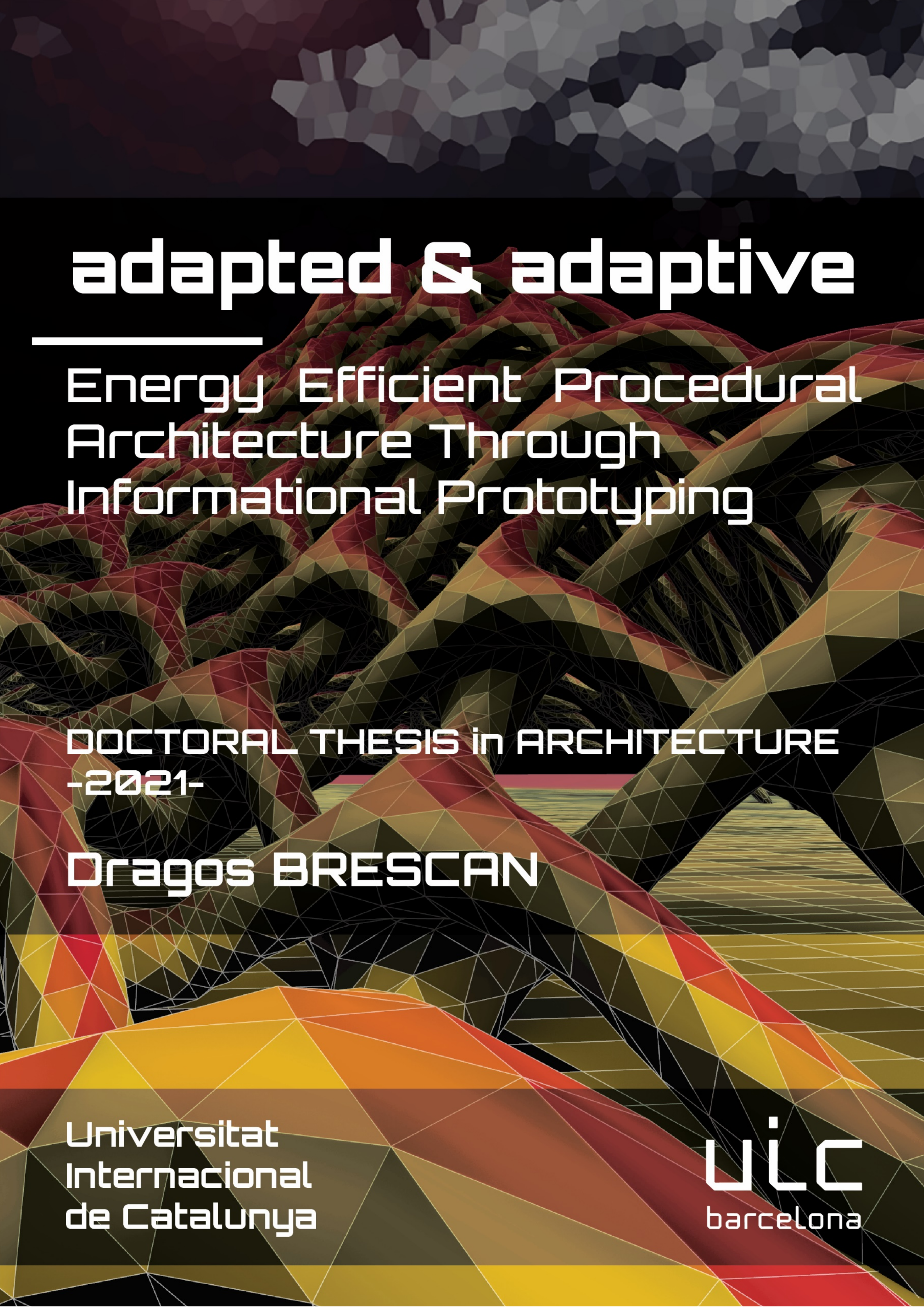
Universitat Internacional de Catalunya
School of Architecture

Tesis doctoral

Adapted & adaptive: Energy efficient procedural architecture through informational prototyping

Dragos Brescan



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- Adapted & Adaptive -

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DOCTORAL THESIS IN ARCHITECTURE

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In the memory of my grandfather,
for his guidance towards the best imaginative
and creative worlds!

May his minstrel stories transcend through time
to all future generations!

Acknowledgments

This thesis is first and foremost devoted to my family: my fiancée Simona, my parents Mady and Marian, and my loving brother Sergiu, as well as Ade and Stefan. Because of their constant support and encouragement, I began this journey and have had the strength to stand and continue.

The thesis may appear to be an advanced specialized proposal with a broad theoretical and technical background, but in fact, it is the result of many experiences within the ample field of architecture. I couldn't have achieved this much knowledge and experience throughout this period without the people I deem close and stood by me in this venture.

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Contents (concise)

Contents

List of Abbreviations

Abbreviation	Meaning	Page
EDIS	Environmental Data Indexing System	2
ABEM	Adaptive Building Efficiency Methodology	2
nZEB	net-Zero Energy Building	8
LEED	Leadership in Energy and Environmental Design	8
LCA	Life Cycle Assessment	19
USGBC	United States Green Building Council	27
CAD	Computer-Aided Design	30
*.epw	EnergyPlus Weather files	31
SBC	Single-Board-Computer	32
RES	Renewable Energy Systems	44
LT	Location and Transportation	58
LEB	Low Energy Buildings	60
MERV	Minimum Efficiency Reporting Value	67
HMRV	Heat Recovery Mechanical Ventilation	81
VIPs	Vacuum Insulation Panels	88
GFPs	Gas-Filled Panels	89
PE	Primary Energy	99
GWP	Global Warming Potential	99
BIM	Building Information Modelling	100
BPM	Building Procedural Modelling	176
GAN	Generative Adversarial Network	202
VR	Virtual Reality	207
AR	Augmented Reality	207
HMD	Head-Mounted Devices	213
IOT	Internet of Things	230
GBI	Green Building Institute	350
IDP	Integrated Design Process	353
ICSP	In-Circuit Serial Programming	372
RTC	Real-Time Clock	373

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Abstract

1. Abstract

1.1. English version

This research focuses on describing the ability of adaptivity toward continual optimization within architecture. The attributes of adaptivity are always reliant on information and the capacity to obtain it. If the source information is incorrect, it is safe to conclude that whatever the output is, it will be neither optimized nor adequately adaptable, resulting in an unsuitable variance.

Thus, the thesis elaborates on how passive and energy-efficient buildings are designed, pointing out that technological systems implemented in these types of constructions go hand in hand with their immediate environment. In this sense, if the surrounding area changes, all systems would be influenced resulting in an overstress. This fact in turn results in the consumption of supplementary resources to recover its balance. Thus, to mitigate this situation the solution proposed will turn to nature to learn about its vast means of adaptation.

Adaptivity represents a process through which an organism can become more tolerant to the alterations of its habitat. This case is also enforced within architecture since buildings are constantly “evolving” following the setting in which they reside. As a result, architecture may be regarded as a form of adaptation.

However, our strive is not concluded with only this statement, since external forces become harsher by the passing of each year. Thus, it is considered that adaptability in architecture has to endeavor towards quicker responses, or at the very least take into consideration the possible climatic shifts of the surroundings.

In the past few years, the development of adaptive architecture has paid attention towards implementing kinetic, dynamic, and responsive systems and facades through experimentations in the fields of materials and mechanisms, i.e., Al Bahar Towers (Dubai), Media-TIC Edifice (Barcelona), Theme Pavilion (Yeosu), etc.; the trend eventually starting to shift focus from surface/envelope towards an intra-

body approach, paying more attention to the user's constant fluctuance within comfort and wellbeing.

Thus, the research assumes that the need to fully combine physical and digital techniques represents a complementary opportunity, and also influences its full impact regarding its climatic circumstances.

For any adapted or adaptive development to function as intended, it is imperative to completely comprehend the environment in which it will be placed. This implies a thorough climate data collection that is specific for every site. In this sense, the approach entails the development of an Environmental Data Indexing System (further referred to as EDIS) dedicated to accounting for the lack of climatic information.

Complementary to this, an Adaptive Building Efficiency Methodology (abbreviated as ABEM) is furtherly envisioned, which is meant to guide architects and designers through the vast disciplines of energy efficiency strategies, adaptivity conceptualizations, and environmental evaluation to achieve the most conscious result for the setting in which it would be developed.

The tools used within the ABEM use a procedural basis with input subjects coming from informational applications derived from energy efficiency standards, and the EDIS collected data.

This research contributes to the development of resource-efficient building methodologies that positively interact with the natural environment. This is made feasible by the EDIS's continuous environmental feedback alongside a highly energy-efficient edifice. Based on the ABEM, methodological inputs include practical and theoretical expertise for greater understanding, execution, analysis, and evaluation of architectural morphologies, building envelopes, and adaptable solutions.

1.2. Versión en español

Esta investigación se enfoca en describir la capacidad de adaptabilidad hacia la optimización continua dentro de la arquitectura. Los atributos de adaptabilidad siempre dependen de la información y la capacidad para obtenerla. Si la información de origen es incorrecta, es seguro concluir que cualquiera que sea el resultado, no estará optimizado ni se adaptará adecuadamente, lo que dará como resultado una variación inadecuada.

Así, la tesis profundiza en la forma en que se diseñan los edificios pasivos y energéticamente eficientes, señalando que los sistemas tecnológicos implementados en este tipo de construcciones van de la mano con su entorno inmediato. En este sentido, si el área circundante cambia, todos los sistemas se verán afectados y se producirá una sobrecarga. Este hecho se traduce a su vez en el consumo de recursos complementarios para recuperar su equilibrio. Así, para paliar esta situación la solución propuesta recurrirá a la naturaleza para conocer sus vastos medios de adaptación.

La adaptabilidad representa un proceso a través del cual un organismo puede volverse más tolerante a las alteraciones de su hábitat. Este caso también se aplica dentro de la arquitectura, ya que los edificios están en constante "evolución" de acuerdo con el entorno en el que residen. Como resultado, la arquitectura puede claramente ser considerada como una forma de adaptación.

Sin embargo, nuestro empeño no concluye sólo con esta declaración, ya que las fuerzas externas se vuelven más duras con el pasar de los años. Así, se considera que la adaptabilidad en arquitectura ha de tender hacia respuestas más rápidas, o al menos tener en cuenta los posibles cambios climáticos del entorno.

En los últimos años, el desarrollo de la arquitectura adaptativa ha prestado atención a la implementación de sistemas y fachadas cinéticas, dinámicas y receptivas a través de experimentaciones en los campos de materiales y mecanismos, es decir, Al Bahar Towers (Dubai), Media-TIC Edifice (Barcelona), Theme Pavillion (Yeosu), etc.; la tendencia eventualmente comenzó a cambiar el enfoque de la superficie/envolvente hacia un enfoque "intra-corporal", prestando más atención a la fluctuación constante del usuario dentro de la comodidad y el bienestar.

Por lo tanto, la investigación asume que la necesidad de combinar plenamente las técnicas físicas y digitales representa una oportunidad complementaria, y también influye en su pleno impacto en relación con sus circunstancias climáticas.

Para que cualquier desarrollo adaptado o adaptativo funcione según lo previsto, es imperativo comprender completamente el entorno en el que se ubicará. Esto implica una recopilación exhaustiva de datos climáticos específicos para todos y cada uno de los sitios. En este sentido, el enfoque implica el desarrollo de un Sistema de Indización de Datos Ambientales (más conocido como EDIS) dedicado a contabilizar la falta de información climática.

Complementariamente a esto, se prevé una Metodología de Eficiencia de Construcción Adaptativa (abreviada como ABEM), que está destinada a guiar a los arquitectos y diseñadores a través de las vastas disciplinas de estrategias de eficiencia energética, conceptualizaciones de adaptabilidad y evaluación ambiental para lograr el resultado más consciente para el escenario en el que se desarrollaría.

Las herramientas utilizadas dentro de la ABEM utilizan una base procesal con temas de entrada provenientes de aplicaciones informativas derivadas de los estándares de eficiencia energética y los datos recopilados por el EDIS.

Esta investigación contribuye al desarrollo de metodologías de construcción eficientes en recursos que interactúan positivamente con el entorno natural. Esto es factible gracias a la retroalimentación ambiental continua del EDIS junto con un edificio de alta eficiencia energética. Con base en ABEM, los insumos metodológicos incluyen experiencia práctica y teórica para una mayor comprensión, ejecución, análisis y evaluación de morfologías arquitectónicas, envolventes de edificios y soluciones adaptables.

1.3. Keywords.

Architecture, Adapted, Adaptive, Energy Efficiency, Passive, Active, Strategies, Biodigital, Procedural Design, Rhinoceros 3D, Grasshopper, Ladybug.

Introduction

2. Introduction

This research presents an essential piece of a bigger puzzle that defines the ability of adaptivity towards constant optimization within architecture, hereby the title, “Adapted & Adaptive”. The aforementioned characteristics are always dependent on information and the ability to gather it. If the source information is wrong, it can be freely assumed that whatever the output is, it will surely be neither optimized nor properly adaptive since it would give an unfit variance.

Observing the way urban and rural environments develop, not only points out the disconnection of inhabitants to the surrounding world, but also the barrier between the built and natural environments, causing them to act against each other. This, no doubt, requires various concerns for its unfolding to be completely understood as a new, evolving form of reality.

Thus, the main point addressed here is the lack of information that would determine an “Adapted and Adaptive” type of architecture that would perform at high energy efficiency standards while meeting the user’s constant needs. This is envisioned over a longer period of time and takes into consideration the environmental changes.

To achieve this status, the domains that take part in these developments need to be fully understood.

2.1. Area of Research and Motivation

This thesis integrates energy efficiency, adaptivity, procedural design and computation, environmental analysis, and informational prototyping into transdisciplinary research that would lead to a viable “adapted and adaptive” development methodology.

The established approaches demonstrate a collection of prototype and tailorable adaptable systems and advancements, emphasizing procedural design processes within the context of developing architectural adaptivity and sustainability strategies.

2.1.1. Context

The architectural domain is one, if not the vastest out of the theoretical and practical sciences. This is due to its use of information and techniques from other domains to generate holistic results that initially were meant to accommodate people. Its evolution in time offered different orientations from proving wealth through artistic exposure to simplistic, yet effective manifestations of functionalities, but it always revolved around its main principle of offering a comfortable environment for people to reside in.

As time passes by, the field of architecture must continually immerse itself in different technological fields in order to meet our needs, and also to perfect and push forward the adaptive architectural applicability.

The present tendencies within energy-efficient and sustainable buildings are mainly represented by the following standards and certification strategies: Passive House, Leadership in Energy Efficiency in Design (LEED), net-Zero Energy Buildings (nZEB), and active house. The whole concept revolves around minimizing the energy use, by optimizing the thermal insulative capacity of the external construction envelope. This in turn branches out to other aspects such as sustainability and user comfort.[1]

A starting point for observing energy efficiency is to associate the building with a microclimate that is reliant on both regular and irregular energy input.[2]

2.1.2. Motivation

Observing the disciplinal disruptiveness within the development of adaptive efficient edifices, founded the motivation of this thesis. This intent is meant to close the gap between the initial phases of the design process, materialization,

[1] Dunja Mikulic and others, 'Environmental Impact of Improving Energy Efficiency of Buildings', *2nd International Conference on Sustainable Construction Materials and Technologies*, November, 2010, 1183–91 (p. 2).

[2] Wim Zeiler and Gert Boxem, 'Active House Concept versus Passive House', *SASBE 2009 - Proceedings of the 3rd CIB International Conference on Smart and Sustainable Built Environment*, 4.July (2009), p. 2.

and performance assessments, and was originally named "Implementation of Adaptive and Interactive Architecture in the Development of Energy Efficient Buildings". The original approach was to build structurally and energy-efficient "informed" edifices from a computational standpoint, in addition to reflecting upon the concept, and challenging the domains of climate data integrity and procedural developments.

Growing efforts in unveiling adequately indexed data while establishing rational and multidisciplinary approaches shifted the study emphasis towards the domain of interactive prototyping in architecture. Based on these facts, the aim is to offer both a reliable system for data indexing and collection, as well as a design-to-development method for a seamless multidisciplinary efficiency approach.

Furthermore, to consciously and creatively take advantage and employ novel techniques of design implementation, innovative methodologies are necessary.

As a result, the essential forgoing knowledge and reasoning processes (that are relevant in the architectural and creative design industries) represent the primary motivators, alongside established subsequent knowledge, which is founded on experimentation.

2.2. State of the Problem and Hypothesis

Personal observations within the implementation of energy-efficient solutions, in reality, raised several issues (such as overheating and overstressing results or obsolete solutions) about the role and influence of modern and developing technical approaches towards achieving structurally, ecologically, and functionally efficient edifices.[3] [4]

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[3] George Buhnici, '#casabuhnici - Cum Am Trecut Peste Iarnă', 2018 <https://www.youtube.com/watch?v=LG1cbFplXTo&list=PL5eGc7CrOWSHiwX23of5ZevAgtTnyMMoH&index=28&ab_channel=GeorgeBuhnici> [accessed 28 April 2018].

[4] Juan MaríaHidalgo-Betanzos and others, 'Overheating Assessment of a Passive House Case Study in Spain and Operational Optimization', *Effective Ventilation in High Performance Buildings: 36th AIVC Conference*, 2015, 645–55.

Albeit, prior to pinning down the study topics, fundamental facts about adaptive methods in the current design, and cutting-edge efficiency technologies in the building sector, must be addressed on a broader scale.

As a result, relevant issues in the domains of energy efficiency, procedural design, environmental design, and interactive prototyping will be investigated in conceptual, methodological, and technical scopes to create a guided research hypothesis.

2.2.1. Problem description

The purpose of this research is to ensure proper environmental data, as well as establish a methodology for adapted and adaptive efficient architectural developments. These aspects address the fact that architects, designers, and clients alike, are bound to fit within stringent rules of efficiency standards (either mandatory or not) to attain quality certifications, instead of focusing on the scenario of continuous suitability of the building (either in terms of the climatic shift of the surrounding environment, the suitability of future inhabitants, or even functional repurposing).

Thus, this thesis' problem statements are divided into various stages and domains, spanning from theory to procedure, and from concept to construction. From a theoretical perspective, the rather novel and emergent topic of architectural adaptivity needs extensive structure underline that can explain both the potential and limitations at various scales and circumstances.

Within energy-efficient strategies, the main encountered issues are that of correct assessment of the site and environmental change.[5] It is imperative to suit the edifice to its environment in a manner that would generate the best indoor comfort quality with minimum resources to sustain it. In general, all characteristics and traits of an edifice are tweaked to generate optimal results for a set of exact

[5] Juan MaríaHidalgo-Betanzos and others, 'Overheating Assessment of a Passive House Case Study in Spain and Operational Optimization'.

scenarios, based on the surrounding environment and its climate.[6] If the environment changes the script, those results will not be optimal nor meet the purpose of the edifice. A good example and quite possibly the most obvious is the global warming effect.[7,8]

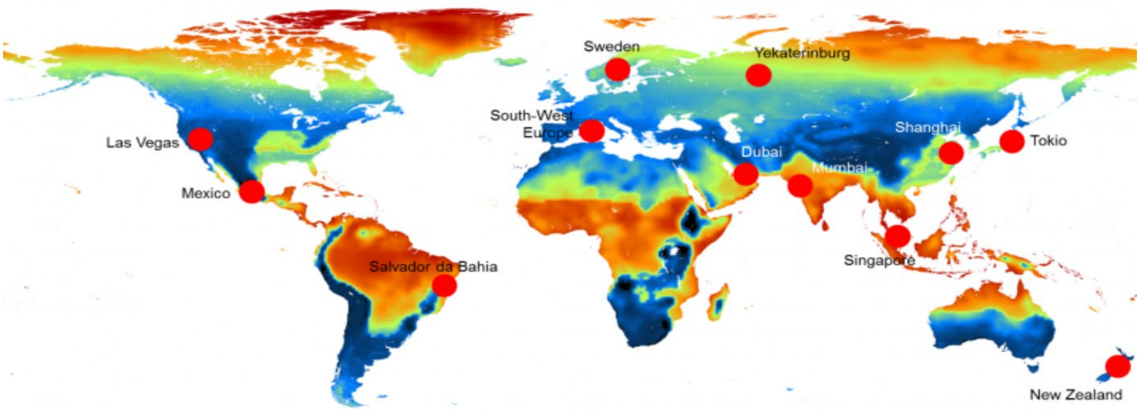

Fig. 2.1 - Passive House in Different Climates (author: Passive House Institute)[9]

Study references were conducted for the scenarios of Northern Spain and Romania since the topic was researched within these locations.

One of our studies of a highly energy-efficient house within Romania shows this drastic effect. The home was designed for a four-season transition with what usually was a harsh winter. The issue is that lately winters became shorter, as well as warmer than usual. The medium temperatures for the winter season were between 1.2°C and 0.6°C (from December to February) in 2001 whilst in 2018 the values were between 3.3°C and 0.9°C (according to the Romanian Ministry

[6] Jürgen Schnieders, Wolfgang Feist, and Ludwig Rongen, 'Passive Houses for Different Climate Zones', *Energy and Buildings*, 105 (2015), 71–87 <https://doi.org/10.1016/j.enbuild.2015.07.032>.

[7] Wolfgang Feist, 'On the Impact of a Warming Climate on the Energy Demand for Cooling and Summer Comfort', *Passipedia*, 2020 <https://passipedia.org/basics/on_the_impact_of_a_warming_climate_on_the_energy_demand_for_cooling_and_summer_comfort> [accessed 1 February 2021].

[8] Jessica Grove-Smith, 'The Impact of Warming Climate Conditions on Buildings', in *24th International Passive House Conference 2020* (Passive House Institute, 2020), p. 1 <https://passipedia.org/_media/picopen/22_fact_sheet_impact_warming_climate_on_buildings.pdf>.

[9] Image source: https://passipedia.org/basics/passive_houses_in_different_climates/introduction

of the Environment), the major differences were mostly noticed due to the clear sky and high solar radiation.[10]

Due to this fact, a highly efficient passive house would not perform optimally during transitional times between winter and spring (February and March months), is optimized for maximum heat gain and minimum heat loss, resulting in an overheated internal environment.

On the other hand, in warmer climates, the discomfort can be identified during the extended periods in the form of cold temperatures (considered cold periods; in the case of northern Spain from 15th of April until the 30th June).[11]

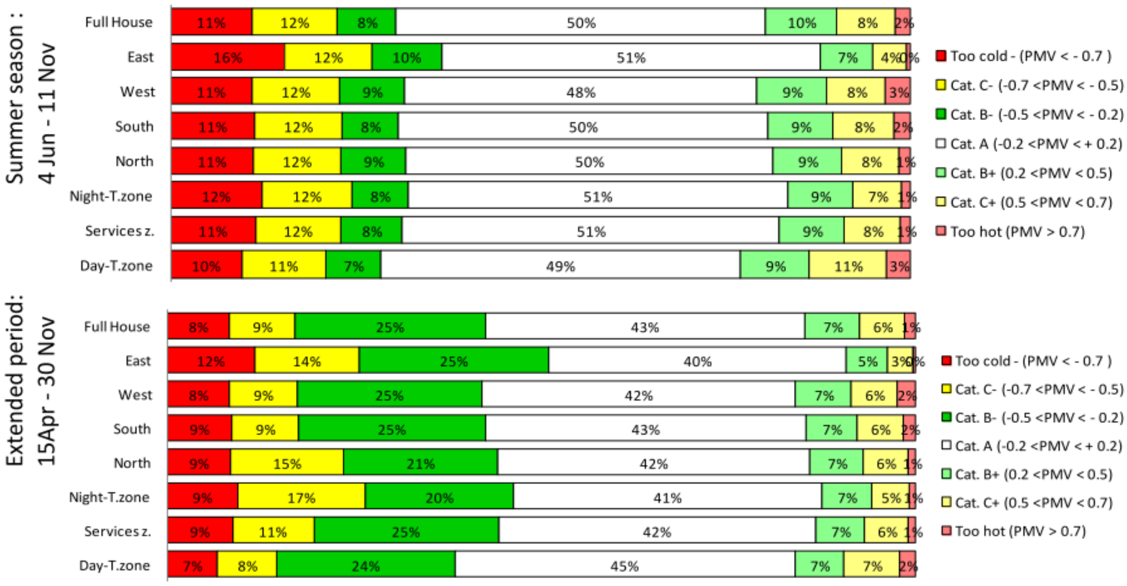

Fig. 2.2 Thermal Discomfort Chart (author: Juan María Hidalgo)[12]

Now, by analyzing the climatic data that was used in the cases of Bucharest and Barcelona, it can be observed that it is based on pure presumptions (having multiple years compiled into a single yearly plot) of the weather and that most of the public data is more than 20 years old. (https://energyplus.net/weather).

