm openings, as these provide significant reductions in the simulation time.

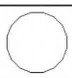
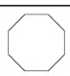
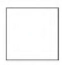
Polygon			Δ (%)		Δ (%)		Δ (%)
Simulation Time (sec)	23953	2127	167.4	422	193.1	88	198.5
Sensible Air Heating [GJ]	15.162	15.134	0.2	15.114	0.3	15.096	0.4
Sensible Air Cooling [GJ]	5.896	5.901	0.1	5.903	0.1	5.905	0.2

Table 6.1: Simulation with different polygonal openings. Δ refers to the percentile variation between the simulation of the 16-side polygon model and the ensuing ones.

As formerly stated, there are five types of diaphragms present in each mashrabiya. For each diaphragm, we assume a minimum opening radius, $r_{\min}$, and an opening amplitude, a, based on measurements from the original geometry. The opening radius for each diaphragm, r (Figure 6.8), is calculated by $r_{\min} + a \cdot f$, where f is a factor between 0 and 1 that describes the level of aperture opening for the façade panels (Figure 6.9). Through Rosetta, we request the simulation of a series of models with static properties that represent different aperture levels for the façade openings.

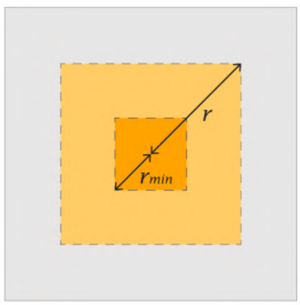
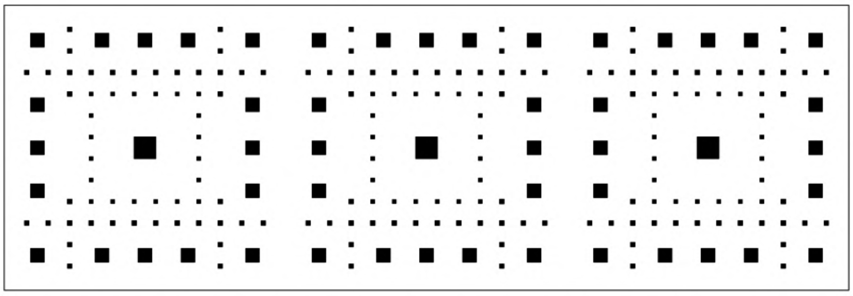
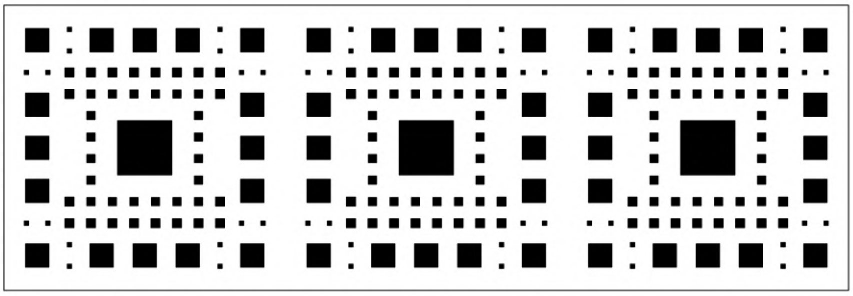


Figure 6.8: Illustration of the opening variation of the façade diaphragms.



(a) $f = 0$



(b) $f = 1$

Figure 6.9: South façade of the simulation model; range of diaphragm aperture (f).

6.3 Energy Analysis

The modeled zone attends to the building program of a small exhibition room, with a maximum occupation of five people and a lighting density of 11 W/m^2. Building construction and material description match those of BESTEST cases 600 and 610. HVAC availability is scheduled between 7 a.m. and 6 p.m., while infiltration is set as constant.

A daylight control system is added to the model, to manage and reduce the use of electric lighting. Through this method, daylight illuminance levels are measured at a reference point, located in the center of the space at the height of 0.8m. The lighting system is triggered by an illuminance setpoint, activating artificial illumination when measurements drop below 500 lux. The control type is set to 'ContinuousOff', meaning that lights switch off completely when the minimum dimming point is reached[1].