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[10] Ministerul Mediului Romania, *Comunicat de Presa Ref: 2018 a Fost Al Treilea Cel Mai Călduros an Din 1901 Până În Prezent*, 2019.

[11] Juan MaríaHidalgo-Betanzos and others, 'Overheating Assessment of a Passive House Case Study in Spain and Operational Optimization', p. 5.

[12] Juan MaríaHidalgo-Betanzos and others, 'Overheating Assessment of a Passive House Case Study in Spain and Operational Optimization', p. 7.

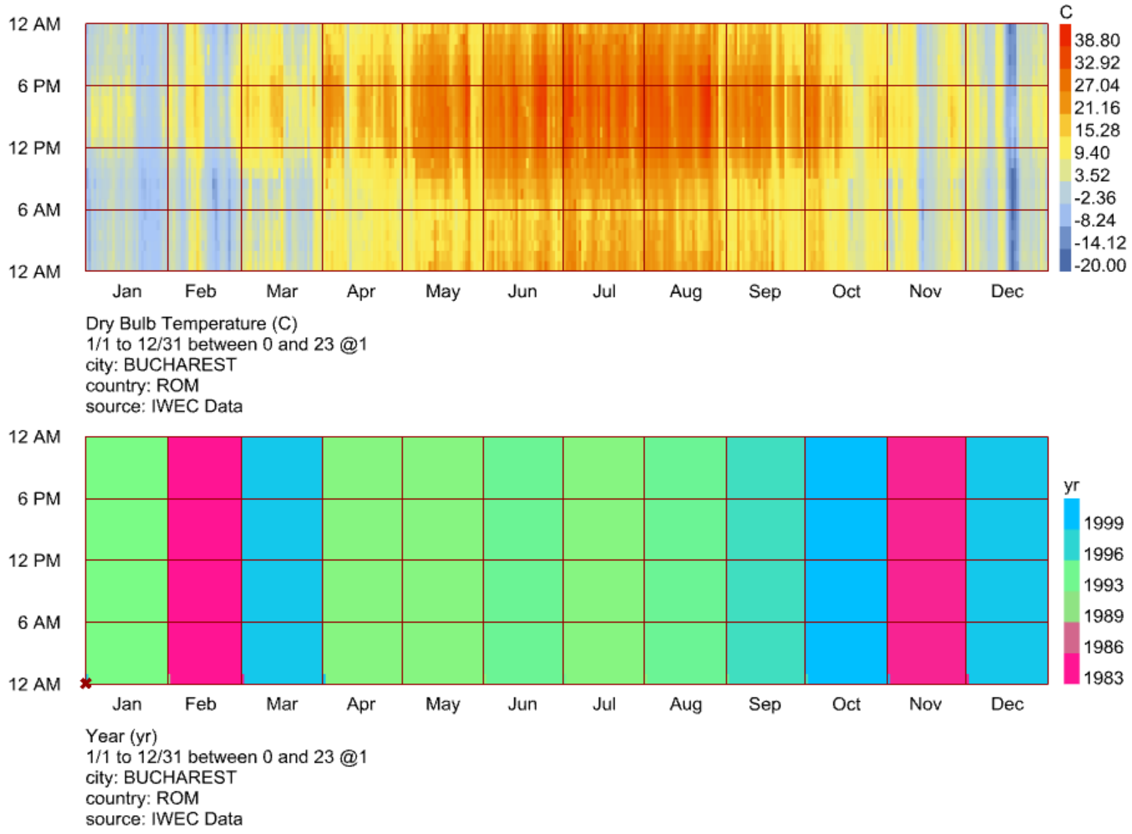

Fig. 2.3 - Top: Hourly Data Plot / Bottom: Year Model Data Plot for Bucharest (Image by author)

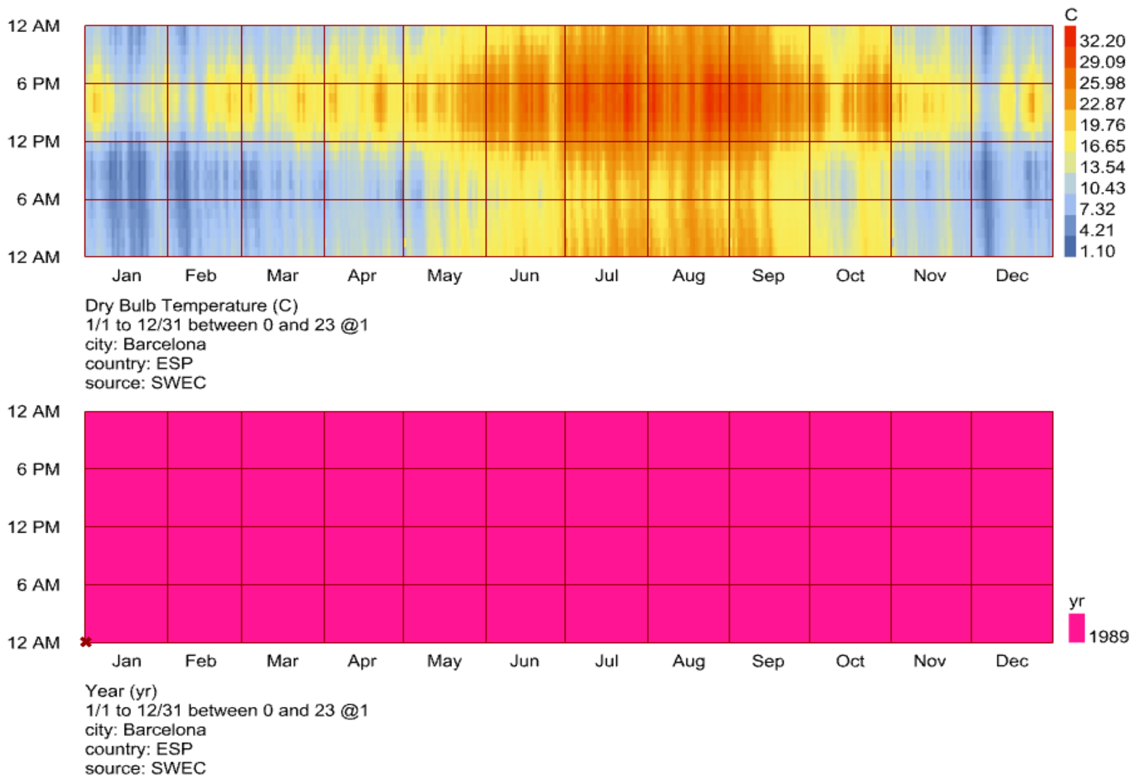

Fig. 2.4 - Top: Hourly Data Plot / Bottom: Year Model Data Plot for Barcelona (Image by author)

Weather data can be attained through different means, one of which is through an online website developed by EnergyPlus (https://energyplus.net/weather). Another method would be by requesting it from official weather stations or through dedicated software, such as Meteonorm (https://meteonorm.com/). The problem here is that most designers don't go through the hassle of asking for data from weather stations, nor want to buy dedicated software, and rely on browsing the web for it; which in theory is not wrong, but there is just a lack of detailed inputs. Also, results from Meteonorm seem outdated, spanning from 1991 to 2009, and are typically collected outside of the studied city.

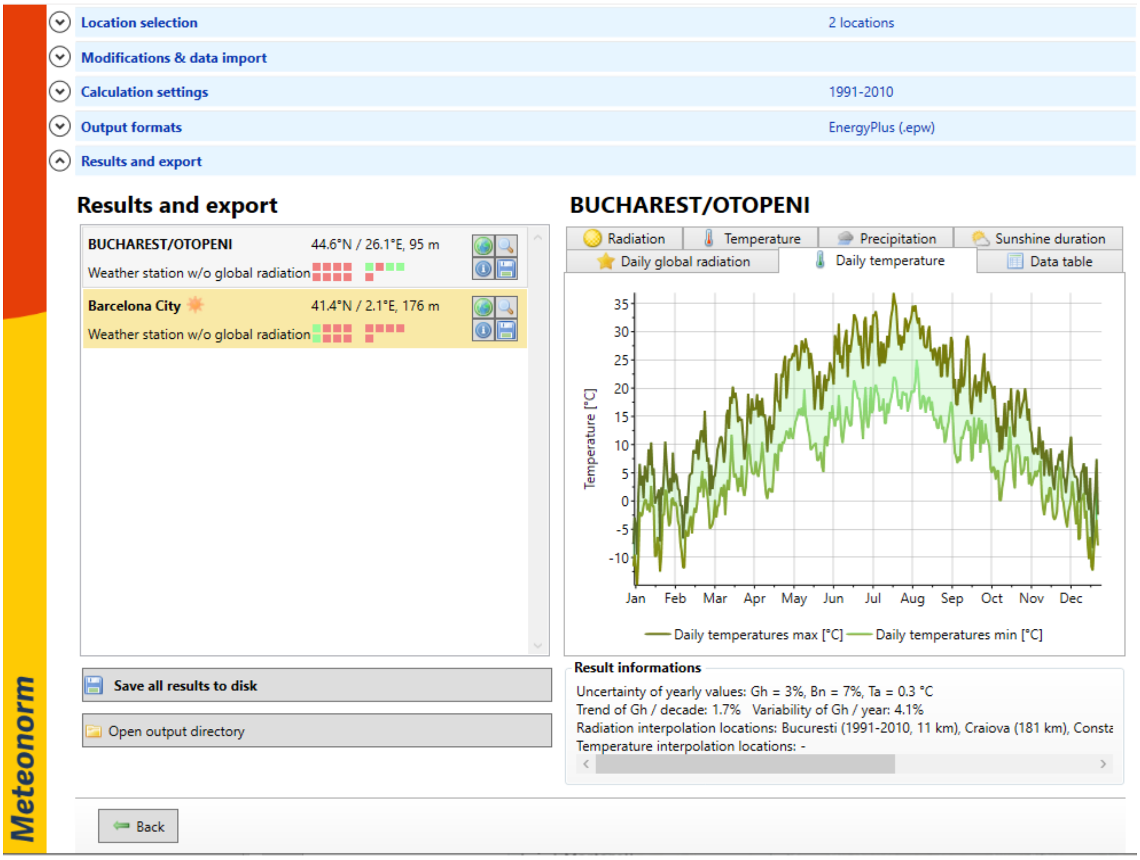

Fig. 2.5 - Meteonorm hourly analysis of Bucharest (image by author)

Regarding the web sources, in the case of the city of Barcelona, the data that can be found online was unfortunately recorded approximately 10 kilometers away from the city, and even worse, as pointed out in Fig. 2.4, it dates back to 1989. In the case of Bucharest, the situation is similar, having the data collection point outside of the city and showing problems regarding its integrity, as presented in Fig. 2.3.

Fig. 2.6 – Barcelona data collection point (blue) in relation to the city (image by author)[13]

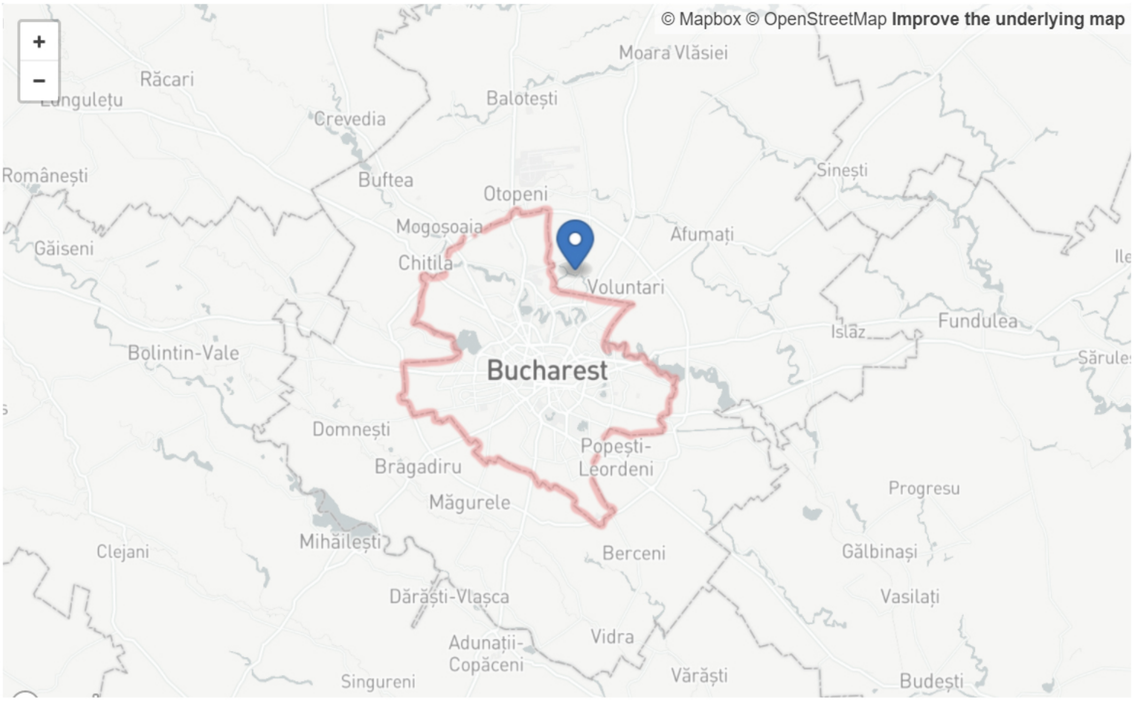

Fig. 2.7 - Bucharest data collection point (blue) in relation to the city (image by author)[14]

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[13] Image Source: https://energyplus.net/weather

[14] Image Source: https://energyplus.net/weather

Designing energy-efficient buildings usually goes by certain rules and in most cases, basic respect of those rules based on an estimate of geographical locations alongside specific constructive solutions will get you quite a positive result. But to develop something that has more complexity, such as an adaptive skin or façade, the requirements and details need to stack up, in order to get the most optimal results out of the system.

Thus, it can be remarked that there is a lack of consistent data and pre-analytical methodologies for designing especially ones that transcend between different disciplines.

Existing Methodological Inconsistencies

From a methodological standpoint, digital design techniques for modeling and simulation of development processes rely significantly on the abstraction of embodiment. The barrier to creative design thinking is mainly represented by the overcompensation of building-related information within digital design platforms, rather than abstraction itself. As a result, one can either conform to the conventional system palette or just blindly adopt traditional construction approaches.[15]

As a consequence, in typical design procedures, a limited number of streamlined strategies for envelopes, computation, and calculation are implemented. Using these, architects investigate and apply various systems, whereas each building approach may require its unique development method, which must be specifically tailored.

2.2.2. Hypothesis

A well-established, and up-to-date environmental database alongside a coherent methodology is essential within the development of adapted and adaptive architecture.

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[15] Petra Schweizer-Ries, 'Energy Sustainable Communities: Environmental Psychological Investigations', *Energy Policy*, 36.11 (2008), 4126–35 (p. 4126) <https://doi.org/10.1016/j.enpol.2008.06.021>.

Thus, this thesis is composed of a series of interconnected investigations and analysis-driven experimentation. The advancement of multidisciplinary development techniques is required in the process of envisioning systems that incorporate analytic methodologies for design. In this sense, it is recommended to move in between multiple domains (such as energy efficiency, adaptivity, and procedural modeling) and match viable aspects from each within a holistic development.

As a result, due to the more empirical character of this approach, limiting it to a lone solid research hypothesis or assertion is insufficient. As a result, the investigation hypothesis is as follows:

Multidisciplinary approaches in architectural processes could enhance and progress the future of environmentally conscious constructions through hybrid intelligence. This implies integrated computational design and site analytics on various levels (such as human-computer intelligence, or methodological interrelations.).[16]

The aforementioned assumption does not seek to justify or refute any current architectural notions, but rather to give a comprehensive framework of architectural conscious adaptivity, using energy efficiency as the objective, and computing and environmental data as the means.

If there are no ways of incorporating analytical and technological practices into these formalized frameworks, then there will almost definitely be an incapacity of designing future scenarios. The distinction between what is physically conceivable and what is sustainable is what prevents the two layers from coexisting.

[16] Philip F. Yuan, Mike Xie, and Neil Leach, *Architectural Intelligence*, ed. by Jiawei Yao and Xiang Wang, *1st International Conference on Computational Design and Robotic Fabrication (CDRF 2019)* (Shanghai: Springer, 2020), p. 82 <https://doi.org/10.13128/Techne-23561>.

2.3. Research Methodology

The thesis employs a variety of research techniques and strategies that are complementary to one another. Iterative explorations, experimental techniques, design, and prototyping-based studies, are meant as cornerstones of the employed research methodologies since the thesis core is built on objective-oriented studies.

2.3.1. Tools and Approaches

Since the main objective of the research is based on buildings' adaptivity end energy efficiency suitability, there will be a certain focus aimed at the interaction between the fabric of the building and the environment. This aspect posits five key approaches:

1. Understanding and synthesizing energy efficiency standards and strategies
2. Conceptualizing the development from an adaptive standpoint
3. Employing evaluation and analysis techniques through a virtual procedural environment
4. Creating and implementing a suitable data collection system
5. Devising a coherent methodology to achieve an adapted and adaptive development concept

In this sense, adding the concept of adaptation within the tight variance of active and passive housings implies a lot of calculus regarding energy transmittance and energy captivation. Passive and active systems are usually combined to attain the best performance, but our sight is not upon compiling existing systems to get the best performance but to unveil new solutions.

To keep everything in order it should be mandatory to analyze the environment and collect defining data, using it to devise an algorithm that will keep everything in check. This way, a computational system that will always generate a result suited for the building's energetic performance in a "prosumer" manner will be created.

All these approaches require a set of digital tools in order to be achieved, thus we posit the following:

1. Rhinoceros 3D as the main virtual medium of implementation
2. Grasshopper as the procedural medium of implementation
3. Ladybug Tools as the environmental evaluation medium
4. Raspberry Pi as a bridge between virtual and actual reality

Through a virtual environment that can simulate different theories, the ability of continuous study of existing concepts, as well as observing microclimates and organisms that behave in the manner of energy conservation can be achieved.

Following these steps, the aim is to obtain new information regarding different material performances as well as its behavior in terms of its shape relative to the environment.

Each of the previously mentioned fields (energy efficiency, adaptivity, procedural design, environmental analysis, and interactive prototyping) contain elements that, while not necessarily valuable on its own, when combined can provide efficient means of generating architectural solutions under specific conditions and, additionally, a range of adaptability that ensures a favorable Life Cycle Assessment (LCA) of the future edifice. The tools at our disposal will help us navigate these fields and manage the elements they output.

2.3.2. A Design and Prototyping based Research

The incipient step toward a more defined path into research is to investigate, document, and develop the tools and principles that each domain governs. These studies and documentation will primarily be defined as inputs, processes, and outcomes that will vary according to the requirements of the development.

After establishing this concept, the next step is to develop algorithmic definitions for the principles and tools that are used. The final step would be to generate multiple iterations of an edifice and test the results to ensure they are satisfactory.

Finally, all results will be documented and evaluated to determine whether they represent a viable continuity or not. Within the following figure, the studied domains within this thesis and their interactions can be observed.

The relationship between these domains can be interpreted in many ways. In order to define the methodology, a more or less linear workflow, based on informational applications and their use for development, must be created.

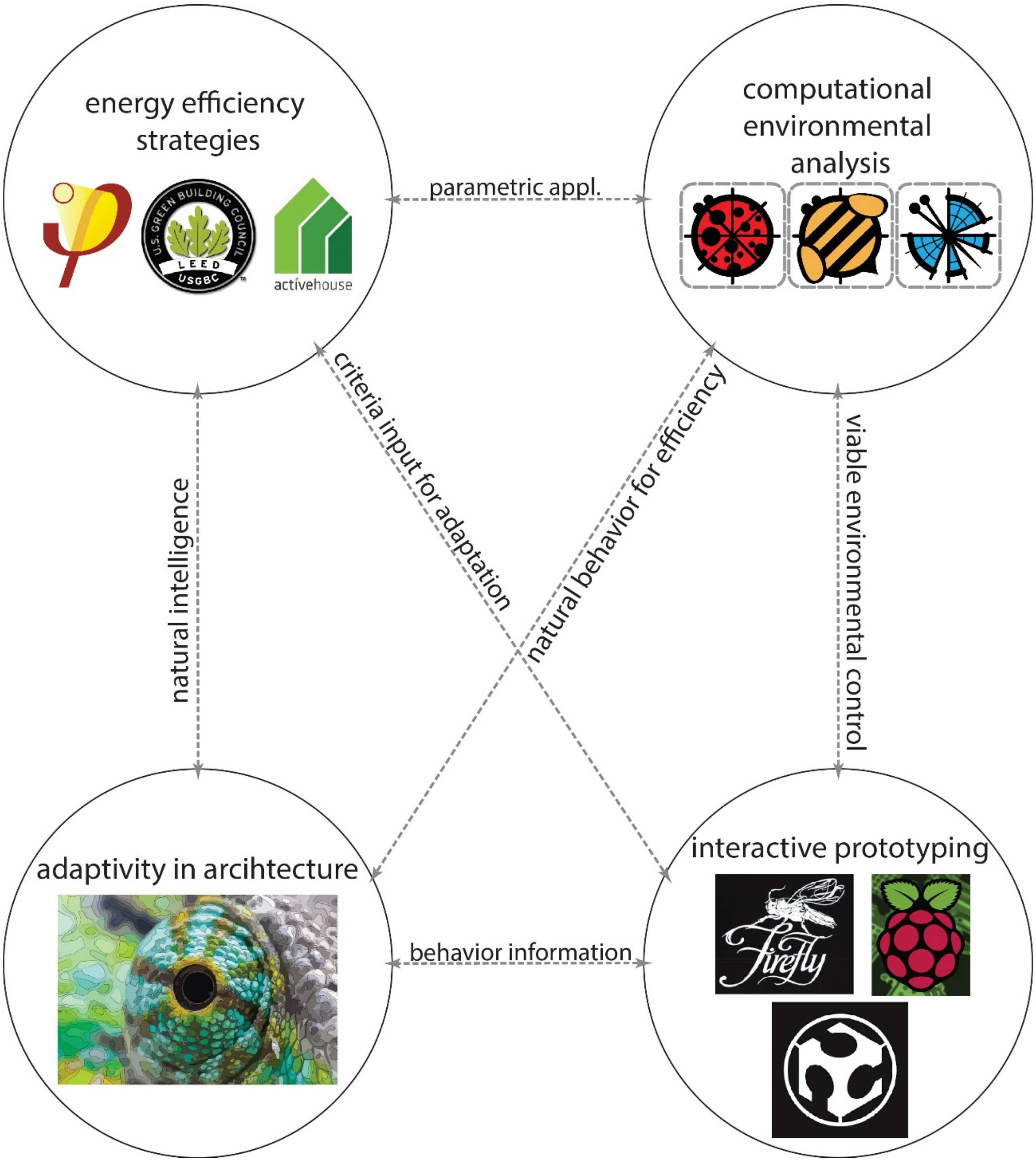

Fig. 2.8 - Relationship Between Domains (image by author)

Thus, the next diagram (Fig. 2.9) will depict our approach, by setting the energy efficiency strategies and adaptivity studies as the incipient stage, under the form of informational applications.

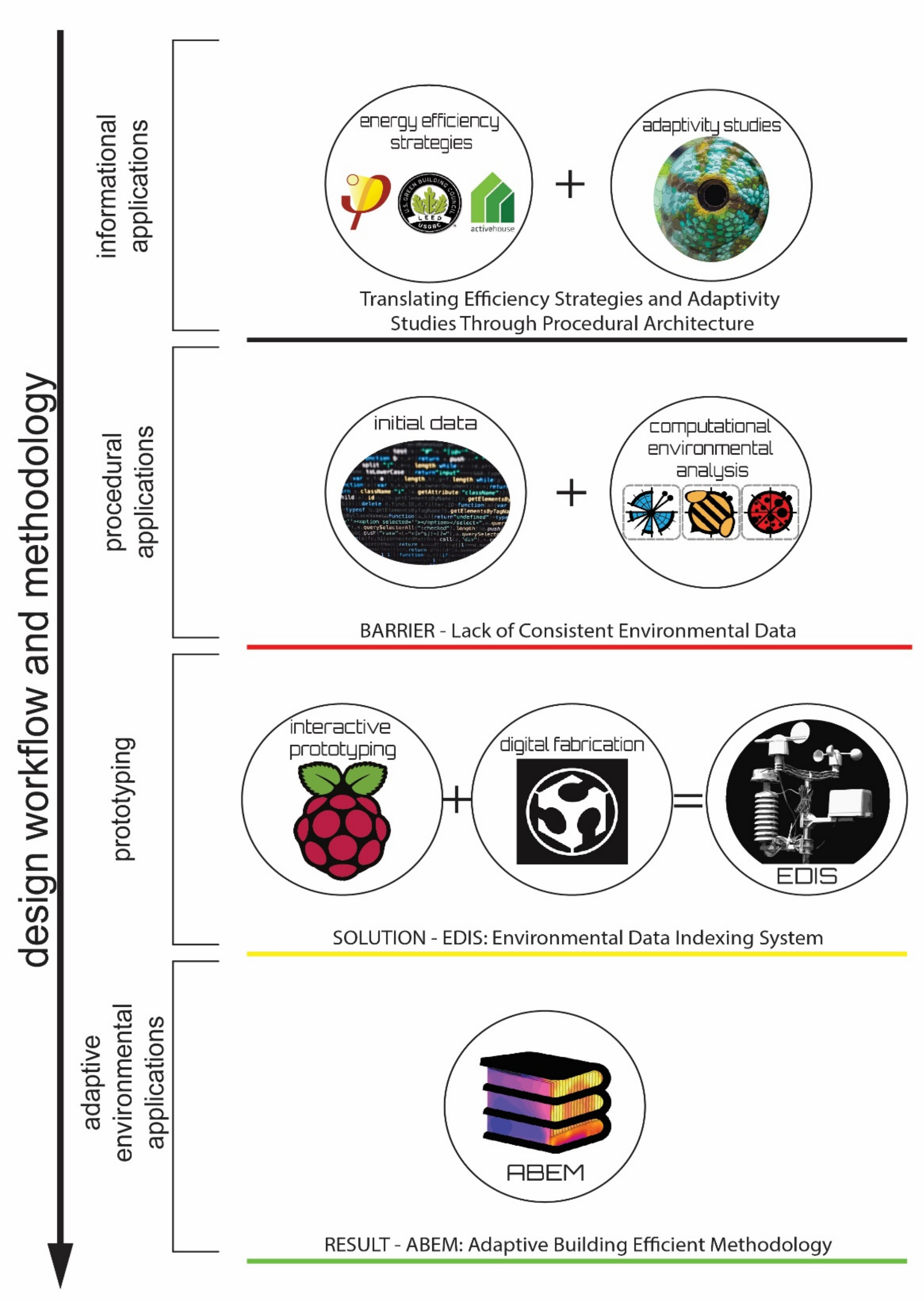

Fig. 2.9 - Design Workflow and Methodology (image by author)

The next step is to move towards an initial data collection based on these applications and shift them towards procedural applications. Finally, the last two stages depend on informational prototyping to generate the exact environmental data and on the newly formed adaptive environmental applications.

2.3.3. SOA and Literature Review

The literature review of this Ph.D. is divided into separate tiers and is distributed across four chapters.

To begin, the first problem description formulation includes theoretical and practical background references for energy efficiency, which are presented in chapter 3: "Energy Efficiency Strategies and Standards". This section will emphasize the Passive House strategies (developed by Wolfgang Feist), the Active House strategies (developed by the Active House Alliance) the nZEB movement (developed by the EU), and the Leadership in Energy Efficiency in Design (developed by the U.S. Green Building Council).

The theory and applications of adaptivity and interactivity in architecture are addressed in chapter 4, "Adaptivity in Architecture", as the second tier of the literature review. As a basis for both conceptualizations and applications of energy efficiency methods, these strategies are presented, examined, and contrasted. The main contributing literature studied and presented was published by Neil Leach, Alberto T. Estevez, Dennis Dollens, Behnaz Farahi, James, and Carol Grand Gould, amongst others.

Thirdly, chapter 5, "Procedural Architecture", contains an overview of the literature on procedural systems enveloping the means of combining both the efficiency standard information and adaptivity solutions. The intricacies of these domains were studied within the works of Arturo Tedeschi, David Rutten, Branko Kolarevic, and Mostapha Sadeghipour Roudsari, amongst others.

Finally, chapter 6, "Informational Prototyping", depicts domain-specific informational prototyping methodologies. This chapter emphasizes the bridge between the virtual and physical mediums, with studies of the works of Sushant

Verna, Rachel Armstrong, Andrew O. Payne, Phillip Anzalone, and Amber Bartosh.

2.4. Inquiries and Objectives

The research focuses on the buildout of technical and informational implementations for adaptive architectural efficient developments, based on the complete environmental spectrum. Centered on the abundance of information, a collection of concepts, systems, and materials that are best suited for the developing site, can be delineated.

Based on efficiency strategy demands the fact that weather data is invaluable in the case of urban planning can be observed. These demands will be affected by the environment, as well as smaller-scale developments that need accurate information to be efficient.

2.4.1. Research Inquiries

Besides today's advanced architectural design and construction technology, the core of this investigation could be traced back to a fundamental challenge in man-made dwellings: imagination and creativity. To enhance existing techniques and further develop and offer suitable methods and appropriate tailored technologies, it is critical to identify domain-specific queries. Thus, we may inquire to ask:

a. How could the presence of adaptivity in architecture be characterized and justified?
b. What are the basic tasks of an energy-efficient system's multidisciplinary and integrated procedural design?
c. How can adaptivity be implemented?
d. How can we perceive and influence the built environment based on the EDIS and ABEM approaches?
e. What are the fundamental requirements for architectural adaptivity in theoretical, methodological, and technical paradigms?
f. What are the foreseeable prospects in architectural research, teaching, and practice for energy-efficient design, adaptivity, data indexing, and their trans-disciplinarity?

2.4.2. Objectives

The objectives are addressing transitions that arise from concurrent disruptive technologies in architectural practice and education, influencing the role and responsibility of designers, manufacturers, and users, rather than delivering an inclusive theory of adaptivity in architecture with a widespread literature review.

a. Exploring and synthesizing available efficiency strategies and adaptive methodologies

The need for energy-efficient developments has grown in response to rising concerns about the negative impacts on the environment and the requirement to provide users with thermal, visual, auditory, spatial, and indoor air quality comfort. The exploration of the most adopted and innovative approaches to highly efficient dwellings will offer great insight in regards to a suitable manner of adaptivity.

Furtherly, understanding the principles of adaptivity from different perspectives will aid the conceptualization process of new developments as well as defining the actual use of the adaptive system.

b. Exploring the medium of procedural architecture

Procedural modeling is a broad category for a variety of computer graphics approaches for generating 3D models from a set of rules, and it may be employed in architectural design and simulations.

The chosen medium for procedural architecture is identified as Grasshopper, a node-based visual programming language within Rhinoceros 3D. Employing these types of tools will enable us to work with, and analyze more information rather than simple geometry. The reason for this approach is because of the large community developed behind the software as well as its high interoperability.

c. Addressing the lack of reliable data

Examining the online available maps, it can be observed that there are no weather recordings at a small scale, so the first objective is to solve this issue (see Fig. 2.6 and Fig. 2.7). This will be addressed by the development of a multileveled sensor, named EDIS (Environmental Data Indexing System), that would record as many weather parameters as possible (for instance dry-bulb temperature, barometric pressure, humidity, windspeed and direction, light intensity, solar irradiance, etc.). The device is intended to be linked to the internet to transfer data wirelessly and at an hourly interval. Another important aspect is the ability to make it autonomous by integrating solar panels.

A future objective is to influence the development of a sensor network all around the city to generate an exact weather map that can be used for any type of analysis or urban growth. Thus, pursuing and forming a system that is continually striving to optimize results and elevating productivity to a new norm of inviolability.

d. Developing a transdisciplinary framework

This objective is meant to devise a solution to make use of the new data sets by providing the framework for the Adaptive Building Efficiency Methodology (ABEM). To do so, the importance of the element that is missing needs to be evaluated, alongside the means through which it can be correctly attained.

In this context, in order to accomplish effectiveness and stability, the design methodology must traverse the complexities of all the disciplines included to gain a systemic understanding, defining our secondary objective.

2.5. Structure and Chapter Outlines

The work is structured in a linear approach through six chapters depicting the theoretical and practical steps towards attaining an energy-efficient, environmentally-aware adaptive building through the means of procedural design and informational prototyping.

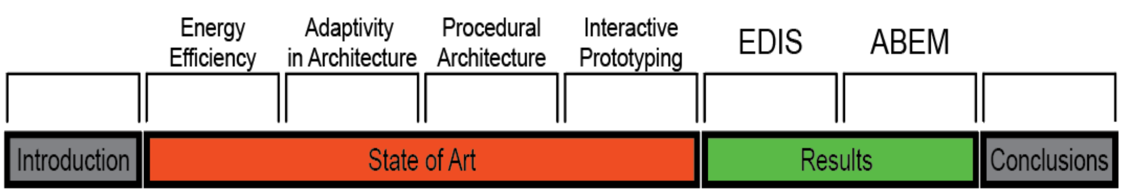

Fig. 2.10 - Thesis Structure (image by author)

In addition to its consideration of the literature and outcomes, the thesis establishes and explains efficiency development basis and theoretical remarks on numerous approaches of adaptive design for architectural applications.

All research is cited and referenced using the "Modern Humanities Research Association 3rd edition" style.

The subjects of each chapter are going to be described within this section.

2.5.1. Main Applications: Energy Efficiency in Architecture

This chapter is meant to introduce us to the world of energy-efficient design through strategies and certifications such as nZEB, LEED, Passive House, and Active House. These are to be considered the main informational applications throughout the whole process of development.

Fig. 2.11 - Passive House Logo[17], Active House Logo[18], LEED Logo[19]

Net-Zero Energy Building

As stated within the European Energy Performance of Buildings Directive, a net-zero energy edifice is a structure proving extremely high energy efficiency. The quantity of necessary energy must be met mainly through renewable sources.[20]

This could include renewable energy obtained on-site or in a neighboring area. In essence, the Directive simply specifies the overall concept, leaving plenty of room for the Member States to fine-tune it. As a result, the standard is extremely flexible, without a unified definition across the EU. Member States are responsible

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[17] Image Source: <https://www.greenbuildingadvisor.com/article/can-passive-house-be-trademarked>

[18] Image Source: < https://www.activehouse.info/>

[19] Image Source: < http://www.peacocksalesco.com/links/leed-logo/>

[20] Wolfgang Feist and Céline Fremault, *Defining the Nearly Zero Energy Building* (Darmstadt: Passive House Institute, 2016), p. 8 <https://passreg.eu/upload/PassREg_International_EN/Flipbook.pdf>.

for defining the nZEB in their national plans, while also assessing the viability of implementing such a notion in their respective regional settings.[21]

LEED

Leadership in Energy and Environmental Design (abbreviated as LEED) represents one of the world's widely used certification programs for green and sustainable buildings. The concept was envisioned by the United States Green Building Council (USGBC) and consists of a series of rating systems dedicated to the design, development, operation, and maintenance of green buildings.

These can be suitable for individual structures as well as building assemblies, such as communities. One of the main goals is to assist owners and operators in becoming environmentally conscious and effectively using resources.[22]

Passive House

The Passive house strategy (also known as Passivhaus) is a stringent, voluntary standard for energy efficiency that employs minimal resources needed for heating and cooling.[23]

Although passive architecture incorporates natural ventilation, a certified Passive House's thermal efficiency is determined by its airtightness. The Passive House movement, known in Germany as Passivhaus, was established in 1996 by Dr. Wolfgang Feist. Since then, it has spread in many other countries throughout the world.[24]

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[21] Wolfgang Feist and Céline Fremault, *Defining the Nearly Zero Energy Building Passive House + Renewables*, ed. by Amina Lang (Darmstadt: Passive House Institute, 2015).

[22] Sam Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, *LEED v4 Practices, Certification, and Accreditation Handbook*, Second Edi (Elsevier, 2016), p. 18 <https://doi.org/10.1016/C2015-0-00887-5>.

[23] Stefano Piraccini and Kristian Fabbri, *Building a Passive House*, ed. by Springer, 1st Editio (Switzerland: Springer, 2018), p. 45 <https://doi.org/10.1007/978-3-319-69938-7>.

[24] Passiv Haus Institut, *Curs Proiectant / Consultant Case Pasive Volumul 1*, ed. by Ordinul Arhitectilor din Romania, 1st edn (Bucharest, 2018).

Active House

Though an Active House may appear to be the polar opposite of a Passive House, the two strategies are not mutually exclusive. Active Houses incorporate passive design principles but take them a step further by self-generating energy, often via photovoltaic panels.

Within a few years of the concept's introduction, several other standards followed its principles, resulting in the creation of new ideas, such as the Passive House Premium standard.[25]

The energy efficiency strategies are concluded within a comparison based on similarities and particularities that will be used to define adapted and adaptive characteristics. The comparison can be found in chapter point 3.6.

2.5.2. Theory and Definitions: Adaptivity in Architecture

Within the Adaptivity in Architecture chapter, a theoretical approach is taken, by studying the timeline of how people built their dwellings, in comparison to nature's approach as well as novel systems that are considered adaptive or interactive.

The Adaptivity Context

The context from which the meanings of adaptivity will derive through an etymological approach is envisioned, defining the concept of adaptivity itself. The means by which this will be done, are based on both practical and psychological perspectives.

Adaptation in Nature

After attaining a foundation regarding what it means to adapt, we continue studying such behaviors that reside in the natural environment. Through this, we will derive the notion of Architectural Biolearning that entails an abstract approach towards the conceptualization of adaptive systems.

[25] Lone Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, *Springer* (Springer, 2018), p. 13 <https://doi.org/https://doi.org/10.1007/978-3-319-90814-4>.

Adaptivity in the Built Environment

This section will provide background knowledge of both past and novel attempts of achieving consistent adaptive edifices from the perspective of intelligence, consciousness, and cognition in architecture.

2.5.3. The Medium: Procedural Modelling

The medium through which the approaches are conceptualized is based on computational and procedural design. The various digital tools aiding us to do so (Such as Rhino and Grasshopper), are described within this chapter.

Procedural Modelling

Fig. 2.12 - McNeel Rhinoceros and Grasshopper Logo (author: McNeel)[26]

Rhinoceros, also known as Rhino is a commercial 3D computer-aided design (CAD) software program produced by Robert McNeel & Associates. Rhino geometry is primarily involved with producing mathematically correct representations of curves and free-form surfaces within computer graphics. The approach is based on the NURBS mathematical model as contrary to polygon mesh-based programs.[27]

Grasshopper is represented by a visual programming workspace for the Rhino CAD platform, created by David Rutten. Components are dragged onto a canvas to create programs, known as scripts or algorithms. The software's extended capabilities include parametric modeling for architecture, structural engineering,

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[26] Image Source: < https://discourse.mcneel.com/>

[27] McNeel, 'Rhinoceros 3D', 2019 <https://en.wikipedia.org/wiki/Rhinoceros_3D>.

and fabrication, as well as lighting performance analysis (normally used for environmentally aware architecture and energy efficiency).[28]

Computational Environmental Evaluation

The evaluations needed to characterize a building as being aware of its surroundings are going to be achieved through The Ladybug Tools. These represent a series of open-source programming plug-ins that aid in environmental design and education. These are referred to as "Ladybug", “Honeybee”, “Butterfly” and “Dragonfly”.

“Ladybug Tools” is one of the most comprehensive environmental design software packages available, linking 3D CAD interfaces to a variety of established simulation programs. Together, “Ladybug” and “Honeybee” shape a design pathway that will take you from rudimentary understandings of climate data to performative design in this matter.

Ladybug is an environmental analysis extension, dedicated to Grasshopper, that enables designers to develop environmentally-conscious designs. The first phase in the design process should employ studies of weather data, providing a detailed understanding to lead designers towards making high-performance design choices.[29]

The plug-in imports generic *.epw files (EnergyPlus Weather files) into the Grasshopper medium. It offers a range of interactive climate graphics to aid judgement through the early stages of design. Ladybug additionally aids in the evaluation of preliminary design variants employing solar radiation studies, a variety of view analyses, sunlight-hours modeling, and many other tools.

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[28] Ahmed Mohamed Yousef Toutou, ‘Parametric Approach for Multi-Objective Optimization for Daylighting and Energy Consumption in Early Stage Design of Office Tower in New Administrative Capital City of Egypt’, *The Academic Research Community Publication*, 3.1 (2019), 1 <https://doi.org/10.21625/archive.v3i1.426>.

[29] Mostapha Sadeghipour Roudsari, ‘Ladybug Tools | Home Page’ <https://www.ladybug.tools/> [accessed 19 October 2019].

Integration of visual programming environments enables real-time feedback on design changes and a high level of customization.[30]

2.5.4. Informational Prototyping

Informational prototyping enables us to narrow the gap between the digital-computational and the physical mediums. By these means, it is possible to develop a sensing device that would inform and influence the efficiency and adaptivity strategies.

Control Boards and Mediums

Firefly

The interactive prototyping domain is generally focused on "Firefly", a Grasshopper plug-in. Firefly represents a complete set of software resources aimed at overcoming the barrier amongst Grasshopper, the Arduino microcontroller, and other input-output devices. This enables instant data flow between digital and physical realms, allowing for unparalleled fluidity in exploring virtual and physical prototypes.[31]

Arduino

Arduino is a microcontroller board that allows you to build machines that have the property to sense and record more of the surrounding environment than your typical personal computer. It's a programming framework for creating board applications that run on an open-source physical computing platform.

The Arduino is intended to create interactive systems that accept input from various controllers or sensors and power a series of motors, switches, lights, and other output devices. Arduino ventures could be independent or interact through

[30] Mostapha Sadeghipour Roudsari, 'Ladybug Tools | Ladybug' <https://www.ladybug.tools/ladybug.html> [accessed 19 October 2019].

[31] Andrew; O'Payne and Jason Kelly Johnson, 'FireFly: Interactive Prototypes for Architectural Design', *Architectural Design*, 83.2 (2013), 144–47 (p. 144) <https://doi.org/https://doi.org/10.1002/ad.1573>.

apps on mobile devices (using Processing, Flash, etc.). The boards may be hand-assembled or bought pre-assembled, offering the open-source IDE free of use.[32]

Raspberry Pi

Single-board computers (SBCs) like the Raspberry Pi are built on a single printed circuit board. They are similar to any PC or laptop but, as most single-board computers, are tiny – around the size of a credit card. That does not mean it is not powerful: a Raspberry Pi is capable of performing many of the functions of a bigger, more energy-intensive system, just maybe not as quickly.

In contrast to a traditional computer, which conceals its internal components under a shell, a Raspberry Pi exposes all of its components, ports, and features. This makes it an ideal tool for learning about the functions of the various components of a computer, as well as for where to plug in the various extras – such as peripherals.[33]

Immersive and Mixed Reality for Data Visualization

Data visualization is one of the cornerstones of environmental evaluation since it offers a different perspective regarding the influence of the surrounding environment. Though taking a step further and bringing those perspectives to a virtually augmented space, more than just basic information can be perceived, by experiencing it visually, overlayed in reality at a one-to-one scale.

Immersive environments could be represented as an effective form of adaptation, by projecting the inhabitant within a specific setting that would account for his needs. In this sense, immersive environments represent the overall aspect of this application, by recreating a selected setting through projections, visual technology, and sound into a real-world experience. These settings are envisioned to be applied equally for both interior and exterior environments.

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[32] Andrew O. Payne, *Interactive Prototyping*, 2013, p. 14.

[33] Gareth Halfacree, 'The Official Raspberry Pi Beginner's Guide', *Raspberry Pi Trading Ltd*, 2018, 240 (p. 11) <https://www.raspberrypi.org/magpi-issues/Beginners_Guide_v1.pdf>.

2.5.5. EDIS and ABEM

The EDIS (Environmental Data Indexing System) and ABEM (Adaptive Building Efficiency Methodology) chapters describe the results that have been achieved through this research.

EDIS

The environmental data indexing system was created in order to attain all the needed information regarding the climate in which future developments would reside. The device is meant to output an *.epw file format that is compatible with the Ladybug plugin. Employing one or multiple devices on-site will ensure correct and up-to-date indexed specific data.

ABEM

The "Adaptive Building Efficiency Methodology" is envisioned by compiling the aforementioned architectural adaptive and efficient solutions, organizing them based on specific biomes and functionalities. Since all systems will be procedurally generated through computational means, adjusting them to any building morphology would be achieved within a matter of minutes. Also, the parametric aspect of the approach would enable us to personalize each system based on the edifice needs.

Within this section, the educational benefit the thesis methodology employs will be also showcased.

2.6. Thesis Contribution and Relevancy

The scientific contributions, whether domain-specific or multidisciplinary, the possible social and environmental consequences, as well as the methodological, technical, and case-specific outcomes, all contribute to the relevance and application of this study.

2.6.1. Scientific contributions

By researching and creating a succession of integrative holistic systems in the form of procedural design methods and data indexing technologies, this research advances knowledge within the domains of architecture and urban environments.

Inputs on the methodological front, based on the ABEM, consist of practical and theoretical knowledge for improved understanding, implementation, analysis, and evaluation of architectural morphologies, building envelopes, and adaptive solutions.

2.6.2. Environmental contributions

The construction industry is thought to be the most carbon-intensive. This research aids in the development of resource-efficient construction systems, and strategies while harmonizing with the natural environment. This is made possible through the synergy of a highly efficient building envelope and continuous environmental feedback provided by the EDIS.

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Energy Efficiency Strategies

3. Energy Efficiency Strategies and Standards

Energy-efficient strategies are defined by their principles or evaluation processes to achieve minimum or positive energy consumption values, as well as a more sustainable approach in terms of material usage, by taking into consideration the immediate environment and its natural resources.

There are quite a lot of strategies that arose, all of which aim to implement a standard that would guarantee the construction’s performance. The following chapters will present some of the most popular of them, as well as some that have yet to gain traction worldwide. The main studied concepts are defined by "Passive House" and "Active House" alongside two certification standards known as “LEED” (Lead in Energy Efficiency Design) and “nZEB” (Nearly Zero Energy Buildings).

The main reason chosen to study these strategies and standards revolves around the interaction between the environment and the occupant. These aspects will define the extent of information needed to achieve a form of an “adapted” edifice that would ensure the wellbeing of both worlds (of the Occupant and the Environment).

Thus, following this train of thought, the most important aspects that have to be accounted for are:

- Sustainability and Environment
- Thermal, electrical, and water demands and efficiency
- Large scale developments and impact
- Material efficiency
- Indoor Environment and comfort
- Design Process
- Occupant Suitability
- Environmental Data Reliability

3.1. nZEB - Net-Zero Energy Buildings

The nZEB is a movement of a standard that aims to evaluate and support energy performative buildings. The whole concept started as an approach towards a more sustainable environment at a larger scale.

The economy's advancement and living standards have steadily improved since the industrial revolution in the 18th century, accompanied by an increase in global population and the resources used to further encourage this development. The upward trend has resulted in an accelerated loss of natural resources, as well as an unanticipated factor: environmental degradation.[34]

Global development is jeopardized by population increase, resource shortages, and pollution. The renowned paper "The Limits of Growth," issued by The Club of Rome in 1972, methodically defined, simulated, and displayed these aspects. Even though the paper's findings were highly disputed, they conveyed a warning about future growth patterns, which assisted in the formulation of a new concept: Sustainable Development.[35]

This notion, introduced by the Brundtland Report, is specifically described as a “development that meets the needs of the present without jeopardizing future generations' ability to meet their own needs”.[36] Because there are so many different elements to consider, putting this concept into practice proved to be a difficult and continuous endeavor.

Furthermore, environmental issues that define global warming and climate change were represented as key repercussions of unsustainable growth, necessitating extra tangible steps toward sustainable practices. [37]

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[34] Susanna Agnelli and others, *The World Commission on Environment and Development* (New york, Oxford: Oxford University Press, 1987), p. 116 <https://libgen.is/book/index.php?md5=78428d67f63dbf20ba026b03f1fc6c88>.

[35] Donella H. Meadows and others, *The Limits to Growth*, *The Limits to Travel* (New York: Universe Books, 1972), p. 157 <https://doi.org/10.4324/9781849773119>.

[36] Agnelli and others, *The World Commission on Environment and Development*, p. 43.

[37] Ion Visa and Anca Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, ed. by Ion Visa, 1st edn (Brasov: Springer, 2014), p. 4 <https://doi.org/10.1007/978-3-319-09707-7>.

The European Union has certain objectives within the building sector, evaluating the domain as being responsible for 40% of energy consumption as well as generating a third of the CO_2 emissions.[38]

The nZEB was adopted as a collaborative part within these objectives to reduce the overall consumption and emissions perceptibly and sustainably. As a result, to accelerate the transition towards a sustainable built environment, an intricate framework has been developed, which includes subsidies and regulatory requirements.