We request a series of energy simulations for models with varying f values, with a timestep of 6. Such means that energy balance calculations are ran every 10 minutes during the yearly simulation. Requested outputs include total heating and cooling rates [W], zone lights electric power [W] and the incident solar radiation on the South façade [W/m^2]. Additionally, measurements for the site's outdoor air temperature are retrieved from the used weather file.

[1]https://bigladdersoftware.com/epx/docs/8-0/input-output-reference/page-016.html

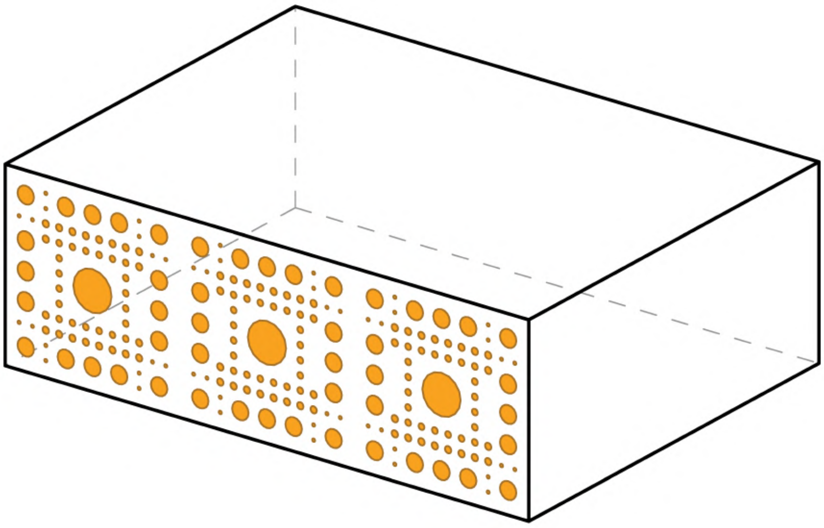


Figure 6.10: Test model using 16-side polygonal openings.

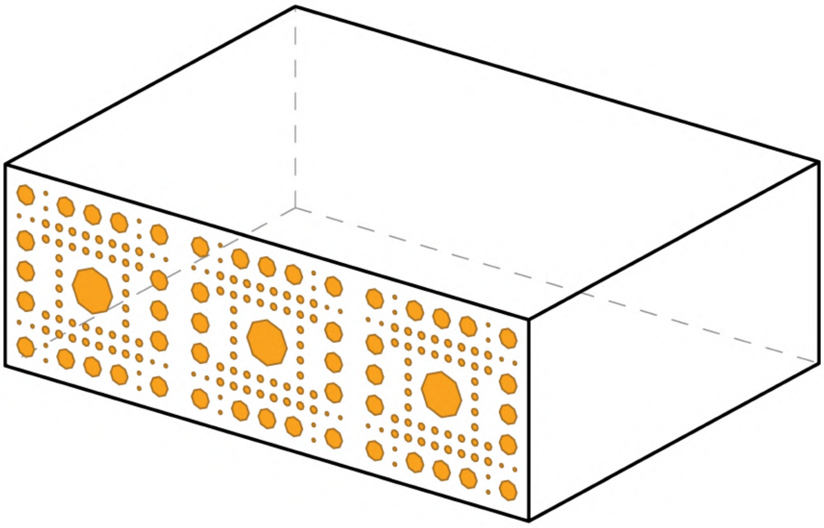


Figure 6.11: Test model using 8-side polygonal openings.

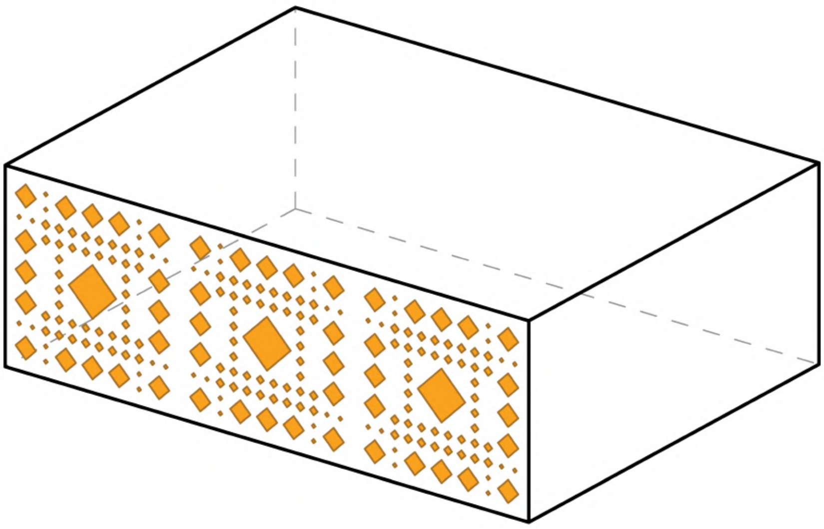


Figure 6.12: Test model using rotated 4-side polygonal openings.