The subsidies are aimed at reducing CO_2 emissions or incorporating Renewable Energy Systems, known as RES, while the regulations cover the Energy Performance in Buildings Directive or the renowned EU directive 20-20-20, which states that until 2020, an average of 20% of total renewable energy sources (RES) will have been installed, alongside a 20% rise in energy efficiency and a 20% drop in CO_2 emissions.[39]

To achieve the Low Energy Building status, the creation of a sustainable built environment necessitates energy consumption reductions (by integrating energy-saving consumers and minimizing as many losses as possible). The substantially lower energy demand could be satisfied entirely or partially by integrating renewable energy systems in nZEB based on sustainable, non-polluting technologies. This progression is rational in theory, but its implementation requires creative ways to make edifices, not just green or efficient, but also inexpensive.[40]

To expedite this operation, a legislation framework was created and was proposed to be adopted throughout the EU by 2018, pressuring all public edifices to satisfy the nZEB criteria by enforcing the same requirements for all new constructions by 2020. As a result, thorough investigations are being conducted

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[38] Wolfgang Feist and Fremault, *Defining the Nearly Zero Energy Building Passive House + Renewables*, p. 8.

[39] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 18.

[40] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. vi.

all over the world to develop unique concepts, technology, and methods for use within the built environment. To achieve a practical result, a multidisciplinary strategy is necessary to produce optimum energy combinations that take into account the accessible renewable energy resources and thus are capable of meeting the building's energy demand.

Synergy can emerge when designing groups of high-performance edifices, forming sustainable communities, if the equilibrium between state-provided and personal utilities is effectively planned.

Energy is the most known worldwide challenge. Energy consumption has been used as a leading indicator of economic progress (primarily industrial) for over a century, with developed countries having the highest per capita values. Based on a 10-year evaluation, the World Bank and the International Energy Agency lately released documentation estimating a substantial increase in energy capacity within the following 40 years to fulfill the requirements of developing nations.[41]

These requirements cannot be met using the present efficiency strategies, which are strongly focused on fossil fuels, as they are primarily accountable for environmental degradation and pollution. These resources are depending on reserves that are rapidly decreasing, which contributes to societal insecurity and the possibility of global cataclysms.

Thus, a massive effort continues to be made around the world to create sustainable resolves to provide energy that may meet progress demands excluding the compromise of either economic growth or personal comfort.

The terminology "Sustainable Energy" refers to the generation of energy from noninvasive and clean sources as well as efficient energy distribution, along with loss reduction.[42]

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[41] Aydin Tabrizi, 'Sustainable Construction, LEED as a Green Rating System and the Importance of Moving to NZEB', *E3S Web of Conferences*, 241 (2021), p. 5 <https://doi.org/10.1051/e3sconf/202124102001>.

[42] Muhammad Mansoor and others, 'A Guidance Chart for Most Probable Solution Directions in Sustainable Energy Developments', *Renewable and Sustainable Energy Reviews* (Pergamon, 2013), 306–13 (p. 307) <https://doi.org/10.1016/j.rser.2013.03.037>.

The development of innovative energy production/consumption systems that are compatible with Sustainable Energy must be accomplished in a reasonable amount of time and the application of these solutions must also be satisfactory, meeting a minimum of three goals:

- Competitive Costs (in contrast to current consumption and production trends)
- Secure Supply (dependence on non-restricted sources)
- Environmental Awareness (for decreasing pollution and climate change on a global scale).

When it comes to building energy usage, this marks a shift away from resolves aimed towards Low Energy Buildings (LEB) and focusing on Nearly Zero Energy Buildings (nZEB). In the built environment, however, this translates into a change of focus from a single building to a community.[43]

3.1.1. Sustainable Communities

There seem to be numerous meanings of "community", the majority of which relate to land and population density. When taking into account the options for resolving the issue of energy efficiency as the major element of a sustainable community, it ought to be noted that technological progress must not be considered as separate from the inhabitants, hence, both technological progress and human development influence one another and expand in tandem. The above implies that both environmental and technological concerns ask to be tackled using resolves that obtain cultural and political recognition, while community educational standards are always improving in order to acknowledge and comprehend innovative solutions.[44]

Furthermore, a community is more than just a collection of edifices. Consequently, it must be implied that when designing collective sustainability the understanding is generated at the building scale and strive for coherence when

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[43] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 18.

[44] Schweizer-Ries, 'Energy Sustainable Communities: Environmental Psychological Investigations', p. 9.

unveiling and applying solutions that are aimed towards sustainable energy generation, built environment, water usage, waste management, and transportation.

Sustainable energy generation, as well as usage, refers to thermal and electric energy generated primarily by renewable sources as an outcome of enhanced energy mixes. Other options may include both immediate site energy systems and larger-scale renewable energy sources integrated into micro-community grid systems.

A sustainable built environment envisions the deployment of "renewable energy systems" mixes efficiently, while energy consumption must be drastically reduced to achieve the "low energy efficiency" condition. This rank is inconsistently defined throughout the world (also within the European Union). Thus, it is unlikely that a set of universal values will be established, given the portion of energy in use by an edifice is highly location-dependent. Once a "low energy efficiency" rank is achieved, meeting at least 50% of energy needs through sustainable sources will qualify for the nZEB status.[45]

Alongside technical strategies, this entails a collaborative assessment of environmental impact and life-cycle, climate influence, and social policy matters, which has thus far limited the development of near-zero energy buildings (nZEB) to a demo/pilot level.[46]

Sustainable water usage implies processing, distribution, reuse, and recycling are all components of a cycle that should be created while safeguarding natural water resources. Also, because these operations consume energy, they must be taken into account within the community's average energy equilibrium.[47]

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[45] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 6.

[46] Danny H.W. Li, Liu Yang, and Joseph C. Lam, 'Zero Energy Buildings and Sustainable Development Implications - A Review', *Energy* (Elsevier Ltd, 2013), 1–10 (p. 6) <https://doi.org/10.1016/j.energy.2013.01.070>.

[47] Petar Sabev Varbanov, 'Energy and Water Interactions: Implications for Industry', *Current Opinion in Chemical Engineering* (Elsevier Ltd, 2014), 15–21 <https://doi.org/10.1016/j.coche.2014.03.005>.

Waste management aims at domestic waste and pollutants resulting from energy generation, as well as wastewater treatment, should be processed to a considerable degree and the remainder should be disposed of under applicable environmental rules.

Sustainable transportation entails reducing emissions and utilizing clean fuels.

Addressing the previously mentioned factors, energy consumption and production must be tackled holistically, with solutions tailored to each component. Communities that are completely self-sufficient in terms of energy are referred to as "energy autarkic" or "energy independent".[48]

The benefit of sustainable communities (along the path of independent energy generation) across a collection of sustainable edifices is based on micro-grids and infrastructures established for electric and thermal energy, fresh water supply, waste and wastewater collection as well as treatment. This enables the use of pre-existing infrastructure and results in fewer changes in the occupants' behavior, hence improving acceptability. The integrated system should be capable of performing the following functions:

- Provide sufficient energy to support the needs of all residents and community facilities;
- Install a storage system to manage the effects affiliated with the fluctuation of renewable energy sources;
- Off-grid operation, allowing the main provider to be used as a storage system. Nevertheless, the system must also have the capability of "stand-alone" operation.[49]

It is self-evident that an optimal population/household size can be determined for establishing a sustainable community. The best solution is mostly determined by

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[48] Matthias Otto Müller and Thomas Hammer, 'Energy Autarky: A Conceptual Framework for Sustainable Regional Development', *Energy Policy*, 39.10 (2011), 5800–5810 (p. 5801) <https://doi.org/10.1016/j.enpol.2011.04.019>.

[49] Callum Rae and Fiona Bradley, 'Energy Autonomy in Sustainable Communities - A Review of Key Issues', *Renewable and Sustainable Energy Reviews* (Pergamon, 2012), 6497–6506 (p. 3) <https://doi.org/10.1016/j.rser.2012.08.002>.

the energy generated from renewable sources, which is the primary characteristic that distinguishes a sustainable community from a conventional one. Thus, numerous researches, consequently, have concentrated on the extent of “energy autonomy” and the allocation of renewable energy sources.[50]

3.1.2. RES in Sustainable Communities

Founded on experiences acquired from past efforts, establishments of urban sustainable communities require accurate planning, optimum design, and valuing local resources without inflicting a threat of resource depletion nor interfering with the ecological balance.

Addressing the energy problem involves large-scale usage of RES to fulfill the demands of the built environment, as defined by the Sustainable Development concept. Solar, wind, water, and geothermal energy can all be processed into thermal and electric energy. This strategy also includes the utilization of biomass, albeit biomass conversion results in CO_2 outputs equivalent to the CO_2 handled throughout the biomass development.

Furthermore, improper design of biomass-based energy systems increases the peril of ecological imbalance; on the opposite side of the spectrum, biomass has historically been opted for all over the world, and thereby adding biomass in the shift to a sustainable built environment would then heighten acceptance of more renewable energy sources.[51]

Given the clear environmental benefits, there may be some impediments to implementing RES, as shown in Table 3.1.

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[50] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 26.

[51] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 33; Feist and Fremault, *Defining the Nearly Zero Energy Building*, p. 31.

Renewable energy system	Objective constraints	Subjective limitations
Photovoltaic systems	Variability in the solar energy potential	Landscape distortion
	Limited efficiency	Possible electromagnetic emissions
	High initial investment	
Solar-thermal systems	Variability in the solar energy potential	Limited architectural acceptance
	Risk of overheating	
Wind turbines	Variability in the wind energy potential	The NIMBY syndrome ("Not in My Back Yard)
	Noise and vibrations	
	High initial investment	
Geothermal systems (ground-coupled heat pumps)	Land availability	-
	Ecological balance	
	High initial investment	
Micro-hydro systems	Point-type resource	Highly difficult to integrate inside a community
	Consistent additional works and systems	
	Environmental distortion	
Biomass systems	Needs additional systems (storage, ash disposal)	-

Table 3.1 - Barriers against Implementing RES [52]

This necessitates fundamental understanding, like in the example of photovoltaics, where innovative materials and assemblies are rigorously explored to attain substantially higher efficiency values than the physical limitation of single-junction cells (33%, under 1 sun irradiation)[53].

This all includes empirical investigation, as the majority of anticipated solutions will be a mixture of innovative materials and enhanced frameworks.

3.1.3. Steps in Developing Sustainable Communities

The methods to establish sustainable communities and, correspondingly, nZEBs generate both general and unique qualities. The underlying premise remains unchanged: optimum solutions must match demand given the available energy, with a high proportion of renewables. Furthermore, the solution must be technically and financially viable, as well as environmentally friendly. The

[52] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 23.

[53] Martin A.Green, 'Energy, Entropy and Efficiency', in *Third Generation Photovoltaics*, ed. by T. Kamiya and others (New York: Springer Berlin Heidelberg, 2006), pp. 21–34 (p. 32) <https://doi.org/10.1007/3-540-26563-5_3>.

following actions should be taken into consideration. Determining the energy demand: the primary difference between developing a sustainable community and a nZEB.

	Common needs in nZEB and communities	Specific needs in sustainable community
Electric energy	Lighting the household	Street lighting
	Household appliances	Wastewater treatment
	Powering the auxiliary equipment of the RES integrated into the building	Powering the auxiliary equipment of community RES
Thermal energy	Domestic hot water	Wastes processing
	Building heating	Wastewater treatment
	Building cooling	Additional heating and drying processes

Table 3.2 - Needs in the development of sustainable communities [54]

As seen in Table 3.2, the electrical and thermal energy demands must be analyzed independently in the initial stages and tandem through an integrated approach.

3.1.4. Demand for electric energy in buildings:

Illumination and household appliance standards may be governed by national or international regulations. Electricity may be needed to operate heat pumps or force distribution in solar systems placed on edifices, relying on the renewable energy source mixes designated for thermal energy generation.[55]

Additional demands for communal electricity:

- The amount of electricity required for community illumination (streets, parks, etc.) and further equipment may be easily determined using the power of the individual user, the number of users, and the mean operating hours per unit.
- Energy required to obtain fresh water (from subsurface sources) and treat it must be included in the energy demand. Water management can be

[54] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 11.

[55] Müller and Hammer, 'Energy Autarky: A Conceptual Framework for Sustainable Regional Development', p. 5802.

organized in two ways: potable and non-potable. Ground water does not require treatment, which reduces electricity use.[56]

- On-site wastewater treatment relies on classic soda and lime systems that must be altered on a regular basis and are inappropriate for usage in communities. Centralized water treatment plants employ more efficient mechanical and biological treatment than individual facilities, with power consumption dependent on water flow.[57]
- Because the supplementary equipment for community renewable energy systems is dependent on the community-level organizations (e.g., big solar-thermal facilities), which are mostly connected to pumping systems, these must be located nearby.

3.1.5. Thermal energy demand in buildings:

One of the required steps in constructing sustainable communities involves minimizing the demands of thermal energy within the built environment, attaining low energy building status.

Domestic hot water, offers a nearly consistent day-to-day usage, by also accounting for around 20% of a building's overall thermal energy demand, with its prices varying according to the location of the building (residential, school, accommodation, etc.).[58]

Heating accounts for the major share of total thermal energy utilized in buildings in temperate climates (over 60%). As a result, significant attempts are being made to reduce heating demand, mostly through energy-saving strategies. Reduced thermal loss necessitates a properly insulated edifice envelope with an optimized opaque/transparent ratio. These customized solutions, which make

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[56] Peta Dzidic and Melissa Green, ‘Outdoing the Joneses: Understanding Community Acceptance of an Alternative Water Supply Scheme and Sustainable Urban Design’, *Landscape and Urban Planning*, 105.3 (2012), 266–73 (p. 271) <https://doi.org/10.1016/j.landurbplan.2011.12.023>.

[57] Guleda Onkal Engin and Ibrahim Demir, ‘Cost Analysis of Alternative Methods for Wastewater Handling in Small Communities’, *Journal of Environmental Management*, 79.4 (2006), 357–63 (p. 358) <https://doi.org/10.1016/j.jenvman.2005.07.011>.

[58] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 12.

use of revolutionary construction materials and technology, can be simply adopted in new buildings.

However, new structures represent less than 5% of the total construction stock, hence, structure upgrade is the most essential element that each home must address, while it is among the most challenging obstacles to overcome. Remodeling at the LEB effectiveness standard implies not only budgetary problems but is nevertheless constrained by the building's particular characteristics in terms of architecture, design, and structure. Furthermore, for edifices of historical significance, keeping the key aspects renders retrofitting extremely complicated (as well as expensive). Solutions tailored to each building are ought to be envisioned and incorporated into a specific architectural community notion.

Cooling (specifically in temperate climates) necessitates a thermal energy demand that is anticipated to be no more than 20% of the overall thermal energy requirement. Natural cooling (such as natural or mechanical ventilation at specific time frames) and shade solutions may greatly reduce thermal demands in properly insulated edifices.[59]

Supplementary community thermal energy demands can emerge from a variety of complementary services (such as swimming pools and greenhouses) that operate continuously or seasonally. Furthermore, based on the extent of each service or facility, recycling processes imply specific quantities of thermal energy.

3.1.6. Assessing the potential of renewable energy sources

Based on the type of energy supply, the potential is either dependent or independent of the site:

Solar energy, wind energy, and, to a certain degree, water flow on minor rivers, are all characterized by site-dependent potential. These have a seasonal change relying on geographical location, while the annual total amount is quite stable. Monthly (or weekly) variations are required for establishing energy mixes based

[59] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 13.

on renewability. The intervals with a decreased potential of each renewable are always highlighted to identify the energy amount which has to be supported by backup sources, as well as the intervals when surplus energy facilitation is anticipated to accurately develop storage systems and contingency measures. As a result, periodical variations must be provided for at least one year, but ideally two to five years.

Because temperatures of the earth at certain depths are mostly consistent, geothermal sources should have site-independent potential. The key constraint is the lack of a suitable area for installing a ground heat exchanger, hence deep drill ones are to be considered. In terms of meteorological data, biomass potential is likewise site-independent, but it is dependent on supply and logistics, with particular aspects for different forms of biomasses: wood, manure, straw, and so on.

Because RES implementation is advised to be implemented at both building and community tiers, the potentials that are site-dependent must be tracked in as many development sites as possible to determine the best options. This is required for compact wind turbines (placed at a reduced height) since the form of the building can have a significant impact on the vertical distribution on edges, corners, and rooftops. This is equally important when installing solar thermo-electric energy converters, because pollution, which is common in urban areas, can alter the direct/diffuse solar radiation ratio, reducing the total capacity and outcome. [60]

The available sites present an additional constraint at the community level and optimal planning requires equilibrium between the land used for agriculture and the land utilized for energy generation (including energy crops).[61] Land used for RES should preferably be of restricted use in agriculture, with one alternative

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[60] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 418.

[61] Md Mizanur Rahman and others, ‘Extension of Energy Crops on Surplus Agricultural Lands: A Potentially Viable Option in Developing Countries While Fossil Fuel Reserves Are Diminishing’, *Renewable and Sustainable Energy Reviews* (Elsevier Scientific Publ. Co, 2014), 108–19 (p. 110) <https://doi.org/10.1016/j.rser.2013.08.092>.

being to plan and undertake soil rehabilitation within the estimated lifespan of the renewable system (20–30 years).[62]

By examining the evolution of various renewable energy sources, their hurdles, and physical constraints, the European Strategic Energy Technology plan distinguishes between RES that are suggested for small-scale installations and the ones which enable large-scale outputs. A concise conclusion entails that electricity generation should take place in large facilities, whereas thermal energy production should take place on-site, on, or adjacent to the buildings, reducing losses during heating agent transport. These proposals should be adjusted to the demands, dimensions, locations, renewable resources available, grid accessibility, etc. of the community. Non-technical parameters to examine include economics profile, wellbeing, heritage, mean education level, and promoting legislative framework. As a result, multiple mix scenarios should be established, with the best one gaining widespread approval (and commitment) within the community.[63]

By taking into consideration the cost-efficacy, indoor climate, and local conditions, the energy performance of the stated buildings' directive targets to advance the general efficiency of the built environment. Through certain studies led by the Passive House Institute, it has been concluded that the most favorable result is obtained through the possibility of heating a building solely by filtered air, harnessed from a heat recovery system. For characteristic floor areas, the case is presented with a heating load of 10 W/m^2 or with a yearly heating demand of approximately 15 $kWh(m^2a)$.

The Passive House Standard has these values as critical compliance. Through its over 20-year success, the Passive House has been proved as an ideal foundation for the Nearly Zero Energy Building.[64]

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[62] Soji Adelaja and others, 'Renewable Energy Potential on Brownfield Sites: A Case Study of Michigan', *Energy Policy*, 38.11 (2010), 7021–30 (p. 7022) <https://doi.org/10.1016/j.enpol.2010.07.021>.

[63] Visa and Duta, *Sustainable Energy in the Built Environment - Steps Towards NZEB*, p. 12.

[64] Feist and Fremault, *Defining the Nearly Zero Energy Building*, p. 9.

3.1.7. City as powerhouses

The first step towards climate protection and regulation starts at regional level, by decreasing the buildings' energy consumption. In terms of climate protection within the building sector 10 measures to raise effectiveness can be defined:

1. Promoting the strategy by constructing new public buildings that belong to the local authorities under the Passive House Standard.
2. Local Authorities can condition land sales only if the future building will incorporate and follow a Passive House Standard alongside the incorporation of renewable energy.
3. Urban master-planning must be adapted by taking into accordance the orientation in relation to the sun, prominent wind direction as well as shading and compactness
4. Social housing companies can vastly contribute by adapting their existing buildings to a Passive House Standard as well as following the standard for future constructions.
5. Development of financial incentive packages for energy-efficient investments addressed to citizens who want to participate in the movement. Incentives dedicated to renewable energy should also be stimulated.
6. Introduction of quality assurance through milestone verifications. The markers should be distributed throughout the planning process as well as building construction.
7. Implementation of pilot projects at an urban scale under the form of either sponsorship or development of climate-neutral urban districts.
8. Implementation of wider support of movements for investors, which includes architects, contractors, manufacturers, planning departments, etc. These can be organized as informative proceedings and instruction workshops that would help the industry obtain the essential knowledge and expertise to develop Passive House buildings.

9. Developing information campaigns to inform and lead household owners to upgrade their energy equipment with more efficient appliances and systems.
10. Inclusion of the Passive House strategy within PR projects showing its efficacy.[65]

[65] Wolfgang Feist and Fremault, *Defining the Nearly Zero Energy Building Passive House + Renewables*, pp. 77–79.

3.2. Leadership in Energy and Environmental Design (LEED)

3.2.1. Introduction: Defining the "Measurable Green Criteria"

Nowadays it can be observed that a considerable portion of building developments are every so often supported by lower-grade design and construction strategies, alongside inefficient means of comfort (air conditioning, heating, and ventilation systems), rendering buildings as the most significant factor of global warming. Within the United States, several federal and private entities try to tackle these problems. Through their initiatives, a flow of intrigue in green and sustainable concepts, through which certain rating systems have arisen, can be observed.[66]

The rating systems are mainly serving two general features: the encouragement of high-performance edifices as well as the generation for sustainable construction. Some of the milestones within these rating systems refer to:

- Procurement: particular procurement strategies that are required to ensure the sustainability of the development.
- Site and environment: Implying environmental impact reduction.
- Material selection: Identification of environmentally friendly construction materials and also what harmful and toxic materials to avoid.
- Waste prevention: Identifying the means to lower the waste amount generated by building projects.
- Recycling: Depicting the recyclable materials at every construction stage while evaluating methods that encourage on-site recycling.
- Energy: Developing means and strategies by guaranteeing and enhancing the energy performance of the building while reducing energy demands during construction. Identifying the potential renewable energy sources for further use.

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[66] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. xxiii.

- Material use and reuse: Identification of optimal material usage and provenance, encouraging material salvaging from demolitions.
- Construction technologies: Implementation of specific systems that could be employed throughout the building process to ensure waste reduction.
- Health and safety: Development of means to raise the living standard for both current and prospective residents
- Indoor Environmental Quality: Solutions for ensuring that IEQ measures are effectively managed and performed throughout the construction process.[67]

3.2.2. LEED Minimum Program Requirements

The first requirement implies that the edifice has to be placed in a definitive location.

Secondly, the LEED project boundaries should embrace all contiguous land in relation to the edifice and must be capable of supporting its regular activities. This condition also implies the altered land in favor of the construction as well as services destined for its occupants such as parking lots and pathways, water treatment equipment, and landscaping.

Finally, the project size must comply with the maximum LEED evaluation capacity.[68]

3.2.3. LEED Operations

Projects can be certified by LEED under certain evaluation or rating systems that define a certain category such as “Building Design & Construction”, “Interior Design & Construction”, “Homes” etc.

Each category has a set of requirements, usually orientated towards green building practices, that earn the project a number of points based on its

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[67] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, pp. 30–31.

[68] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, pp. 36–37.

performance. “Certified”, “Silver”, “Gold” or “Platinum” statuses can be attained based on the total of accumulated points, and the development is then labeled as a “LEED certified” project.[69]

3.2.4. LEED Categories and Point System

LEED categories vary in their rating method relying on established compulsory fundamentals and a variation of awards within seven defining categories:

- Sustainable Sites: offering 26 obtainable points
- Water Efficiency: offering 10 obtainable points
- Energy and Atmosphere: offering 35 obtainable points
- Materials and Resources: offering 14 obtainable points
- Indoor environmental Quality: offering 15 obtainable points
- Innovation in Design: offering 6 obtainable points
- Regional Priority: offering 4 obtainable points

Based on the points earned within the aforementioned categories, the project will be classified within one of four levels of certification:

1. Certified: raging between 40-49 credits
2. Silver: raging between 50-59 credits
3. Gold: raging between 60-79 credits
4. Platinum: obtaining over 80 credits[70]

a. LEED variations and systems applied around the world

An elaboration regarding LEED variation systems applied around the world can be found in Appendix A.2.1

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[69] U.S. Green Building Council, *Green Building Design and Construction*, *Building Design and Construction*, 2009, p. xxiii.

[70] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 76.

b. The Green Globes Initiative

The United States has a variety of green building evaluation procedures, with the two most commonly used for commercial buildings being LEED and Green Globes. Further Information can be found in Appendix A.2.2

3.2.5. LEED Technical Requirements and Documentation Process

The LEED "Green Building Rating System" (abbreviated as GBRS) represents the result of the USGBC's ongoing efforts to establish a worldwide standard aimed to define what a "green building" is. This is all envisioned to increase the productivity and quality of service provided by contractors and the well-being of the occupants and the economic sustainability of buildings that incorporate proven green strategies and creative practices. [71]

The GBRS is a general agreement nationwide standard aimed towards promoting the development of high-performance, environmentally aware edifices. The majority of LEED services are free to download from the United States Green Building Council's website.

Credit Categories

The most recent rating system emphasizes energy conservation, reduced emissions of CO_2 as well as environmental and public health issues.

While acknowledging the value of the LEED software, Charles Crawford, professor and architect at the "NewSchool of Architecture and Design" in San Diego, believes it has major flaws. He states that "the points program they administer is heavily tilted toward rewarding greener technology over basic 'passive' principles. So, for example, you get more points for an energy-efficient air conditioner than you do for a naturally ventilated building".[72]

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[71] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 49.

[72] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 73.

The professor also cites LEED's seeming disregard for the large quantities of fuel spent in international transportation, pointing out that A green product made by a company in another country and transported to the United States is frequently awarded more credits than one made locally.

Many of these concerns have been addressed in the latest ranking systems, which have been correctly phrased. The new methodology aligns each group's precondition or credit structure (as depicted in Table 3.4) into a mutual divisor. This implies that an equivalent collection of credits is usually provided under each rating scheme (Fig. 3.1). [73]

Credit Category	New Prerequisite	Revised Prerequisite
Sustainable Sites	Environmental site assessment now applicable to schools and healthcare; site management policy	Updated reference standard for construction activity
Water Efficiency	Building level water metering	water use reduction now split into outdoor and indoor water use reduction
Energy and Atmosphere	Building level energy metering	Fundamental commissioning of building energy systems now called fundamental commissioning and verification; updated reference standard for minimum energy performance
Materials and Resources	Construction and demolition waste management; PBT source reduction - ongoing purchasing and waste policy; facility alterations and additions policy	storage and collection of recyclables
Indoor Environmental Quality	Green cleaning policy	minimum indoor air quality performance; environmental tobacco smoke control; minimum acoustical performance

Table 3.3 - Updates for the LEED credit categories' requirements [74]

Other major amendments include the addition of Regional Priority points and a modification to the credit allowances. The USGBC intends for the program to pass through a said "predictable development cycle" to aid constant

[73] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 74.

[74] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 74.

enhancements and enable the market to actively engage in LEED's evolution and growth.

The overall credit distribution for these categories is amounted to 100, with 6 additional credits for Design Innovations as well as 4 more for Regional Priority.

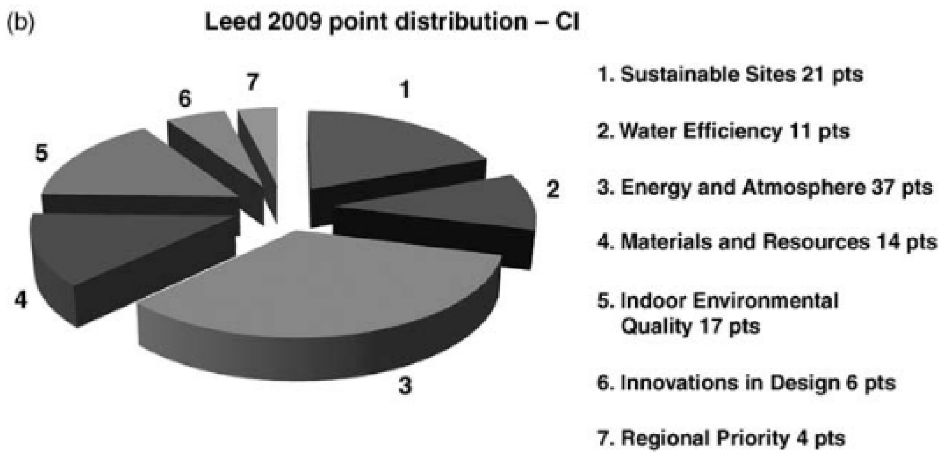

Fig. 3.1 - The LEED™ point distribution system[75]

Location and Transportation

Development teams are inspired through the credits assigned for Location and Transportation (LT), to utilize existing infrastructure systems, which brings a positive impact on the climate and human health. Thus, within the Location and Transportation class, building location considerations are rewarded with credits that promote compact development, efficient transit, and proximity to services like restaurants and parks.

Transportation Recommended Practices:

1. Promote alternate modes of transportation to driving to mitigate the negative environmental effects of car use; additionally, search for a location that is well-suited for mass transit use, i.e., near public transportation.
2. Designate parking spaces for environmentally aware automobiles.
3. Decrease parking capacity and promote ride-sharing.

[75] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 75.

4. Embrace safe bicycle stowage, changing rooms, showers, etc.[76]

Credit Category for Sustainable Sites

The San Elijo Lagoon Nature Center in San Diego County, California, is an ideal illustration of a contemporary edifice developed to attain a gold certification in LEED's program. The construction's insulation was produced from recycled denim and the waste from demolition and construction was repurposed or recycled in proportion of 90%.[77]

A green roof on top of the building filters pollutants from rainwater, in favor of the Sustainable Sites category, since it promotes the use of alternative means of transport, site disruption reduction, and rainwater treatment. Thus, the building's site irrigation and bathrooms use recycled water.

Fig. 3.2 - San Elijo Lagoon Nature Center (author: Zagrodnik + Thomas Architects)[78]

Following the identification of a site, it is critical that the building design utilizes the existing conditions to their full potential while minimizing disturbances to the surrounding environment. Thus, projects that decrease the heat island effect,

[76] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 77.

[77] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 78.

[78] Image source: https://bwesd.com/project/san-elijo-lagoon-nature-center/

reduce light pollution, and include onsite renewable energy are being credited. Sustainable Sites category Practices:

Choosing a site for a project:

- Identifying and building projects on suitable sites to mitigate the environmental effects of construction.
- Choosing brownfield or infill sites for construction in preference to reduce building footprints and increase the use of available land
- Choosing densely settled or well-serviced to take benefit of established infrastructures
- Interference with present ecosystems should be avoided; adequate space is necessary
- Protect and save the current natural features such as plants that need little water and no pesticides. Compost and mulch use should be promoted.
- recycled content and furnishings are encouraged

Reducing the heat island effect:

- Reducing the area affected of a site, caused by absorbed heat in surfaces that are dark-colored. This may disrupt local microclimates and raise cooling loads over the summer period.
- Using cold roofing techniques such as green roofs or light-colored coatings
- Parking is encouraged in garages, preferably underground.
- Where appropriate, the use of shade trees and lightly colored pavement is encouraged.

Light pollution resolutions:

- Designing proper lighting to avoid unnecessary emissions into the night, since a lit night sky has a detrimental impact on neighborhood comfort and migratory bird habits. This can be attained by employing low-intensity, shielded fixtures with sufficient cut-offs, as well as turning off or dimming lights during non-business hours.

Credit Category for Water Efficiency

This category's objective is to promote water conservation, by using the least amount of water possible and can be envisioned through management strategies. These maximize the beneficial use of available water resources for individuals and the environment. Credits are awarded to structures and landscapes that conserve drinkable water used for irrigation and wastewater processing. [79]

An underlying solution to water conservation is to reduce waste, not to limit use. Customers can help by repairing leaking faucets, installing displacement devices inside WC tanks, and running washing machines and dishwashers at maximum capacity, among other habits. Water conservation and rainwater management techniques can be established and employed collaboratively in a variety of environments and mostly work in conjunction with site-related initiatives to enhance different building systems.

"Practice Green-health" lists recommends the following measures for establishing a water management program:

- Examining the existing water use by positioning water meters in strategic areas within the building and recording water readings weekly while analyzing the results. It is important to keep a lookout for areas of heavy water use, patterns, and unusual occurrences.
- Identifying water-saving opportunities by repairing drips, spills, and extraneous flows and making improvements to more efficient washing, laundry, and kitchen procedures. It is important to create a list of opportunities that include equipment solutions.
- Determining the cost of opportunities as well as their possible investment recovery.
- Identifying and prioritizing opportunities for water preservation.
- Creating a budget-friendly phased schedule.
- Obtaining financing.
- Putting the strategy into action.

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[79] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 80.

- Determining and recording success.[80]

Credit Category for Energy and Atmosphere

The primary requirement in this class is that the structure undertakes essential commissioning to guarantee that the building systems are working as intended. Other requirements for this category embrace achieving minimum energy efficiency while not using chlorinated fluorocarbon-based refrigerants in new building heating, ventilation, air conditioning, and refrigeration equipment.

The Energy and Atmosphere category has lately added a new requirement: building-level energy metering. To comply with the criteria of this condition, the edifice must have installed a system of meters (or submeters) to record the overall energy usage of the building as regularly as possible, preferably at monthly intervals. The development is also required to provide the data to the United States Building Council for a period of five years. Within this category, an extra credit for more stringent monitoring of energy consumption can be gained.

The “Optimizing Energy Performance” credit was updated as compliance to the newer base norm, while including two additional points for advanced metering and demand-response services.

Extra points are awarded for improved appointing long-term continuous assessment and verification of construction results. Green buildings use advanced efficient technologies and techniques to improve energy quality. Several features of an edifice’s architecture can affect its energy output and incorporating energy conservation strategies can result in numerous important utility rate savings.

Passive design strategies usually hold a huge impact on the energy efficiency of a building. Such procedures embrace adequate building morphologies and

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[80] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 83.

orientation, passive solar designs, and appropriate usage of natural illumination.[81]

Best Practices:

- Proper evaluation of the HVAC system is critical for energy demands. Where appropriate, active techniques such as on-demand controlled ventilation, speed-controlled supply, heat recovery, and economic cycles are ought to be used.
- Eliminating the use of harmful refrigerants to mitigate the development's possible negative effects on global warming or ozone depletion.
- Whenever possible, using high-efficiency “Energy Star” appliances and household electronics.
- Combining a suitably sized and energy-efficient climate system with a proper thermal building shell.
- Reducing the amount of electricity used by equipment and appliances, such as converting to energy-efficient light sources, will result in significant savings.
- Aligning energy-efficient lighting with daylighting techniques, as well as the implementation of energy-efficient systems with controllable lighting intensity. Motion sensors that are linked to dimmable switches must be taken into account.
- Using light colors as much as possible for both wall and roof finishes. Wall and ceiling insulation should be high-performance in terms of thermal conductivity. Because of the low angle of the light, smaller windows can be used on east and west exposures to minimize heat gains.
- Ensuring that suitable construction systems commissioning is performed to ensure that the development's efficiency-related systems are correctly planned, fit, configured, and running as envisioned.

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[81] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, pp. 83–84.

- Ensuring that the building envelope and its features are optimized for energy efficiency by focusing on insulation, glazing ratios, and window frame performance.
- Thinking about using renewable energy sources like on-site power providing systems. These include thermal and photovoltaic panels as well as wind turbines.
- Promoting the use of green power by choosing renewable energy providers.
- Using measurement and verification systems to track the energy used by the building, providing valuable data about the building's efficiency while defining possible maintenance needs aiming at performance optimization.
- Computer-aided modeling offers tremendous potential and is a valuable method for optimizing the electrical and mechanical systems' design, as well as the structure's insulating shell.[82]

Credit Category for Resources and Materials

Since the USGBC first launched in 1999, this category has possibly undergone the most important improvements. One of the major changes that affect many credits is the use of regional materials. For the development team to benefit from the certification, local materials must be collected, assembled, and mounted within a 100-mile range. It is imperative to prioritize life-cycle approaches alongside the number of goods measured by type, as well as material cost.

In general, the Materials and Resources class implies that a dedicated zone should be established on site for the processing and stowage of recyclable materials, ideally during design and operations. Points are also provided to designs that salvage sections of an existing edifice, as well as designs that incorporate a building waste management strategy, reducing landfill growths.

According to the "Commercial Interiors Reference Guide", building material selection is imperative in sustainable developments because of the widespread network of extraction, processing, and compulsory transportation stages.

[82] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 85.

Certainly, the amount of energy and resources needed extends the development's effect well beyond the construction itself. As a result, cautious material selection and discarding will significantly reduce a building's environmental impact. In the Sustainable CI book the authors, Penny Bonda and Katie Sosnowchik note that in the beginning, designers must recognize that sustainable materials should possess specific characteristics: they should be healthful, resilient, suitable, and easy to maintain, with low environmental consequences during their life cycle.[83]

Protocol Overview:

- Reusing as many construction materials as feasible while providing readily available collection and stowing points for recyclability.
- Using building waste management procedures to minimize debris.
- When designing new office spaces, products bought and produced locally must be prioritized.
- Resources with a high proportion of recycled content ought to be preferred.
- Resources that are quickly renewable, recovered, or refurbished should be prioritized.
- Using wood that has been approved by appropriate organizations wherever possible.

Credit Category for Material Efficiency

When choosing sustainable construction materials and resources for development, it is mandatory to begin by assessing several critical inherent characteristics that ought to have an adverse influence on the environment. These comprise of: reduced or no exhaust of detrimental air emissions, reduced or no toxicity, high recyclability, resilience, and longevity. Also, these resources need to be produced locally.

The utilization of recycled goods similarly contributes to the development of recycled material markets, reducing landfill growth. Other material efficiency

[83] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 87.

methods, such as dimensional planning, contribute to a reduction in the amount of construction materials required as well as a decrease in building expenses. Plans for material management should be developed for deconstruction, demolition, and construction.

Credit Category for Indoor Environmental Quality

The Indoor Environmental Quality (IEQ) class aims to guarantee that inhabitants of green buildings provide adequate illumination, thermal comfort, and proper indoor air quality, among other things.

To contribute to the comfort and welfare of the inhabitants, it is important to consider adequate indoor air quality in the environment as a prerequisite. In addition, the IEQ credits address issues such as natural illumination, vistas, thermal comfort, and materials with no release of pollutants. Credit is also given for employing fresh air supply monitoring systems, installing CO_2 sensors, increasing ventilation efficacy, managing indoor air quality before habitation, and permitting inhabitants to adjust the systems in each individual zone.

It is critical to reduce the risk of indoor microbial contamination by using antimicrobial materials and ensuring proper roof and site drainage. Furthermore, appropriate bathroom airflow, effective air-conditioning coil drains, and the implementation of humidity-controlling building systems are also necessary.

“Enhanced Indoor Air Quality Strategies” is a novel class that, in addition to increased ventilation requirements, includes CO_2 monitoring, as well as air pollution and cross-contamination prevention. The fundamentals of the credit are determined by whether the building uses natural, mechanical, or mixed-mode ventilation.[84]

Best practices for Interior Environmental Quality:

- Highly effective ventilation and filtration systems prevent the build-up of poor air quality.

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[84] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 89.

- Using zero or low volatile organic compounds will benefit the indoor air quality.
- Absorptive resources stowed on-site must be protected from damage.
- During development, air handlers should result in a minimum efficiency reporting value (MERV) of 8.
- Air filtration is required with a minimum of a two-week flush-out. Where occupants are vulnerable to fine particulates, biological contaminants, and potentially hazardous pollutants, exchanged air must have a MERV rating of 13 or more.
- considering daylight and views within the design.
- Keeping occupants comfortable with adaptable elements such as thermostats or motorized windows.
- The Heating, Ventilation, Air Conditioning system, and building envelopes must be planned to meet ASHRAE 55-2004 prerequisites.
- Complying with the Sheet Metal and Air Conditioning National Association's design guidelines (Sheet NAQQG).
- The paints and coatings used must be tested for VOC compliance: wall and ceiling paints, clear water-based finishes, anti-based sealers, and shellac comply with Green Seal Standard GC-03. Anti-rust paints for ferrous surfaces are tested for compliance.
- Carpet & Rug Institute's Indoor Air Quality program requirements are obligatory for all carpet systems. Composite products made of wood fiber and resin must be free of urea-formaldehyde.

Credit Category for Design Process and Innovation

The purpose of the Innovation and Design Process class is to offer development teams the chance to earn credits for exceeding criteria for innovative performance, in Green Building classes that are not included by the GBRS. [85]

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[85] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 92.

Credit Category for Regional Priorities

Developments will gain up to four of the six available credits by implementing strategies defined by that area's USGBC or an afferent section. Every Regional Priority credit earned awards one point, limited to a total of four. Though the U.S. Green Building Council has constantly emphasized "Integrated Project Design", it only now grants 1 credit for employing a coordinated development procedure from the preliminary stages throughout all design phases.

Development teams must define possible collaborations through credit categories and register how their preliminary assessments influenced the project criteria and design basis. The aim is to encourage the acquisition of points that tackle geographically precise goals. Environmental, public health, and social equity are all issues that need to be addressed. These claims have been listed as posing supplementary regional significance for the development's area by the USGBC councils.[86]

Credit Category for Integrative Processes

This requirement necessitates the use of an ongoing research strategy within developing projects and allows the team to consider the owner's long-term priorities since the beginning of the design development. When evaluating this category, the emphasis must be on establishing cross-disciplinary interactions and collaborations.

The classification entails preliminary research in the domains of energy and water usage, together with site conditions, building morphology, and orientation, as well as the building envelope – areas where the architect and structural engineer should be of assistance. Similarly, projects can gain a point by analyzing synergies between different simple "passive" methods and systems. These can affect energy usage and inhabitant comfort, such as building envelope factors, glazing, and efficiency technologies.

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[86] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 94.

The category is also meant to acknowledge developments for its creative building features and awareness of its sustainability, taking into account innovative thinking and exploration of previously unexplored fields.

Construction commissioning entails inspecting and modifying mechanical, electrical, and plumbing systems to make sure the equipment meets the owner's design specifications.

LEED also implemented a ranking system within this category for existing large structures (usually including facilities such as data and distribution centers, warehouses, accommodation, etc.) known as Building Operations and Maintenance.[87]

Certifications, Submittals, and Project Documentation

LEED accreditations are intended to also deliver independent, extraneous assurance that a construction development meets the uppermost green building and efficiency standards. All certified buildings include a plaque, that is a nationwide acknowledged sign indicating that a construction is environmentally sustainable, aware, productive, and safe. LEED-Online functionality allows development team affiliates to upload credit templates, monitor CIRs, handle key project information, access customer support, and connect with evaluators during all the stages of the design process. There are five fundamental steps to the LEED certification process:

1. Project registration.
2. LEED standards compliance.
3. Acquiring technical support.
4. Project documentation in preparation for certification.
5. Claim certification.[88]

[87] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 95.

[88] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*, p. 96.

3.2.6. Green Delivery Systems Versus Traditional Ones

Further information regarding the differences between green delivery systems and conventional ones can be found in Appendix A.2.3

3.3. Passive House

Being one of the most popular energy efficiency strategies, the Passive House standard represents a globally recognized development protocol for constructions with near-zero energy consumption. The concept was devised by Doctor Wolfgang Feist and Professor Bo Adamson in 1988.[89]

The standard aims to establish performance prerequisites that include both technical and thermophysical features of the designed or improved edifice, by bringing the total energy consumption to an efficiency of nearly zero by also improving the level of indoor comfort. The strategy devised certain standard values as a benchmark that would qualify a building as being passive.

One of the first regards the energy demand for cooling and heating that should be lower or equal to 15 kWh/m^2. Secondly, the primary energy demand should be lower or equivalent to 120 kWh/m^2/year.[90]

Heating loads resulting from all systems such as main heaters, cooling, ventilation, lighting, etc. should be less or equal to 10W/m^2. Finally, one of the most important features that needs to be respected is the total building airtightness which translates to $n_{50} \leq 0.6$/h, which refers to the air changes under a difference of pressure equal to 50Pa.[91]

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89 'Passivhaus Institut' <https://passivehouse.com/> [accessed 1 April 2020].

90 Piraccini and Fabbri, *Building a Passive House*, p. 150.

91 Passive House Institute, 'Airtightness Test', 2019 <https://passipedia.org/planning/airtight_construction/general_principles/blower_door_test> [accessed 2 April 2020]; Mary James and James Bill, *Passive House in Different Climates / The Path to Net Zero*, *Journal of Chemical Information and Modeling* (New York, London: Routledge, 2013), LIII <https://doi.org/10.1017/CBO9781107415324.004>.

3.3.1. The six laws that enable the Passive standard

The most important design and technological construction solutions for meeting the standard are as follows:

1. High insulated building envelope. The composite performance of the envelope should reach the parameters of thermal transmittance as $U \leq 0.15\ W/m^2K$
2. Mitigation of thermal bridges. Thermal bridges are the sensible points where our thermal transmittance equation can become false.
3. Window Performance. The windows need to be highly performant in terms of transmittance and insulation.
4. Correct orientation and exposure towards the sun. This will ensure the building's ability to collect as much passive energy as possible.
5. Airtightness. Having an airtight building envelope ensures both the high performance of the insulation as well and in turn offers the smallest ratio of energy transfer.
6. Usage of a regulated mechanical ventilation system that has an incorporated heat exchanger and a battery for post-processing. This system ensures a high indoor comfort through its air filtration system as well as low energy consumption due to its heat recovery function that uses the exhausted air flow to heat the fresh air flow.[92]

[92] Passiv Haus Institut, *Curs Proiectant / Consultant Case Pasive Volumul 1*.

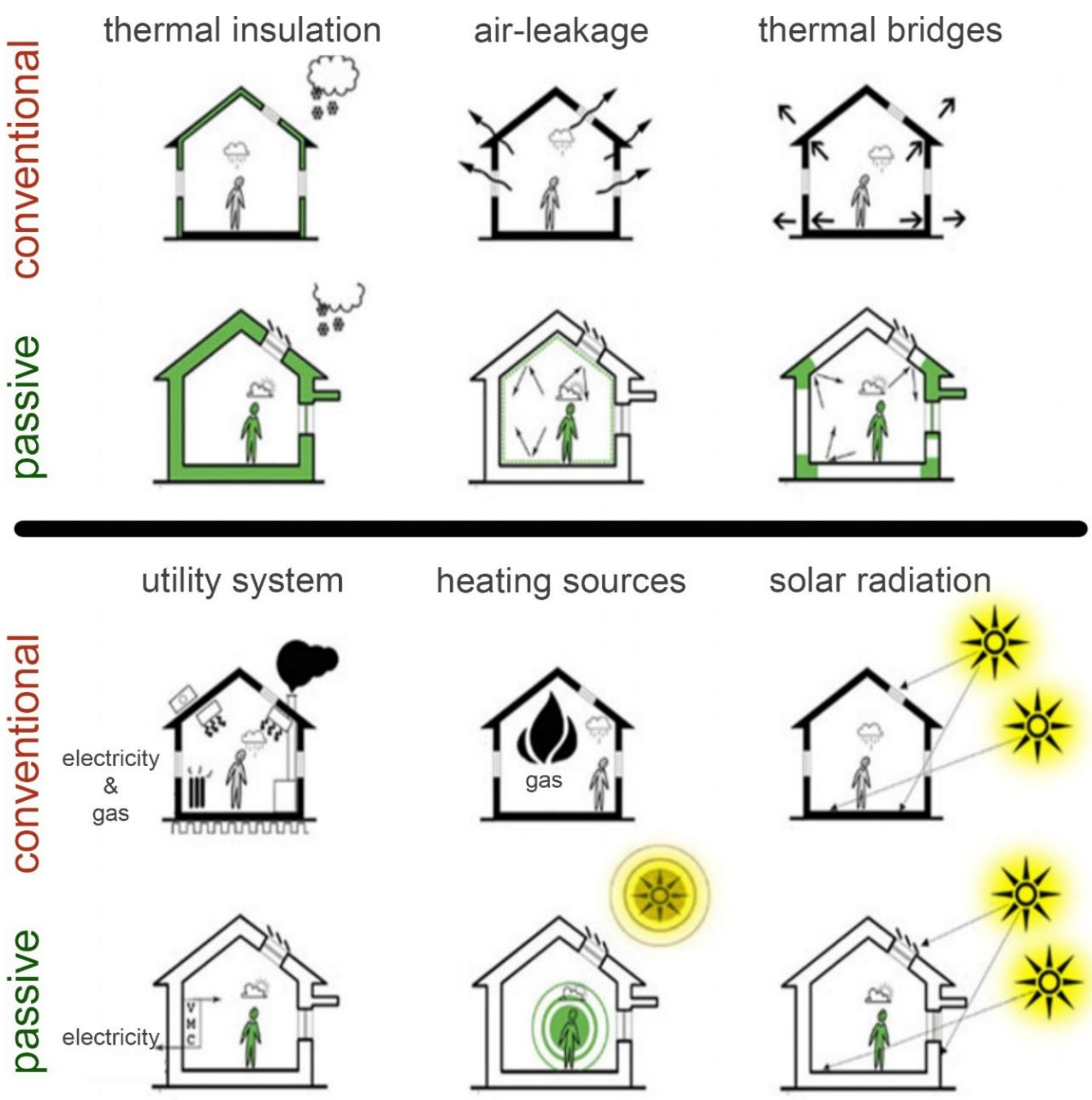

Fig. 3.3 - Comparison of a regular house versus a Passive House (authors: Piraccini Stefano, Fabbri Kristian)[93]

3.3.2. Building Envelope

The entire building enclosure is thermally insulated to a high standard. Under central European temperature conditions, the heat transfer coefficients (U-values) for the roof, the external walls, and the floor slabs range from 0.1 up to 0.15 W/(m^{2}K). When building passive houses, these values should not be impacted by the construction method.