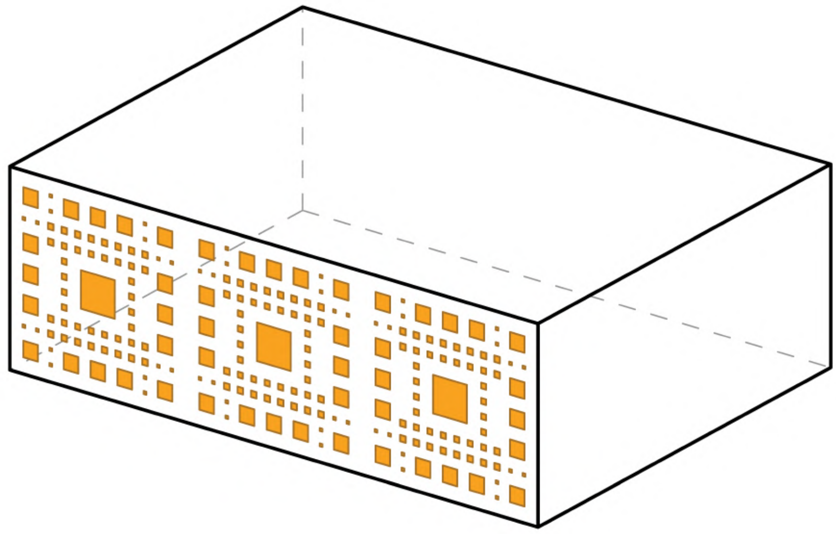


Figure 6.13: Final geometry for the case study.

6.4 Optimization

The control system of the Arab World Institute was originally designed to activate the diaphragms based on the amount of daylight. In the present case study, we optimize not only the lighting, but also the thermal comfort conditions of the simulated zone. To carry out this task, two sensors are defined, namely the (1) façade incident solar radiation and the (2) outdoor air temperature. The goal is to find the optimal value of f, i.e., the aperture level that yields the lowest energy consumption, for the correspondent combination of values formed by the two sensors.

The total energy use for each simulation timestep is calculated as the sum of the heating, cooling, and lighting energy use. The heating and cooling energy use is determined from the heating and cooling energy needs divided, respectively, by a Coefficient Of Performance (COP) and an Energy Efficiency Ratio (EER). In the present study, COP and EER assume the standard values of 3 and 3.4, respectively. After performing the necessary simulation analyses, we:

1. Examine the values' distribution;
2. Locate the analyses for which the change in the f factor would not increase or decrease the energy use. Such could be explained by the chosen time-schedules (e.g. between 5 and 7 a.m., when the lack of occupancy and HVAC availability produces a null energy consumption). As these values do not provide any valuable data, we eliminate those records;
3. Remove the analysis outputs for which the difference in the f factor

was larger than the average, to avoid abrupt changes in the diaphragm openings.

Further discrepancies in the output values of consecutive analyses might occur. Such can be explained by the delay between the triggering of the radiation and temperature sensors and the actual effects of closing/opening the diaphragms. To minimize this effect and remove noise from the collected data, we interpolate the values whenever an abrupt change is detected. For example, if the optimal opening factor is 0.2 at 10 a.m., 0.6 at 11 a.m. and 0.4 at 12 a.m., we make a more gradual variation of values by changing the opening factor of 11 a.m. to 0.3.

After processing the simulation data, we create a scatter plot describing the variation of the opening factor, f, with respect to the incident solar radiation and the outdoor temperature levels. However, given the amount of generated points, the scatter plot does not provide a clear view of these variations. Therefore, we aim for the design of a control surface that would allow the prediction of an optimal diaphragm behavior according to the output of the sensors. To do so, we approximate a surface using the cubic Smooth Bi-Variate Spline interpolation technique (Craven and Wahba, 1978). The resultant surface from the connection of these splines defines a control strategy for the adaptive shading device formed by the façade diaphragms.