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[93] Piraccini and Fabbri, *Building a Passive House*.

When the outside temperature is high, good thermal insulation has a favorable effect by providing heat protection. Even with limited mass, highly insulated buildings exhibit high-temperature amplitude absorption (e.g., double gypsum plasterboard panel). As a result, daily changes in outside air temperature have no influence on the interior of the structure. A prolonged building time-constant is calculated by dividing the edifice's internal heat capacity by the mean transmittance of the structures that make up its thermal envelope, rendering a thermally accessible building mass more useful. This makes it simple to cool a passive house at night with open windows while still maintaining cool temperatures during the day.[94]

Exfiltration air currents can penetrate the thermal insulation, causing higher ventilation heat losses and reduced insulation performance. This can result in severe functional loss, particularly in passive houses, which employ extremely thick insulation layers to achieve low heat transmission losses. Apart from airtightness, appropriate wind resistance is also required for good thermal insulation.[95]

3.3.3. Thermal Bridges

Thermal bridges form in standard component connection zones or in regions where the structure has been weakened: in these circumstances, heat loss estimations based on U-values and standard component surfaces are inaccurate. Thermal bridges are particularly noteworthy for two reasons:

- The internal surfaces of the components are often cooler than those of ordinary construction components. This can result in mold, condensation, and, in the worst-case scenario, moisture penetration into construction components.

[94] Fabio Bianconi and Marco Filippucci, *Digital Wood Design: Innovative Techniques of Representation in Architectural Design* (Springer, 2019), p. 1511 <https://doi.org/https://doi.org/10.1007/978-3-030-03676-8>.

[95] Donald B. Corner, Jan C. Fillinger, and Alison G. Kwok, *Passive House Details: Solutions for High-Performance Design*, 1st edn (New York: Routledge, 2018).

- Heat losses normally rise. In the case of linear thermal bridges, such as the connection between an exterior wall and a basement ceiling, the difference between actual heat losses and “standard” heat losses calculated for standard components is proportional to the length of the thermal bridge and represents the thermal bridge loss coefficient Ψ.[96]

However, in the majority of cases, thermal bridges may be avoided. Insulation should be installed in such a way that it completely covers the surface of the structure without gaps. Calculating heat loss using exterior dimensions (as is customary for the energy balance) is recommended. As a result, negative Ψ-values are generated, thus, thermal bridges no longer need to be considered.

This simplifies designing and also avoids thermal bridge issues. This method is referred to as “thermal bridge-free construction”. As a result of the fact that a substantial percentage of building component connections (e.g., outer wall to outer wall) has negative-values, component connections with Ψ values up to 0.01 W/(mK) are nevertheless regarded thermal bridge-free and inconsequential in the energy balance.

3.3.4. Window Performance

The overall performance of a passive house design is contingent upon the windows contributing meaningfully to the shell's thermal integrity. While designating high-quality windows is critical, it is not sufficient, since their efficiency is also determined by how they are designed and installed. Thermally, the glazing in a passive house window typically performs better than the frame, thus, it is preferable to utilize fewer, larger units than increments of smaller ones. This reduces the frame-to-glazing area ratio and therefore increases the amount of solar gain through a given wall opening.

Passive houses utilize the most performative windows currently available on the market, with three critical points to consider: glazing with three panes or an

[96] Piraccini and Fabbri, *Building a Passive House*, p. 131.

equivalent glass combination, warm edge spacers, and window frames that have been specially insulated.

These components contribute to the development of a window with half the heat loss of a normal modern one. With the proper orientation and limited shade, these high-quality windows lead to a positive energy balance in passive houses, even throughout the crucial winter season, because they allow for indirect and direct sunlight radiation to flow indoors.

Both the U-value of the elements, as well as the temperature coefficient at the lowest point of the component, are used to validate Passive House compatibility for windows. Within each environment, the Passive House Institute computed the maximal heat transfer factors of installed certified transparent Passive House building components, which are shown in the image below.

Region	Maximum heat transfer coefficient	
	$U_{w,inst}$	U_w
Arctic	0.45	0.40
Cold	0.65	0.60
Cool-temperate	0.85	0.80
Warm-temperate	1.05	1.00
Warm	1.25	1.20
Hot	1.25	1.20
Very Hot	1.05	1.00

Fig. 3.4 - Maximum Heat Transfer Coefficient (author: Passivhaus Institut)[97]

It should be noticed that the table shows two diverse U-values. One of the window ($U_{w,}$ including glazing, transparent material edge, frame, etc.) in addition to the predicted U-value of the mounted system, accounting for installation thermal bridges ($U_{w,inst}$).[98]

[97] Image Source: https://blog.passivehouse-international.org/ug-uf-uw-uwhat-an-intro-to-the-u-value-and-those-most-important-to-passive-house-design/

[98] Piraccini and Fabbri, *Building a Passive House*, p. 132.

The following is the complete equation for finding $U_{w,inst}$:

$$U_{w(inst)} = \frac{U_g A_g + U_f A_f + l_g \Psi_g \ (+l_{inst} \Psi_{inst})}{A_g + A_f}$$

Fig. 3.5 - $U_{w,inst}$ Formula (author: Passivhaus Institut) [99]

The formula accounts for the glazing's dimensions and insulation (A_g and U_g), the frame's size and insulation (A_f and U_f), as well as the heat losses at the glazing edge (Ψ_g) and installment (Ψ_{inst}). Thermal bridge coefficients, denoted by the Ψ symbol, describe the additional thermal flow caused by a linear thermal disorder or change in morphology.

According to EN 10077, the heat transmission coefficient of a warm window (U_w) is less than 0.8 W/m^2, thus, even on cold winter nights, the inside surface temperature remains at 17°C due to reduced heat loss. Even close to the window, comfort is exceptional under these conditions, having no vexing "cold radiation". This eliminates the need for radiators near the window, which were previously required.[100]

3.3.5. Site and Climate

A detailed investigation of the potential site is one of the first actions in building design. The following characteristics are very important for a passive house project:

The first principle to consider is the climate and microclimate, which is described by seasonal temperature and humidity cycles, daily temperature ranges, solar exposure on the site, and wind patterns. Secondly, we should envision the physical structure, which includes topography, water flows (both surface and subsurface), vegetation, and opportunities for access.

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[99] Image Source: https://blog.passivehouse-international.org/ug-uf-uw-uwhat-an-intro-to-the-u-value-and-those-most-important-to-passive-house-design

[100] Tobias. Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*, 3rd Revise (Wien / New York: Springer, 2009), p. 18.

The follow-up is represented by the regulatory context, which includes the size and boundaries of the property, the buildable area, height restrictions, and approved uses (zoning). Finally, we'd have the architectural context, which would include nearby structures (in terms of scale and function) as well as the materials used.[101]

In this sense, a site that meets the design preferences for a high-performance building is clearly desirable. Major rooms will be able to open to the sun and the outside space if the property faces south, while parking, entry vestibules, and service areas can all be found on the north side of the building.

These qualities are not required for a passive house, although they are typically seen in successful builds. Structures and their surroundings should eventually form a mutually beneficial relationship. Site characteristics should aid in reducing the building's environmental stress, while in response, the structure should help to improve the site's ecosystem and microclimate.

In a passive house, site and orientation still play a role, but the structure does not rely on them to provide a significant level of energy collection. In addition to sunlight, views, and a temporal connection to the outdoors, well-placed windows provide useful gains during the winter. Allowing solar gains to create a demand for cooling energy is not acceptable. External shade, whether provided by trees and shrubs or movable building components, is required during hot seasons.[102]

3.3.6. Airtightness

A building's envelope should be as airtight as possible, this being the only way to avoid damage caused by condensation of water vapor in air currents as it passes through unsealed joints from the interior to the exterior. As a result, airtightness is often required by construction technology standards. Excellent airtightness is

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[101] Donald B. Corner, Fillinger, and Kwok, *Passive House Details: Solutions for High-Performance Design*, pp. 37–40.

[102] Donald B. Corner, Fillinger, and Kwok, *Passive House Details: Solutions for High-Performance Design*, pp. 37–40.

critical in passive houses since the infiltration currents cannot be routed through heat recovery systems, resulting in increased heating requirements.[103]

A Passive House has to ensure the airtightness of n_{50} smaller than 0.6 1/h (where n_{50} is the air pressure test value), which must be evaluated and certified on the completed building using the blower door test. The assessment determines the quantity of air seepage through the building envelope and must be performed in compliance with ISO 9972.

Blower door examinations are used to determine the n50 value, which is the volume of air exchanges per hour with a pressure differential of 50 Pascals between the exterior and interior. The resultant result is directly proportional to the amount of air that enters the edifice.

The procedure is performed by a technician who attaches a device consisting of a fan enclosed in an airtight sheet to the building's entryway. The device has integrated pressure sensors that measure the differences between internal and external pressures. The sheet should be fitted hermetically, fastened to the fixed frame of the door.

While the fan is activated, all accesses with the exterior are ought to be cut off, whereas communication with all indoor environments must proceed. The blower door creates a pressure differential between the interior of the building envelope and the exterior environment, which may be modified by adjusting the fan's revolutions. The procedure is closely monitored by dedicated software that collects data from the device's sensors. The volumetric flow degree of air permeability is defined by the air flow induced by the pressure differential.[104]

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[103] Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*.

[104] Stefano Piraccini, ‘Designing Airtightness’, *Green Energy and Technology*, 0.9783319699370 (2018), 203–32 (p. 158) <https://doi.org/10.1007/978-3-319-69938-7_8>.

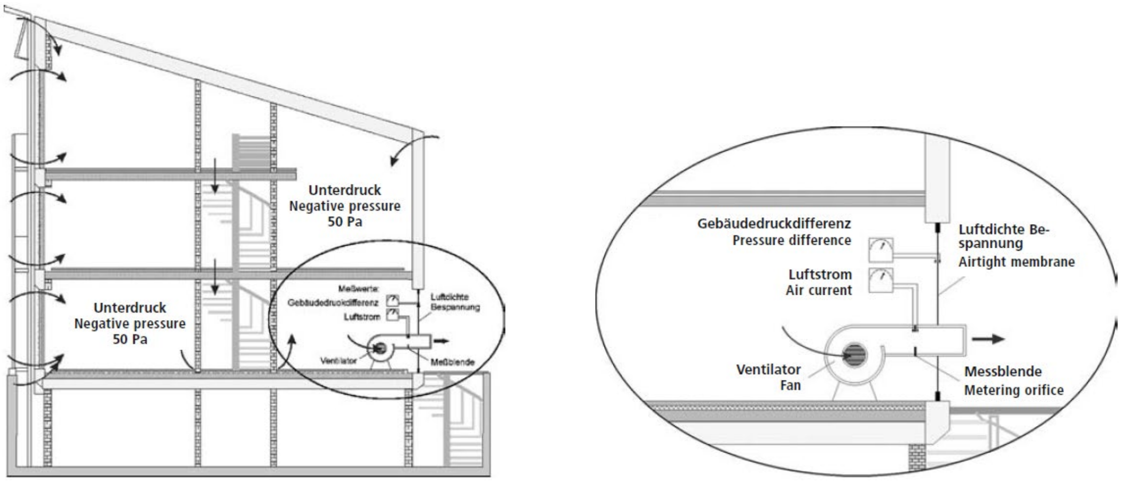

Fig. 3.6 - Blower Door Test Illustration (author: Waltjen Tobias.)[105]

Advantages of airtightness:

The primary advantage of airtightness is that moisture-related construction damage is avoided. Exfiltration is the word used to describe air transfer from the inside to the outside via leaking joints. The amount of water vapor contained within a cubic meter of interior air is significantly greater than the amount contained in the outer air. When heated air carrying water vapor escapes via a joint, this will inevitably cool it down.

Thus, during the cold season, its temperature routinely falls below the condensing threshold. This results in condensation within the joint, which allows for the development of moisture within the building component. This process is inevitable when air currents leak through construction joints, resulting in eventual building deterioration.

Another benefit is the avoidance of drafts and cold feet. Wind-related breezes via building component joints can be rather unpleasant; further, because the pace and direction of these infiltration currents can fluctuate significantly. It is critical to avoid them in passive houses, as they increase the heating demands necessary to compensate.

[105] Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*, p. 17.

Infiltration currents entering the building must be heated to room temperature. This implies that throughout the cold season, any leakage or infiltration results in heat loss, which is uncontrollable, as it fluctuates significantly in terms of the wind and outside temperature. Airtightness can only be attained via meticulous design and execution. To seal the building, one leak proof layer must be constructed. The airtight layer must be traced around the entire building in all sections without any interruptions, projected ventilation apertures being the sole exceptions.

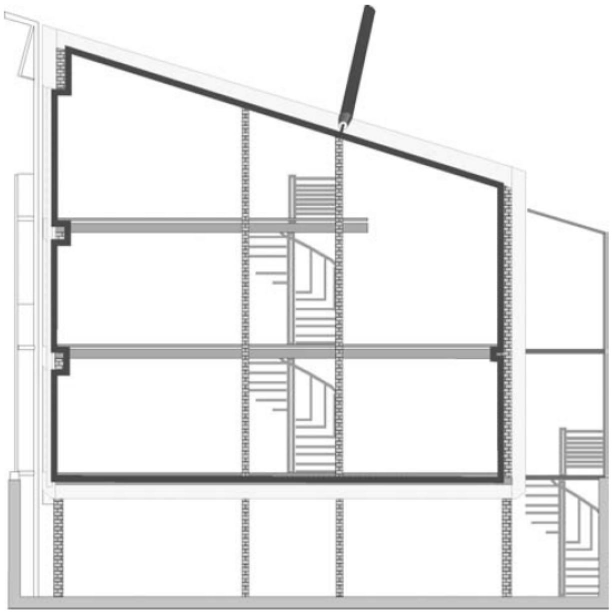

Fig. 3.7 - The airtight shell covers the heated volume completely and can be traced in each cross section without lifting the pencil from the drawing [according to Peper 1999} [106]

3.3.7. Heat Recovery Mechanical Ventilation (HRMV)

Heat recovery using exhausted air is the only way to meet the extremely low heating energy demands of passive buildings. Without heat recovery, ventilation heat losses would be so severe that reducing heating energy demands to less than 30 kWh/(m^2a) would be unachievable.

Supply and exhaust air systems are proven to be especially useful because they often remove frequently vitiated air from rooms that generate it (kitchens,

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[106] Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*, p. 24.

bathrooms, etc.) while providing fresh, unpolluted air to the rooms that are most frequently used (living rooms, bedrooms, etc.). As a result, there is a high level of air hygiene. Heat recovery requires only a small extra effort. The system only provides as much fresh air as is required to assure resident comfort and health.[107]

Modern ventilation technology enables available heat recovery efficiency ranging from 75 to more than 95%. The quantity of heat recovered with a counter-flow heat transfer medium system with energy-efficient EC motors equivalates to 8 to 15 times the amount of electricity consumed for ventilation.

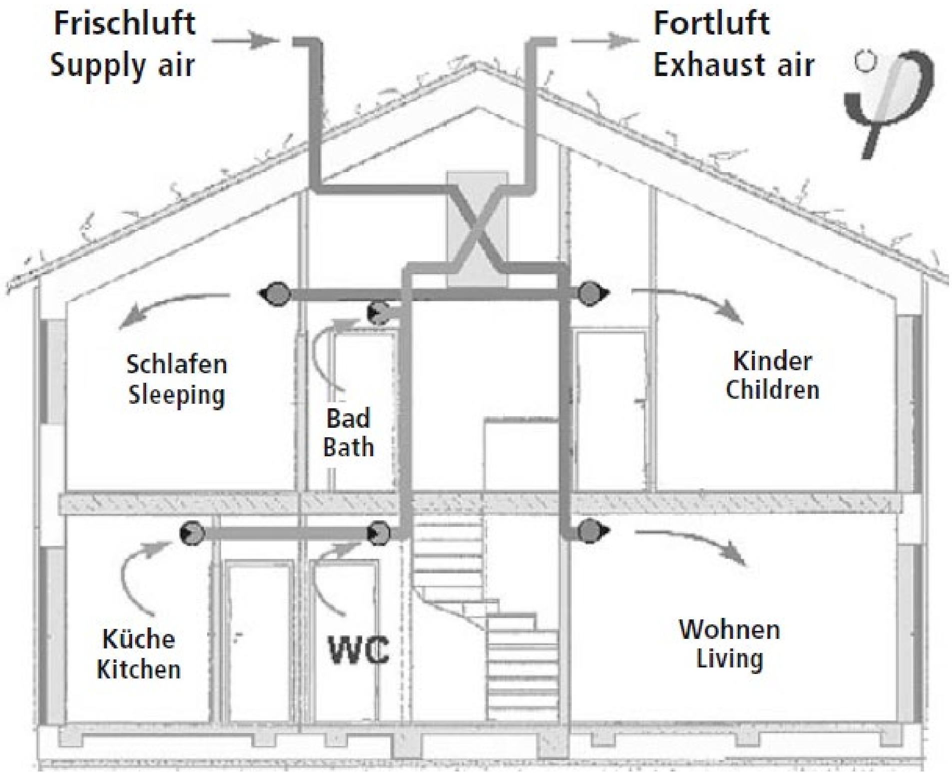

Fig. 3.8 - Heat recovery Ventilation System layout (author: Waltjen Tobias.)[108]

It is possible to utilize air or sole geothermal energy transfer system as an optional addition since it ensures frost-free building air supply when properly installed. Due to the heat recovery system already installed, the resulting heating energy savings are going to be minimal, but the geothermal energy transferal system can

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[107] Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*, p. 16.

[108] Waltjen, *Passivhaus-Bauteilkatalog: Ökologisch Bewertete Konstruktionen / Details for Passive Houses: A Catalogue of Ecologically Rated Constructions*, p. 17.

be employed as frost protection for heat recovery, which would otherwise necessitate a separate solution.

The aforementioned systems should complement and enhance the building's wider architectural objectives, which are reflected in the building program, general shape, fenestration, mechanical equipment, and energy-generating elements' spatial accommodation.

Furthermore, the systems should be able to detect and respond to changes in building occupancy as well as energy availability from both local and grid sources.[109]

3.3.8. Energy Efficiency

The energy efficiency case within a passive house depends on the thermal envelope performance. This performance is achieved by analyzing each material used in the composite based on its density. Based on the fact that the material density is directly proportional to the thermal delay, through the above-mentioned analysis we can determine the thermal transmission coefficient of the composite.[110]

3.3.9. High Indoor Thermal Comfort

The quality of the interior thermal comfort is regarded as being very high because passive houses do not have sudden changes of temperatures within the interior of the thermal envelope. Such temperature differences appear in traditional houses alongside certain cardinal points and by the windows.

Depending on the season the influences can be felt with different intensities due to the high differences of the internal surface temperatures keeping valid the context of a thermostat set at 20^{o} C.

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[109] Franca Trubiano, *Design and Construction of High Performance Homes*, ed. by Franca Trubiano (New York: Routledge, 2013) <https://www.routledge.com/Design-and-Construction-of-High-Performance-Homes-Building-Envelopes-Renewable/Trubiano/p/book/9780415615280>.

[110] Passiv Haus Institut, *Curs Proiectant / Consultant Case Pasive Volumul 1*.

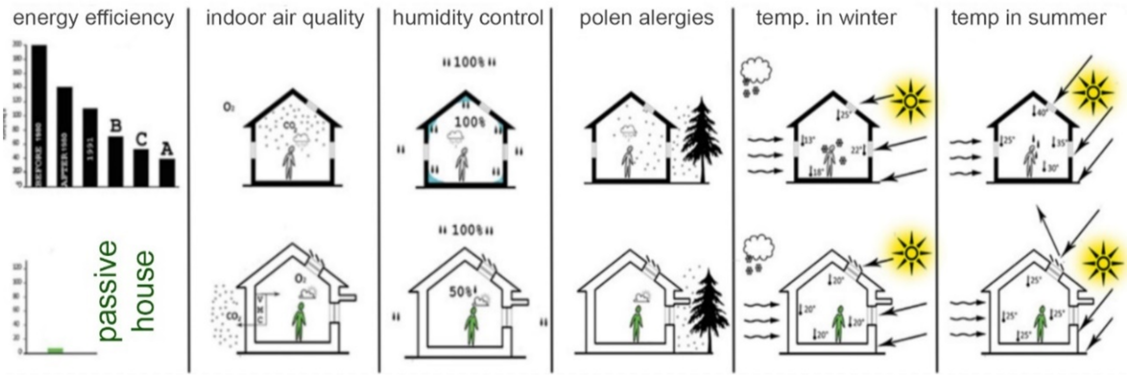

Fig. 3.9 - Difference between a conventional house (top) and a Passive House (bottom) (author: Piraccini Stefano, Fabbri Kristian)[111]

As an example, we can analyze a room that is located in a harsh environment within an outdoor temperature of -5ºC and an interior central temperature set to 20ºC. Within a poorly insulated house, the recorded temperature values by the window glazing would be at around 16ºC, 11ºC by the frame, 16ºC by the inner wall, around 9ºC by the corners, 10ºC where the external wall would meet the slab and a lowly 5ºC behind cabinets that reside against exterior walls. Within this context, the high temperature differences contribute to mold formations that highly impact both the health and comfort of the user.

Taking the same example, within a Passive House that takes into consideration the amplitude of the insulation, thermal bridge protection as well as high-performance window frames, the temperatures registered would be recorded as around 18ºC by the window glaze, 16ºC by the frame, 19.5ºC by the inner surface of the wall, 18ºC by the inner corners and around 16.5ºC behind cabinets.

All of the differences in elements are used to generate a more constant interior temperature that aids both the user and the built environment.[112]

Within the design process of a Passive House, the interior surface temperatures must be constantly confirmed using software programs that tackle thermal bridge calculations (such as THERM), as well as condensation generation. The surface condensation arises when moist air comes into contact with cool surfaces,

[111] Piraccini and Fabbri, *Building a Passive House*, p. 34.

[112] Passiv Haus Institut, *Curs Proiectant / Consultant Case Pasive Volumul 1*.

reaching the dew point temperature. Designing a proper thermal envelope of a Passive House ensures a minimum oscillation of temperatures across a yearly span between 20ºC in winter and 25ºC in summer. These temperatures are perceived as being comfortable in the condition that the air is at a constant relative humidity of 50%, a condition that is achieved due to the heat recovery ventilation system that performs as a mechanically controlled ventilation system (CMV) that should be evaluated in the PHPP spreadsheet.[113]

The Heat Recovery Ventilation (HRV), is defined by working between two sources of air flow at different temperatures (interior and exterior air). The heat recovery system works by using the residual heat within the residual air to preheat the fresh supply air, thus reducing both heat and cooling demands.[114]

The CMV (controlled mechanical ventilation) is intended to change the whole indoor air volume of the building once every three hours on average with certain exceptions depending on the building destination. Through this process, the stale air is more efficiently replaced than utilizing ventilation through open windows.

The core advantage of ventilation systems is that the air is rendered rich in oxygen, and poor in carbon dioxide. The system is also equipped with air filters that further improve the air quality. Concerning air flow discomfort, the machine runs at a low constant air rate at a value of around 3 meters per second rendering it unperceivable. All the system ducts are insulated both in terms of thermal leaks as well as in acoustic breaks and silencers, keeping it under 25dB.

3.3.10. Form and Structure

At an initial stage, designing a Passive House relies on a suitable form that would represent optimal support for a high-performance envelope. This should account for as fewer thermal breaks as possible, as well as on the volume orientation and

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[113] Wolfgang Feist and others, *Passive House Planning Package - The Energy Balance and Design Tool for Efficient Buildings and Retrofits*, ed. by Passive House Institute, Version 9 (Darmstadt: Passive House Insittute, 2015).

[114] Pinar Mert Cuce and Saffa Riffat, 'A Comprehensive Review of Heat Recovery Systems for Building Applications', *Renewable and Sustainable Energy Reviews* (Elsevier Ltd, 2015), 665–82 (pp. 6–7) <https://doi.org/10.1016/j.rser.2015.03.087>.

glazing, to exploit the beneficial solar gains (during winter) and minimize the negative ones (during summer). [115]

The three stages intended for design:

The preliminary stage entails a basic volume construction of the building as well as its internal function distribution.