6.5 Results and Discussion

Figure 6.14 illustrates the results of the performance analysis, overlapped with the resultant control surface for the façade diaphragms. This surface enables the optimization of the opening factor, as it allows us to determine which would be the best f value for specific levels of outdoor temperature and incident solar radiation on the adaptive façade.

The analysis scatter plot contains a significant amount of outlier values. Such means that multiple values of f in the same timestep may result in equally low building energy needs. It can also mean that for different moments with similar environmental conditions, different optimal responses can occur. Another possible cause for the outliers are the chosen light dimming strategy, which largely affects the total energy sum.

As expected, the value of f decreases as the outdoor temperature and incident solar radiation increase. The site location of the case study translates into a saturation of higher opening factors, as temperatures in the region often fail to surpass 0°C during periods of cold weather. As the diaphragms are fully open the majority of the time, the control system is still

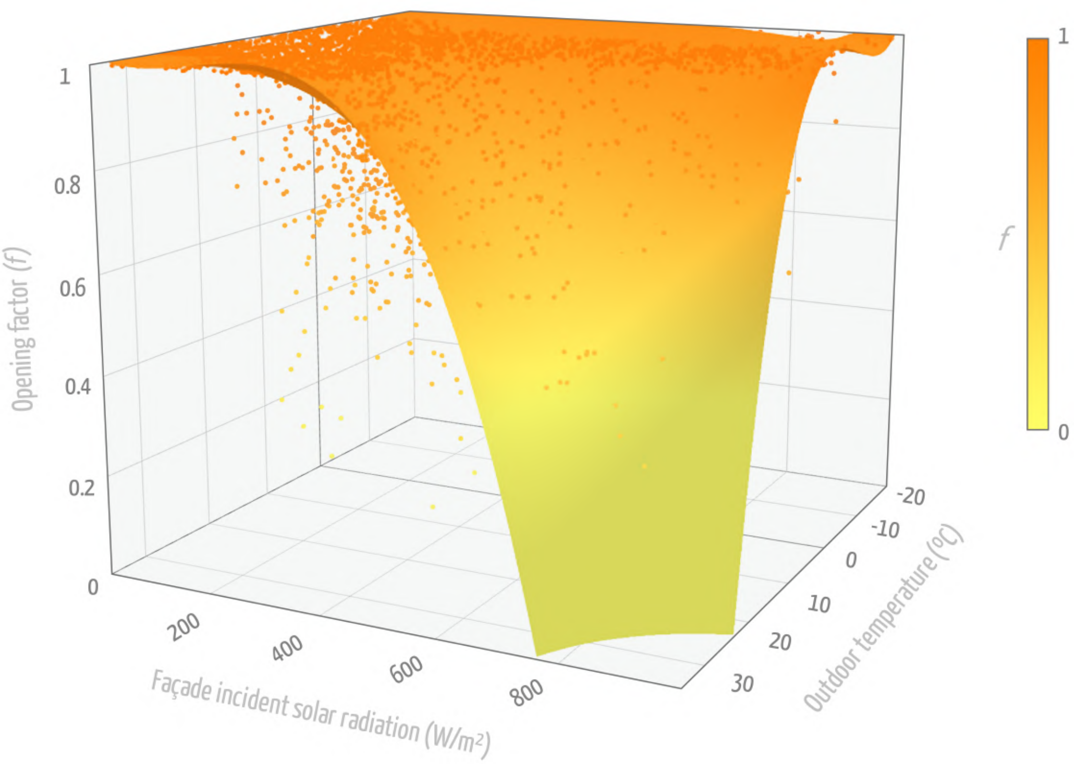


Figure 6.14: Optimal opening factor (f) for the adaptive façade diaphragms, in function of the façade incident solar radiation and outdoor air temperature levels.

not optimal, showing a need either for the addition of façade panels or to increase the opening area of the existing ones.

Note that the purpose of the proposed AD strategy is not only to inform architects about possible savings in energy loads, but also to help identify design changes that can positively alter the building's performance. In this example, this is demonstrated by the discovery of the saturation that is happening at lower temperatures, suggesting that changes should be made to the façade's design. The final outcome of the developed work, therefore, satisfies the initial aim of developing an early-stage, performance-based design approach for adaptive façade systems.

CONCLUSION

Architecture faces unprecedented demands to reduce the environmental damage of constructions, to employ the use of renewable energy sources, and to establish reliable and accurate performance analysis methods for buildings. As the interface between interior spaces and the outdoor environment, the façade is a key building element which can considerably influence energy use, indoor climate, and occupant comfort levels. Recently, adaptive façade concepts have become a research topic of significance in the area of sustainable design, given their potential to reduce a building's energy demand while providing new design opportunities.

There is a growing interest in the use of building performance simulation (BPS) strategies in form-finding approaches, mostly towards the integration of parametric models with dedicated analysis software. It is hypothesized that the combination of computational modeling, simulation and optimization can form an essential resource in stimulating the development of adaptive façade technologies. However, this is a complex task, and currently available BPS tools lack capabilities to support this process (Loonen, 2018).

We present a unified Algorithmic Design (AD) approach that combines, in an early design stage, the parametric modeling and the energy performance analysis of buildings with moving components. After validating the workflow, the proposed methodology was applied to a case study, where a reactive façade mechanism was represented by a set of models with static properties illustrating different stages of motion. Simulation results were gathered in a post-processing stage, being further interpreted to find the most favorable façade configuration at each simulated moment. The processed analysis output was, then, used to define an optimal control strategy for the case study, based on solar radiation incidence and outdoor temperature levels.

Final Considerations

MODELING APPROACH

Many design studios use traditional 3D modeling tools to visualize design solutions. However, these tools are often handled through a direct manipulation of geometry, which can limit and effectively restrict the exploration of more complex design options. The presented AD workflow creates the possibility of quickly generating several design options from the same parametric model: through this method, the implementation of design changes can be achieved in shorter timespans. Moreover, we integrate the generation of parametric models with the execution of energy analysis into a single algorithmic description, which can potentially reduce the amount of additional work from the project team.

WORKFLOW VALIDATION

To ensure an efficient workflow, we used an inter-model comparative approach to assess the validity of basic functionalities required for energy simulation. BESTEST cases 600 and 610 were used as a baseline for comparing the outputs produced by the AD model. The discrepancy between simulation results is considered to be within an acceptable range: however, it is important to consider that comparative testing is simply an approximation towards the actual efficacy of simulation software. This validation serves to demonstrate that the presented AD workflow is computing solutions that are reasonable, when compared to the standalone use of EnergyPlus for building modeling.

ANALYSIS RESULTS

The retrieved analysis output was sorted, exposing the façade configurations with the lowest energy consumption at each simulation timestep. To define an optimal adaptive control system without abrupt changes in the façade's geometry, we smoothed the output values that significantly deviated from the average. The remaining output was assembled into a scatter plot, defining the best performing façade configurations with respect to the sensors' output. The final outcome of the analysis can further inform future design decisions, thus carrying out the outlined objectives.

APPLICABILITY OF WORK

The application of AD strategies has often raised concerns in architectural practices. The requirement for programming knowledge is often seen as a setback, as it is less cost-effective and implies considerable time investments for a design team to properly acquire the necessary skills and techniques. However, as projects reach wider scales, this initial cost can be quickly recovered when there is a need to incorporate design changes, as the architect can quickly generate a different model by simply adjusting a set of parameters. By joining the form-finding and performance assessment stages into an integrated process, the knowledge and experience gained by an analytical consideration of design can be formalized, structured and incorporated into the architectural design practice. The access to feedback over the performance of multiple design solutions is facilitated, as simulation is executed right after the geometry is generated. Despite being generally associated with cutbacks on creative thinking, AD allows for the exploration of building geometries that, otherwise, would not have been considered. Furthermore, this work proves that the integration of energy analysis into an AD process enables the finding of informed solutions in shorter timespans, which can benefit the design of complex buildings with adaptive components.

Future work

It should be noted that the contents of this thesis are part of a wider research process. This section highlights the main topics towards further developments of the presented methodology, from complementary research to new modeling and simulation approaches for adaptive façade concepts.