The next phase is to define all of the building's specific dimensional and functional solutions, as well as the norms and legislation while establishing detailed specifications for all of the elements in order to carry out the construction.

The final stage is determining the complexity of the passive house design, which includes measurements for thermal bridges, heat transfers, and airtightness, as well as selecting the appropriate technologies and high-performance elements that support the overall design, such as high-quality window frames.

All of this information should be run through the PHPP spreadsheet to check and record the procedure as evidence for when the building is certified. Through this documentation, a designated "verification" sheet can be obtained, indicating whether or not the energy efficiency of a Passive House was achieved, as well as its level of performance.

Preliminary Design Phase: The Correct Morphology

Optimal Passive House shapes are usually compact (less surface offering less dispersion) and allow for high solar radiation exploitation in winter and thorough shading in summer. Though, this is not always the case due to legal frameworks and compositional problems, lot orientation, material requirements, and so on.

The morphology is critical in terms of containing the dispersing surface and managing solar radiation, as well as in terms of the materials employed to define the surface. In this context, for measurements of energy output, we input information regarding shading elements and glazing to evaluate the thermal

[115] Piraccini and Fabbri, *Building a Passive House*, pp. 51–54.

load caused by solar radiation. Furthermore, in areas characterized by hot summers, supplementary data is demanded to monitor overheating, for example:

Furthermore, in regions characterized by hot summers, additional data are requested to monitor overheating, such as:

- external absorptivity, which relies on surface color;
- external emissivity, determined by the material's ability to reflect the sun rays;
- shading reduction coefficient, relating to the population density in which the building is located.[116]

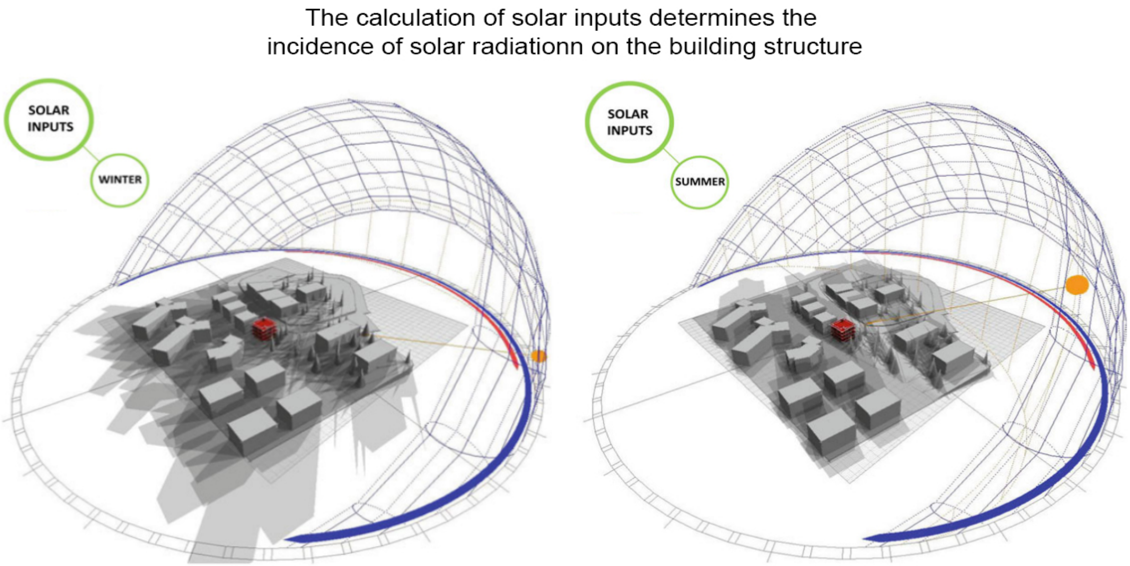

Fig. 3.10 - Simulation of the solar radiation based on winter and summer seasons (author: Stefano Piraccini) [117]

Building Material Sustainability & Thermophysical Performance

The Passive House strategy does not impose in its protocols of energetic standards the choice of building materials; thus, the materiality choices are all up to the designer and his clients. This usually depends on the budget allocated for the building as well as on the design ethic.[118]

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[116] Piraccini and Fabbri, *Building a Passive House*, p. 56.

[117] Piraccini and Fabbri, *Building a Passive House*, p. 58.

[118] Piraccini and Fabbri, *Building a Passive House*, pp. 16–19.

“If you can't measure it, you can't improve it” - William Thomson Lord Kelvin's slogan - demonstrates how important assessment and calculation are in the completion of a project.

Fundamentally, the goal is to obtain the best feasible thermal insulation coefficients, i.e., lowest possible material thermal conductivity and thermal transmittance. This is typically effective in cold areas when building envelopes ought to have the lowest attainable U-value. Nonetheless, as a result of solar heat gains and high heat loads emanated by various interior devices and activities, even colder environments may experience lengthier periods of overheating. Historically, the approach focused on insulating the building adequately in warm areas to account for seasonal changes and times of the year with a heating requirement.

Thermal conductivities of classic insulating materials such as mineral wool, extruded, and expanded polystyrene is usually between 33 and 40mW/m^2(mK). Polyurethane is also utilized as an insulating material, with conductivities ranging from 20 to 30mW/(mK). However, while polyurethane is safe in its intended application, it poses substantial health dangers in case of fire hazards.[119]

On the topic of performative construction materials, recent developments started to heavily influence the industry with novel technologies.

Vacuum insulation panels (VIPs) define avant-garde thermal insulation, offering conductivities spanning from 3 to 4mW/(mK) within its initial state, to usually 8mW/(mK) after 25 years, due to moisture and air diffusion flowing through the vacuum envelope into its main material, that uses an open pore structure. Thermal conduction between 50 and 100 years might be significantly higher than this number, based on the type of vacuum insulation panel envelope.

This unavoidable rise in thermal conductivity is a significant disadvantage of all VIPs. Another weak point of the VIP envelope is represented by puncturing, which

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[119] Bjørn Petter Jelle, Arild Gustavsen, and Ruben Baetens, ‘The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow’, *Journal of Building Physics*, 34.2 (2010), 99–123 (p. 101) <https://doi.org/10.1177/1744259110372782>.

could be caused by nails or other objects, generating a 20mW/m increase in thermal conductivity. Thus, VIPs must not be cut or punctured at the construction site since it will lose a significant portion of insulation efficacy.[120]

Other cutting-edge thermal insulation technologies are available. In concept, the technology underlying gas-filled panels (GFPs), is similar to the vacuum insulation panels, that rather than vacuum, the GFPs use a gas that is less conductive than air, such as xenon, krypton, and argon. Maintaining a low-conductive gas concentration inside the panels and preventing moisture and air infiltrations are critical for the panels' thermal performance.

One of the most performative and manageable material developments is Aerogel, with the highest potential among all others. At lower pressures, thermal conductivity as low as 4mW/(mK) can be achieved by using carbon black to limit radiative propagation.[121]

A good trait of this material is that its compression strength is great, but due to fragility, it has a very low tensile strength, demanding an addition of a carbon fiber matrix to improve its capacity. Commercially accessible aerogels, on the other hand, were reported to have conductivities as little as 13mW/(mK) under ambient pressure and the downside is that the production cost is still rather high. [122]

Building Physics

Researching and analyzing the thermo-physical data aids in the investigation of whether the technical solution chosen enables the fulfillment of the minimal requisites imposed by legislation and regulations. To meet the aims of energy performance, these are made available within the design procedures of the Passive House standard. The Building Physics factor simplifies the laws of thermal kinetics into numeric values determined as reported by the technical

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[120] Jelle, Gustavsen, and Baetens, 'The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow', p. 101.

[121] Jelle, Gustavsen, and Baetens, 'The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow', pp. 102–3.

[122] Jelle, Gustavsen, and Baetens, 'The Path to the High Performance Thermal Building Insulation Materials and Solutions of Tomorrow', pp. 102–3.

standards, allowing for the assessment of the technical solution's physical behavior. [123]

Essentially, transmittance values (U) are derived from the energy exchanges through radiation, convection, and conduction, calculated per the building standards. The following Building Physics principles define what can be used to manage a building's energy performance:

- thermal transmittance U, quantified in $W/(m^2K)$.
- conductivity k, quantified in W/(mK).
- thermal bridges W, quantified in W/(mK).
- solar transmittance afferent to windows with clear glazing, windows with diffuse glazing as well as shading devices
- glazing elements' actual solar amassing area and opaque building elements' actual solar amassing area

3.3.11. The PHPP - Passive House Planning Package

The PHPP is a convenient energy-efficiency planning tool for architects and designers, that is backed by several thousand users within the Passive House community. Further information can be found in Appendix A.3.1

[123] Piraccini and Fabbri, *Building a Passive House*, pp. 130–31.

3.4. Active House

The active house concept is mainly focusing on residential buildings and their interior comfort. The whole concept revolves around energy efficiency strategies combined with detailed devotion to the inhabitant's health and comfort as well as the surrounding environment and climate. The principle seeks pioneering technical methods alongside goals of architectural eminence and environmental development, all in favor of energy efficiency.[124]

The strategy focuses on three steps in order to achieve its performance. Firstly, it implies certain principles that provide a wide overview over the concept and state of thought. Secondly, it focuses on gaining insight and knowledge regarding the development process as well as technical specifications, combining them within a holistic approach of design. As a third step, we are provided with certain guidelines that address the process of planning the Active House construction. These three steps aim to solve three main challenges that the building industry faces lately, comfort, energy, and environment.[125]

The key principles of the Active House are always focused on the aforementioned terms of comfort, energy, and environment and aim for a fully combined or integrated methodology resulting in the high-quality state of the construction. Through this approach, the architecture will engulf user benefits such as reduced consumption, healthy indoor environment, adaptive comfort as well as an unimpacted outdoor environment.

The whole integration provides further value to energy, comfort requirements, environment, and ecology, forming a grand whole, through an interactive system that is adding to the ease of the user interface. The strategy key principles are as follows:

Comfort. The indoor climate should guarantee superior interior air quality, suitable thermal, acoustic and visual comfort. Another key aspect of this is the

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[124] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, pp. 1–2.

[125] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 8.

user control of the indoor environment thus encouraging a more responsible environmental behavior.

Energy. Concerning energy efficiency, the system is required to perform in the most optimized manner possible and be user friendly in terms of control. The main aim of this principle is to exceed the legitimate minimum regarding energy efficiency by exploiting a diversity of energy sources meant to be incorporated in the development.

Environment. Environmental influence is one of the main concerns and the strategy tries to make use of it by making use of the cultural and local resources without imposing. The materials that are being used are thought of as being reusable to minimize the impact of ecological damage.

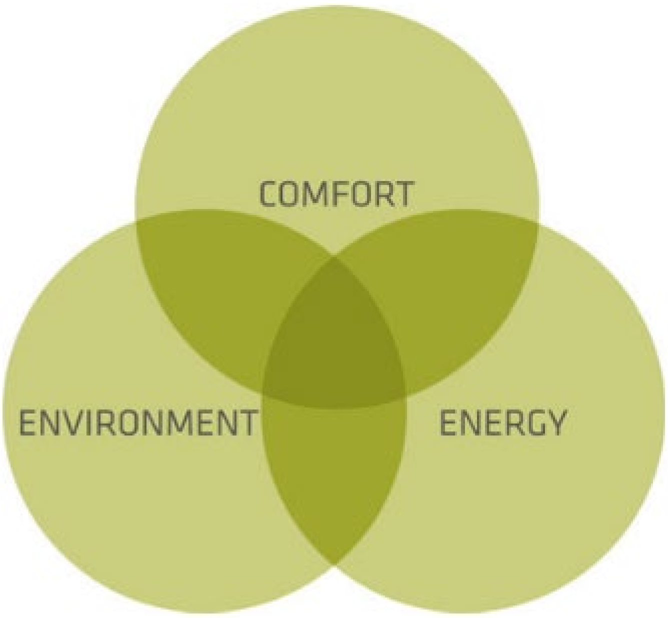

Fig. 3.11 - Active House key principle (author: Active House Alliance)[126]

3.4.1. General Comfort Criteria

The founders of the strategy implemented a way to evaluate the gathered data through a graph in the form of a radar. The graph is divided into three major areas dedicated to the initial principles.

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[126] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 9.

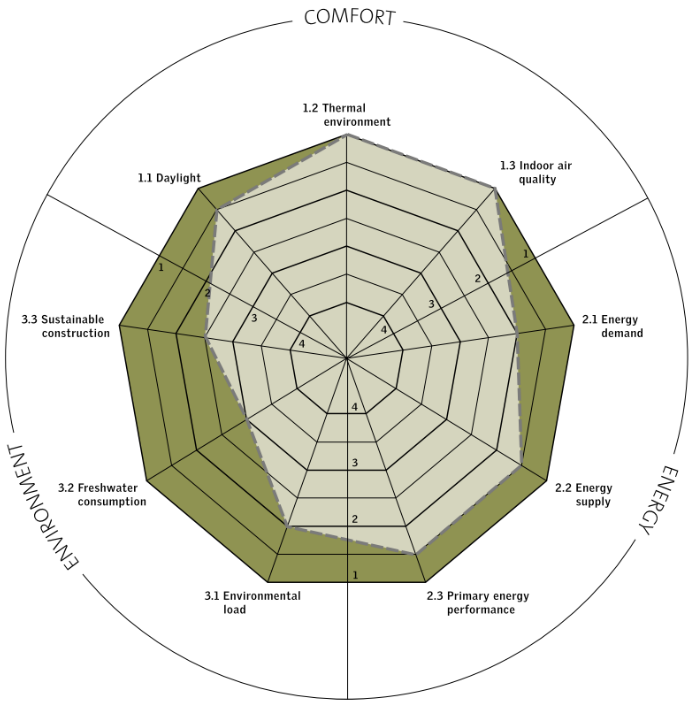

Fig. 3.12 - Example of an Active House Radar (author: Active House Alliance)[127]

Depending on how well the building performs in each area, the graph shows the general state of 'activity' of the building within its representation. The key individual elements are evaluated from 1 which is the topmost level of performance to 4 which represents the least performative.

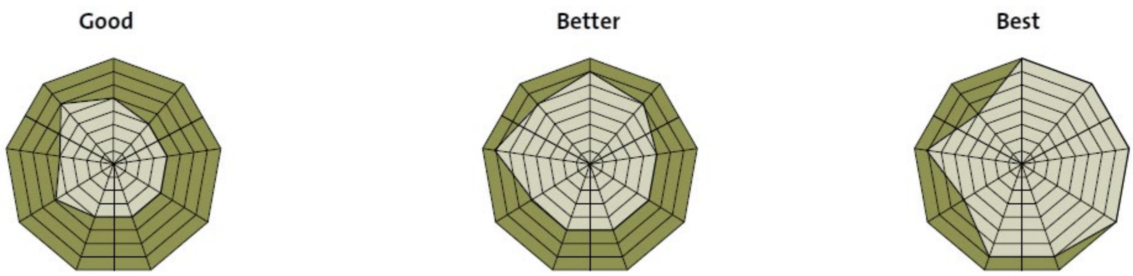

Fig. 3.13 - Performance levels shown within the Radar (author: Active House Alliance) [128]

The Active House Radar views the level of performance within each category as a state of ambition and shows how each of them is balanced against and depend on each other.

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[127] Kurt Emil Eriksen, Carsten Rode, and Pierre-Alain Gillet, 'Active House - The Specifications Index', 2013, p. 13.

[128] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 13.

3.4.2. Comfort Category

Getting the best comfort for the interior environment usually comes along with a lot of data that needs to be analyzed in terms of interior climate, air quality, and daylight alongside other elements that are usually overlooked within residential buildings such as indoor acoustics.

Judging by the fact that we are spending most of our time indoors the principle focuses on bringing the beneficial outdoor factors within, such as daylight and fresh air, trying to positively impact the levels of wellbeing.[129]

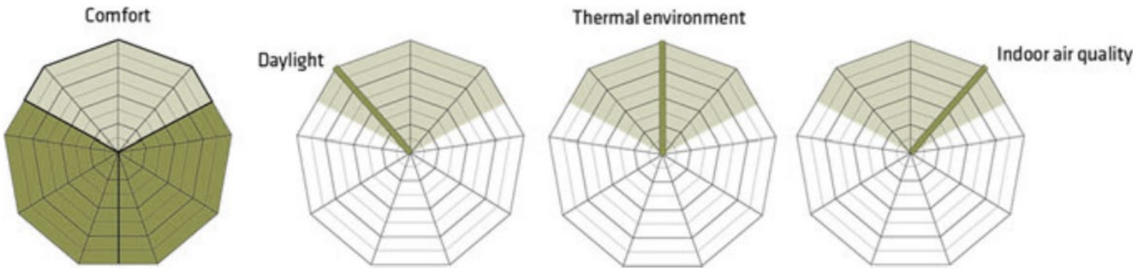

Fig. 3.14 - Comfort area on the Radar (author: Active House Alliance) [130]

a. Daylight

Daylight is one of the most important factors in terms of indoor general comfort and climate. Natural light has both the property to generate a favorable environment and to bring in energy. Adequate lighting done through a well-designed façade provides an array of health benefits to the inhabitants of the building. Keeping this in mind electric lighting during daytime should rarely be a necessity which in turn should lower energy consumption.

The amount of light needed for a room is assessed using a mean daylight factor level on a horizontal test plane and is calculated through validated simulation software programs. The factors are assessed for each room and are weighted in order to give an average suitable for each function dedicated to the enclosure.

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[129] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 10.

[130] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 16.

One of the most important aspects to take into consideration is the shadings of the outdoor environment such as neighboring buildings and vegetation.[131]

b. Thermal Environment

A pleasing thermal medium is important for a comfortable edifice and an active house provides an ideal thermal environment. Satisfactory thermal comfort, in both hot and cold seasons, improves the disposition, heightens efficiency, and, in some cases (for example, nursing homes), avoids and alleviates disease.

Active Houses must avoid overheating in the hot period and optimize interior temperatures in the cold one, without wasting electricity. This can be done using simple energy efficiency solutions that are effortlessly maintained, wherever possible. No criteria are imposed for minimum temperature in summer (cooling period) or maximum temperature in winter (heating period) since both are determined by the practices of the building's users.[132]

Methods of evaluation:

- A thermal simulation technique should be employed to calculate the interior operative temperature at room level, at hourly intervals to objectively assess the risk of overheating. Adaptive temperature thresholds are suggested during the hot season in residences lacking MCU's (such as centralized air conditioning). Since the overall allowed interior temperature is affected by the outdoor weather, parameters rise throughout hotter periods.
- The rules should be applied for at least 95 percent of occupancy time.
- The average value for the individual parameter is determined by the area with the lowermost rating.[133]

[131] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, pp. 12–15.

[132] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, pp. 15–17.

[133] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 16.

c. Indoor Air Quality

In terms of well-being, air quality is one of the main factors that play the part. Having high air quality comes with a handful of benefits and solutions in terms of odors, low levels of humidity, mold prevention, and a resultant of low levels of carbon dioxide. The approach is mainly focusing on natural controlled ventilation that would minimize the use of energy as opposed to the general HVAC systems and hybrid systems. The requirements revolve around data reading the indoor carbon dioxide levels during occupied and unoccupied time intervals.[134]

3.4.3. Energetic Evaluation Category

The Active House concept relies on the "Trias Energetica" approach which implies a three-step strategy in order to achieve an efficient sustainable design, defined by limitation of energy consumption by combating waste, making maximum usage of energy from sustainable sources, and optimizing usage of fossil fuels. Approaching by manner, we observe that the most feasible energy source is the conserved one.[135]

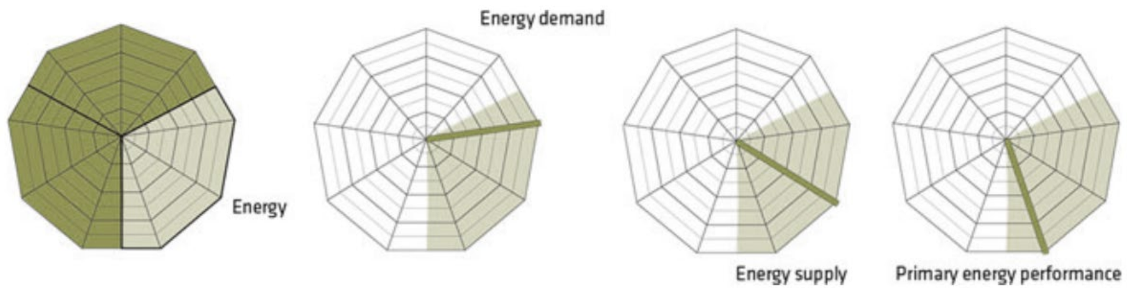

Fig. 3.15 - Energy area on the Radar (author: Active House Alliance) [136]

Purposes

1. Reducing the building's energy consumption. To accomplish this, we will use energy-efficient solutions and design steps such as the building's orientation, materialization, and form.

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[134] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 20.

[135] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 19.

[136] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 20.

2. Obtaining the remainder of the energy required from renewable and CO_2-free sources, either on the house, the plot or from the local energy grid.
3. Any extra energy demand can be sourced through highly efficient energy conversion processes using fossil fuels.[137]

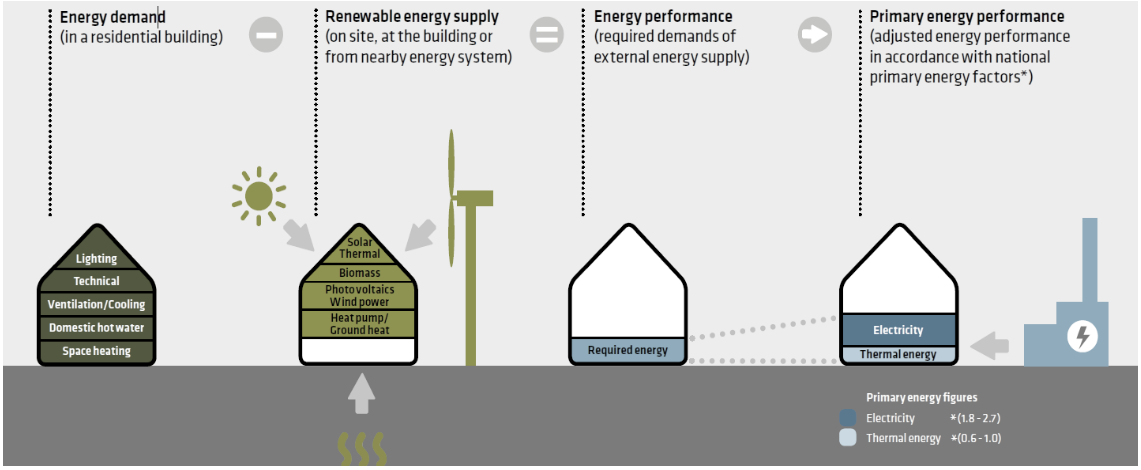

Fig. 3.16 – Energetic Evaluation Schematic (author: Active House Alliance) [138]

a. Energy Demand

Calculations for energy demand depend on the consideration of the total energy needed for the edifice, such as ventilation, water heating, lighting, etc. All the demand is calculated within the design phase of the house. The design solutions revolve around solar energy gain through building orientation, natural ventilation, and high-performance insulation.[139]

b. Energy Supply

Dedicated edifice energy supply needs to be oriented towards renewable and carbon dioxide neutral energy sources, considering the performance classification selected. The strategy does not impose any specific type of renewable energy source, but it encourages the documentation of the system and its genuineness.[140]

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[137] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 23.

[138] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 23.

[139] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 21.

[140] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 22.

c. Primary Energy Performance

This category is founded on a calculation that includes both energy demand and renewable energy supply.[141]

The equation states that primary energy performance is equal to the difference between total energy and the renewable energy used, multiplying it by the national primary energy factors. These factors determine the amount of Primary energy in each unit of supplied energy.[142]

3.4.4. Environmental Impact

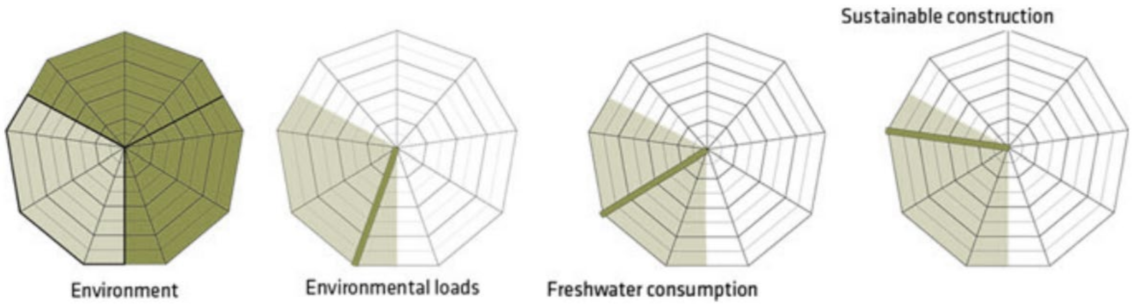

Fig. 3.17 - The Environmental Impact area on the Radar (author: Active House Alliance) [143]

The Active House concept focuses on diminishing as much as possible the environmental impact as a result of built environments, thus taking into consideration challenges at local, regional, and global scales. The main elements of focus are regarded towards ecology, culture, and materiality. These in turn dictate the amount of non-renewable energy consumption, emission environmental loads, and freshwater consumption.