MODEL FLEXIBILITY

We applied a design approach that implies the simulation of a series of static models to assess the overall performance of an adaptive façade. This process, however, has a high computational cost, specially when there is a high level of model complexity involved. This can be reflected as an obstacle towards the comparison of different design solutions and, as such, the presented approach requires further development. Future work comprises the exploration of new variable building geometries and material properties, using enhanced modeling techniques and performance metrics.

SIMPLIFIED WORKFLOW

In Chapter 2, we reviewed the drawbacks in the abstraction mechanisms of visual programming languages (VPL), emphasizing a general lack of scalability which compromises the performance and legibility of complex programs. In that regard, future developments of the presented methodology comprise the removal of VPL-based tools from the workflow. This is seen as a limitation, considering that a future objective is to expand this AD approach further from an early design stage, integrating the generation of models with high levels of complexity and detail.

ITERATION

In the context of computer programming, the term 'iteration' defines the repetition of a set of instructions a specified number of times or until a designated condition is met. One limitation of the presented workflow is that it does not yet encompass iteration processes, where analysis results are used to improve the original design. For instance, in the case study developed in Chapter 6, this could be used to identify an optimized number of façade panels or the limits of the diaphragm opening ranges. We are currently working on incorporating this feature.

TIME-DELAYED FEEDBACK

The methodology presented in Chapter 4 implies that we can sum the outputs of energy demand obtained from separate performance simulations.

However, it cannot be assured that a succession of optimal sets of values returns the lowest possible total energy demand over a certain period of time (Goia and Cascone, 2014). This means that what we consider an optimal opening factor at a certain timestep, does not take in consideration the conditions of the previous timesteps. The system's reaction time is also an influential factor for the interpretation of simulation outputs: when external conditions imply a shift in building geometries, there is a considerable delay between the control action and the changing conditions within the building. Improvements regarding our methodology could be achieved by attributing a time-continuity factor to energy simulations, so that the conditions at the end of one simulated timestep would define the initial conditions for the next one, along with the introduction of coping strategies regarding the reaction time of adaptive systems.

MAINTENANCE

Numerous buildings have designed innovative adaptive façade technologies that, upon construction, suffered mechanical faults which reduced their usability. Aedas' Al Bahr Towers (Figure 6.15) and Jean Nouvel's Arab World Institute (Figure 6.16) are pertinent examples of this inconvenient.

Figure 6.16: Mechanical diaphragms of the Arab World Institute – damage to the arm that transmits the force of the motor to the diaphragm actuation mechanism (source: Meagher (2015)).

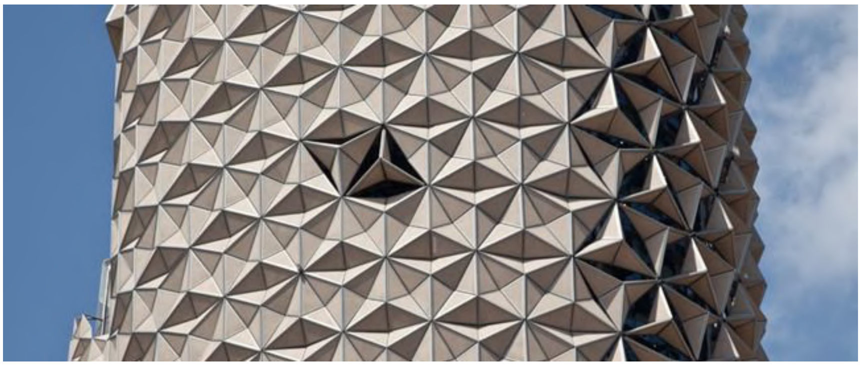


Figure 6.15: Mechanical malfunction on one of the Al Bahr Towers (source: https://www.techzug.com/architecture/the-al-bahar-tower-abu-dhabi.html).

The increase of façade responsiveness is directly related to the increase of system complexity, inflating construction, installation, and maintenance costs. Moreover, adaptive systems require a large amount of energy for operation, which should ideally be lower than the energy saving (Barozzi et al., 2016). These aspects will have to be considered to ensure the sustainability of the systems. Future developments in our methodology aim to ensure that the ease of maintenance is considered throughout the design process and that the benefits of fixing the system are more valuable than abandoning the project, or the system becoming obsolete.

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