The main process of this development is focusing on LCA (Life Cycle Assessment) that ensures the lifespan of the materials used, their production processes, their use in construction as well as their end life management. The

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[141] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 28.

[142] Roger Hitchin, 'Primary Energy Factors and the Primary Energy Intensity of Delivered Energy: An Overview of Possible Calculation Conventions', *Building Services Engineering Research and Technology*, 40.2 (2019), 198–219 (p. 202) <https://doi.org/10.1177/0143624418799716>.

[143] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 23.

strategy considers that the LCA should be in accordance with the local standards, but offers a benchmark of 50 years as reference.[144]

The main aspects of the Environmental impact analysis focus on Environmental Loads, Freshwater Consumption and Sustainable Construction.

a. Environmental Loads

The strategy heavily relies upon the LCA (Life Cycle Assessment) of the entire construction and its components, in addition to Primary Energy (PE) measurements, Ozone Depletion Potential (ODP), Global Warming Potential (GWP), Photochemical Ozone Creation Potential (POCP), Eutrophication (EP) and Acidification Potential (AP).

More details regarding Environmental Loads can be Found in Appendix: A.4.1.

b. Freshwater Consumption

The freshwater consumption approach has a double spectrum regarding also wastewater generation as a result of its minimization. Some of the most popular solutions regarding freshwater consumption mitigation are grey and rainwater systems, water-saving tabs as well as hydrophobic materials for ease of cleaning.[145]

c. Sustainable Construction

Sourcing and sustainable construction are rigorously taken into consideration within the strategy. The main approach is analyzing the content of sustainable material used by considering 80% of the building's mass and categorizing it by pre-consumer, post-consumer, and internal recycling. All materials used that are bought from recycling stations need to contain a certification to be taken into consideration.[146]

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[144] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 30.

[145] Feifer and others, *Active House: Smart Nearly Zero Energy Buildings*, p. 27.

[146] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 40.

d. Qualitative Parameters

Other essential aspects to consider while building an Active House are contained within these parameters. There are frequently process-oriented issues; some offer guidelines on how to reach the quantitative success standard mentioned, while others offer guidelines on how to adopt a rather improved integrated procedure (biodiversity, society, and local environments).

PARAMETER	CRITERIA	ARGUMENTS/ANSWER	YES/NO
Demand on individual products and construction elements	Have the chosen products and construction solutions been evaluated from a cost-efficient, life-cost perspective and maintenance view?	All main solutions (roof, wall, foundation, and windows) have been calculated from a cost-effective perspective within the individual solutions' lifetime An evaluation of maintenance of technical solutions will be carried out.	YES
Architectural design solutions	Have architectural design solutions been used to reach a holistic approach to the building, as well as to reach a low energy demand?	During the design phase, alternative design solutions have been modeled in BIM and the predicted performance of energy, indoor comfort, and environment has been evaluated. The results were used to adjust and optimize the architectural design solution.	YES
Demand for individual appliances	Have the best energy-performing solutions for appliances been chosen?	All white goods are minimum class A+ and all installed/in-built lamps are LED and evaluated for light quality	YES

Table 3.4 - Example of the use of qualitative parameters, based on energy demand (author: Active House Alliance) [147]

3.5. The benefits of energy efficiency strategies and evaluation systems

It is pretty obvious that efficiency strategies are worthwhile to implement within any project due to the resulting low cost of maintenance alongside high levels of interior comfort, but through a competitive aspect, also push forward the laws and levels of sustainability through which we can maintain the environment within healthy levels.

[147] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index', p. 42.

Implementing energy-efficient solutions to all stages of the supply and demand chain might greatly minimize the negative consequences of energy usage on the environment and human well-being, while also increasing the availability of primary energy reserves and attaining maximum advantages in terms of outputs from available energy. Costs can be decreased for both suppliers and consumers while ensuring continuity of energy-dependent activities.

Measures to optimize the energy consumption of each phase will contribute to an increase in the final result, so even minor changes should have a big influence.

Indeed, the combined impact of improved supply and demand-side for energy efficiency means that the strain on producing facilities is reduced, which may assist in maintaining older systems and equipment in working order. This is because lower total loads generally allow the equipment to operate at less than full capacity or to be halted more often (or for extended periods of time) for preventative maintenance.

Outdated infrastructure often requires more maintenance: depending on the required features. As a response, overall system dependability may be increased.

Lack of legislative or regulatory measures, a lack of knowledge and understanding of possible advantages, a failure to prioritize appropriate energy management and a lack of technical competence to find, assess and execute energy efficiency solutions are all barriers to reaching a proper degree of energy efficiency improvement throughout all sectors.

In certain cases, technological and financial constraints are also present but, improving energy management is always a low-cost measure that yields immediate and significant advantages.

3.6. Similarities and Particularities of energy efficiency standards

In terms of nZEB, the main focus relies on a large scale as a movement more than a strategy. The approach takes into consideration the constant urban development from individual buildings to entire residential areas, all based on minimizing energy consumption.

LEED, on the other hand, focuses on evaluating existing buildings by taking into consideration a set of categories that define the level of effect the edifice has in relation to the environment and its efficiency, as well as comfort aspects regarding the occupants, by tying the process in a holistic perspective.

In terms of the Passive House standard, thermal exchange systems, proper lighting, and the building's placement on the site are the defining factors for a correct operation. The ventilation and geothermal heat exchange systems are the most important of all systems. While maintaining a convenient and comfortable indoor temperature, it also improves air quality by introducing fresh filtered air on a regular basis and recovering heat from the output air.

Geothermal heating, being rather more invasive concerning the site, provides a reliable method of regulating indoor temperature regardless of the season without using much energy, simply by transferring the temperature to the ground.

The defining characteristics of the Active House principles are focused on the implementation of energy-gathering technologies. In other words, the concept is geared toward self-generation of energy. Apart from the obvious benefit of self-sufficiency, it also repurposes the existing energy grid, which was designed to provide energy but is now used to trade it between consumers and providers.

Even though the two solutions (Passive House and Active House) appear to be opposed, they are both based on similar laws and both rely on the environment to function properly. The environment itself is constantly changing in terms of temperature, both regulated and unregulated. The regulated way is symbolized by the gradual change of seasons, whereas the unregulated way is symbolized by weather anomalies. Additionally, any nearby environmental change has a substantial impact on the temperature of an energy-efficient building.

To satisfy these requirements, the Passive House strategy places a premium on lowering the building's energy demand, by focusing on the thermal envelope's performance. Thus, we need efficient insulation for walls, roofs, and floors, performative frames for windows and doors, construction free of thermal bridges, and airtightness.

3.6.1. Points of Comparison

Going back to the initial reasons backing up the study of energy-efficient strategies and standards we can now objectively analyze the common and different aspects they infer. Thus, a parallel can be observed in Table 3.5.

Since the strategies might indirectly touch on some of the comparing points, the analysis will be done by rating ranging from one to three points:

- One point would infer that the implication is indirect
- Two points would be considered as an incomplete approach
- Three would be considered a full approach

Category / Strategy	nZEB	LEED	Passive House	Active House
Sustainability	✓✓✓	✓✓✓	✓✓	✓✓✓
Thermal, Electrical, and Water Demands and Efficiency	✓✓✓	✓✓✓	✓✓✓	✓✓✓
Large-Scale Developments and Impact	✓✓✓	✓✓	✓	✓
Material Efficiency	✓	✓	✓✓✓	✓✓
Indoor Environment and Comfort	✓	✓✓	✓✓✓	✓✓✓
Design Process	✓	✓	✓✓✓	✓✓
Occupant Suitability	✓✓	✓✓	✓	✓✓✓
Environmental Data Reliability	✓	✓	✓	✓✓

Table 3.5 - Points of Comparison

a. Sustainability and Environment

Observing sustainability factors it can be deduced that most strategies either fully focus or incompletely addresses them.

In this sense, the nZEB movement’s approach is clearly a benefit in terms of sustainability, since the premise is to reduce energy consumption by as much as possible. The same aspect can be seen within the Passive House standard since it is being acknowledged by the nZEB as being the perfect fit towards achieving their set purpose.

Looking closely at the means of development within the Passive House standard, it is observable that their approaches are highly oriented towards energy consumption and generation (based on the accreditation awarded; Classic, Plus, or Standard), without always taking into account material provenance but it's transmittance factor.

On the other hand, LEED and Active House strategies highly focus on sustainability, starting with material type and provenance as well as means of transporting it. From the energy consumption perspective, they value highly efficient solutions and try to reward the approaches accordingly.

The nZEB might be regarded as a level above LEED in terms of building energy efficiency, with the quantity of energy generated equivalent to the quantity of energy used, resulting in a net-zero energy building.

Moreover, the source of energy is another aspect that is taken into consideration, may it be from onsite sustainable resources (such as photovoltaics), or from the origin of the central grid.

b. Thermal, Electrical, and Water Demands and Efficiency

Demands in all standards are highly regarded, with very slight variations. The value of the demand and efficiency is risen within this research since exact values can be used to determine a clear necessary of an adaptive approach.

From the thermal demand and efficiency standpoint, it can be observed that most strategies focus on building orientation on its designated site, as well as on the equipment used to meet those demands.

In this particular scenario, the Passive House standard has the most rigorous approaches, posing a clear requirement of 15 kWh/m^2 for heating and cooling. The only approach that is lacking in rigorosity in this particular case is that of water demand and efficiency.

The rest of the studied strategies focus on demands and efficiently in a more relaxed manner, without imposing a direct value to follow. A good example stands within the nZEB movement that analyzes both the climatic and economic situation of the development site and sets the standard accordingly.

c. Large-Scale Developments and Impact

Large-scale developments refer to general urban planning and approaches. In this aspect, the Passive House and Active House movements need to be considered as indirect actors since the benefit comes from each individual building, not as a whole final result.

Thus in this aspect, the nZEB movement is particularly efficient since the main reason for implementation addresses the minimization of energy consumption at an urban scale, focusing on efficient communities and implementing renewable energy sources.

On the other side, LEED is also offering a good perspective due to the general approach of their certification standard. Its viability and ability to categorize buildings based on the set criteria can influence new developments as well as the integration of already built ones.

The comparison perspective of Large-Scale Development is of great importance in order to define the built environment as well as its impact on the natural one. Thus, this implies a careful analysis of the site and its surroundings to ensure a minimum of intrusiveness.

d. Material Efficiency

Material efficiency is one of the defining factors of energy efficiency standards since construction materials represent the border between the accommodated interior environment and the natural exterior one.

The Passive House offers a very clear approach regarding material choices that heavily relies on the energy transmittance value. The materials themselves are not only analyzed individually but also complexly under different combinations.

The other studied standards and movements do not impose any strict criteria based on material efficiency in terms of energy transmittance but follow the interior comfort level that is been set. However, there is a higher interest in material influence regarding occupant health.

The relevancy of this perspective resides in the ability to quantify material efficiency and use it holistically throughout the development process.

e. Indoor Environment and Comfort

Occupant interior comfort is a clear subject within the approaches of both Passive House and Active House strategies alike. Starting with the design phase of any development the main purpose of the standards is to ensure the indoor environment as being optimum for its inhabitants. These aspects revolve around temperature, humidity, lighting, ventilation, and acoustics.

The LEED certification also considers this but at a broader scale of compliance, whilst the nZEB movement achieves indoor comfort indirectly through its general objective which is to minimize overall consumption by avoiding energy loss.

The aspects of comfort and wellbeing are critical when designing a properly adapted edifice since the interior environment has to be envisioned as suitable for the occupants as well as taking into consideration the external factors of the surrounding environment.

f. Design Process

The design process category in this setting is mainly covered by the Passive House and Active House strategies. These employ a clear plan on how to design the building accordingly to get the best results, whilst the LEED and nZEB are more suggestive and focus more on the result, rather than the process.

This aspect is most important in terms of the methodology employed to achieve a certain type of behavior within the building, as well as its interaction with the surrounding environment.

g. Occupant Suitability

The occupant suitability is perhaps one of the most omitted aspects of energy efficiency strategies, especially the ones that are very rigorous. The reason for this is because the analysis of the behavior and way of living of the occupants is varying from one climate or culture to another.

Thus, in this sense, the Active House concept is the standard that pays the most attention to what criteria the inhabitants deem comfortable. LEED and nZEB, on the other hand, is analyzing the edifice after it has been built, thus can account for their hobbits.

This is not to say that the other standards are wrong, but to point out that personal preferences might interfere with the strictness of the resulting data. Even if the Passive House has a clear plan for different climates and biomes in terms of energy conservation, the habits of the people inhabiting those areas vary greatly. As an example, a person that lives within a cold climate can deem fit dwelling in a 21°C interior environment all year round, whilst a person who lives in a warm or hot climate would have issues during cold seasons.

The best approach in developing adapted and adaptive buildings is to account for the occupant’s needs as well as its relationship with the environment in which he resides.

h. Environmental Data Reliability

The final point is considered the most critical, and that is the focus on reliable environmental data. Most strategies and standards offer a database that in most cases has been collected rather far away from the setting in which the building is being developed. As an example of provided data, we can find yearlong analysis through Meteonorm or the energy plus website. But unfortunately, the data collected might be from a remote weather station or from another urban area that posits different climatic properties.

One of the main purposes of this thesis is to provide means of mitigation for data reliance, that should be ensured for the immediate environment, it being either natural or built.

Adaptivity and Interactivity in Architecture

4. Adaptivity in Architecture

4.1. The Adaptivity Context

> "Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations and is one of the basic phenomena of biology." - Charles Darwin.[148]

In architecture, the terminology of "adaptation" refers to the shifting morphologies of an architectural element. These morphologies are the products of timely changes as well as the development of architecture as a social entity, technical commodity, and activity. Associated developments have arisen through the years of architectural evolution, altering notions of how structures are designed and constructed.[149]

Changes within the environment that arise over time, for instance, a day, may be a continuous influence pushing deviations that must arise in an architectural development, resulting in regional adaptations. Climatic variation at a global scale, causes an architectural entity to change periodically for function purposes and to maintain itself. [150]

Architectural adaptation is a prolonged process that develops over time and through generations, with technological advancements, financial assistance, and cognitive processes all contributing to adaptive retort and reaction.

Architectural morphologies evolve in response to the epoch in which they are created and implemented. The adaptive morphologies emerge as a result of ever-changing periods, community forms, financial aid, consumer demands, and

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[148] Charles Darwin, *The Origin of Species*, ed. by David Quammen (Pennsylvania State University, 2001).

[149] Sushant Verma, *SUPER-COMPLEXITY CONTROL*, ed. by Rachel Armstrong and Andrew Adamatzky, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 99 <https://doi.org/10.1017/CBO9781107415324.004>.

[150] Verma, *SUPER-COMPLEXITY CONTROL*, p. 99.

environmental influences.[151] The term "adapt" derives from the Latin “adapto”, which stems from “ad” ("towards, to, at") and "apto" ("prepare or adjust"). To put it simply, “adapt” implies to "adjust toward." [152]

The concept of adaptive architecture is misapplied in a variety of developments that claim to be adaptive but actually make a minor contribution to long-term adaptations. Adaptation happens over generations, with continuous changes, feedback, and survival of the fittest. Many projects attempting to address adaptation are subjected to the categories of interactive, kinetic, dynamic, or responsive systems. Although these activities are associated, they may not always lead to adaptation over time.

An intelligently programmed system of reaction and feedback must be integrated within an element for it to be correctly referred to as adaptive. This represents a complex system characterized by a non-linear and multi-layered operation. A rather extreme example for this might be the Media-TIC Building, in Barcelona (due to the myriad of sensors and active systems employed within the facades).

Fig. 4.1 – Media-TIC Building (authors: José Miguel Hernandez, Iwan Baan)[153]

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[151] Neil Leach, *ADAPTATION*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 131.

[152] Verma, *SUPER-COMPLEXITY CONTROL*, p. 99.

[153] Jean Baptiste Izard and others, ‘Integration of a Parallel Cable-Driven Robot on an Existing Building Façade’, *Mechanisms and Machine Science*, 12 (2013), 149–64 (p. 151) <https://doi.org/10.1007/978-3-642-31988-4_10>.

Adaptation should be seen as essential to any organism's survival. Adaptation, it may be said, is the key logic that underlies existence itself. As a result of evolution, the natural world has evolved and survived.

When flu viruses adapt to vaccination, we can observe the adaptation process in action at microorganism level, through generational evolution. We can also depict on-the-spot adaptation, manifesting in animals (most especially in the mimic octopus and the chameleon) pointing out physical adaptation to their surroundings. On a broad scale, we can observe adaptation in effect within nature, in the diverse behavioral structures in the massing of individual agents. These include swarm behaviors such as those of fish schools of bird flocks.[154]

Humans are also capable of adapting. Indeed, some scientific views hold that humans are continuously changing psychic entities that are constantly processing external impulses. As a result, humans should be seen as mutated species, constantly evolving and mutating as part of the inevitable battle for survival.

This poses an intriguing architectural query: what part does adaptation play in architecture if humans are continually evolving and mutating beings?

Undoubtedly, we are able to notice two connected types of adaptation amid humans and their dwellings, in which edifices have adapted in response to their instincts and have been influenced by their surroundings.[155]

As Winston Churchill remarked:

"We shape our buildings, and afterwards our buildings shape us."

So, what precisely underpins this need for humans to relate to their constructions? Why do architects want to create structures that are related to the human body? Any effort to link the shape of a building to the morphology of a

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[154] Leach, *ADAPTATION*, p. 130.

[155] Leach, *ADAPTATION*, p. 130.

person has to originate from a profound psychological urge to create a supposed relation amid humans and their surroundings.

The research is aimed to investigate this psychological need concerning human-physical environmental adaptation in two terms: "*autoplastic adaptation*" and "*alloplastic adaptation*". This describes the human needs to adjust accordingly to their surroundings and then asks if the ability of buildings to adapt to their occupants can point to a significant psychological function for interactive architecture.

4.1.1. Autoplastic Adaptation

Sigmund Freud, Franz Alexander, and Sándor Ferenczi, among others, coined the term "autoplastic adaptation." When confronted with a challenging situation, autoplastic adaptation refers to the subject's attempts to adapt to the external environment.[156]

A good instance of autoplastic adaptation occurs in jail, where prisoners psychologically adapt to the environment. Weirdly enough they also become comfortable there, in contrast to the hostility it may pose, in the same way, that kidnapped victims may develop "Stockholm Syndrome" and develop a bond with their abductors. For example, in the Alcatraz Penitentiary, a prisoner known as Leon Thompson developed such a tight relationship to the holding cell that he believed he had become a part of it, as well as the cell becoming a part of him, stating:

> *"I knew every mark, everything in that cell. The cell quickly became a part of me, or I became a part of the cell. I couldn't imagine living somewhere else in the prison except in my cell. It was almost as if I were returning to embrace an old friend, because it was a part of me." (Leon Thompson)*

Another example is also pointed out in the well-known story of Nelson Mandela, who, following his release from South Africa's Paarl Open Prison, hired an

[156] Leach, *ADAPTATION*, p. 131.

architect to construct a duplicate of the bungalow where he had been detained. This might be because he began to feel at home in that setting. These events appear to be intense manifestations of the human instinct to either seek familiar surroundings to deem home or to become acquainted with the unknown.[157]

4.1.2. Alloplastic Adaptation

In addition to "autoplastic adaptation," Freud, Alexander and Ferenczi introduced the "alloplastic adaptation" concept. While autoplastic adaptation corresponds to the subject's desire to adapt himself to the surrounding environment, alloplastic adaptation denotes the subject's desire to make the surrounding environment adapt to him, when confronted with a tough situation.[158]

As a compulsory extension and implication of the premise of mimesis, we should also recognize the capacity of humans making the environment adapt to them.

4.1.3. The relationship between Alloplastic and Autoplastic adaptations

In a dialectical system, these two logics can be seen as fundamentally opposed. However, both logics depend on adaptation, and both affect a mode of identity. Between one animate object and another, as well as between one inanimate object and another, there has to be some kind of equivalency, for any kind of identification to occur.

A premise within the identificatory situation of integration is that we should somehow compare oneself with the inanimate architectural environments as animate beings. This establishes the contrast between life and death, as well as animate and inanimate beings. In this sense, we can either "play dead" and grow inert like our immediate environment, or we can animate it and make it like us. Such dynamics can be understood by psychoanalytic debate, in which the life and death intuitions persist as central impulses. A good analogy for this can be found in Greek mythology, in the difference amid Daedalus, who was said to be

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[157] Leach, *ADAPTATION*, p. 131.

[158] Leach, *ADAPTATION*, pp. 134–35.

capable of bringing statues to life, and Medusa, who transformed everything in her path to stone.[159]

As a result, we may propose two dialectically connected judgments: the desire for people to become inanimate, as the landscape of constructions that surround us, and the desire for people to "animate" the inanimate environment of constructions. Michael Taussig alluded to this reciprocal phase of adaptation, defining mimesis as "the art of becoming, of becoming other".

But, in wake of contemporary research of interactive environments, how do we apply this theory?

Surely, it appears that an entirely novel logic of animated architecture has lately emerged, owing mainly to the commercial disposal of electronics such as sensors, microcontrollers, servos, and plug-and-play devices (for example the Kinect, an optical camera assembly which can be repurposed and programmed to track human behavior within interactive installations). Apart from electronics, we can also depict smart materials, such as shape-memory alloys.[160]

These instruments enable us to not only "imagine" the world as animate, but of it actually being so. Furthermore, developments like Behnaz Farahi's interactive installation "Alloplastic Architecture" demonstrate how using a dynamic tensegrity assembly can "mimic" human behavior, whereat the human body could be seen as a tensegrity sort of structure, having bones act as compression members, tissues as inactive tensile features and muscles exerting as active tensile elements.[161]

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[159] Leach, *ADAPTATION*, p. 136.

[160] Leach, *ADAPTATION*, p. 137.

[161] Leach, *ADAPTATION*, p. 137.

Fig. 4.2 - Representation of Behnaz Farahi's adaptive tensegrity structure (author: Behnaz Farahi)[162]

As a result of this, we can conclude that a new chapter in the field of architecture has opened up, with two major implications for previously assumed constants in the field of design.

Implementation of activation mechanisms that alter the morphology of an architectural setting based on the dynamics of the user, in conjunction with a subordinate set of devices that monitor the said dynamism, offers the possibility for “animating the inanimate” exceeding the psychological inclination to view the inanimate environment in animate conditions. Secondly, the aforementioned technological advancements question the prevalent belief that technology causes alienation, by demonstrating that, oppositely, technology has the ability to resolve it.[163]

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[162] Behnaz Farahi, ‘Alloplastic Adaptation’, 2012 <http://behnazfarahi.com/alloplastic-architecture/>.

[163] Behnaz Farahi, ‘Alloplastic Adaptation’.

But, perhaps most significantly, this begins to imply that interactive architecture may enable an important cognitive role in diminishing the possible alienation of humans from their surroundings. For if we believe that the motivation enforcing “autoplastic adaptation” is meant to adapt the self to the environment, then architecture must certainly play a role in facilitating that development. Simply put, the design will make us comfortable in our surroundings and become a part of them. Contextually, architecture can be viewed in inanimate terms as the design of architectural form.[164]

The intention of enforcing “alloplastic adaptation”, by definition, pushes to make the world conform to the individual. Though some kind of phantasm of adaptation can be encouraged using the creation of methods, such as Dali's "paranoid critical method", stating that correct adaptation must undoubtedly rely on definite physical adaptation.

So, rather than shape, we are concerned here with the adaptation of the morphology and the elaboration of a material that can embody and resemble human body behavior. [165]

4.2. Adaptation in Nature

Taking a look back through history, at the very beginning we can see that humankind has not only used nature as a source of material and food but also as inspiration. People took hints from other species on how to build huts more efficiently both in terms of materials and constructional systems.

Nature has created a plethora of adaptable mechanisms. We can use these natural processes as a method of biological computation to learn while also taking advantage of their inherent adaptability. Rather than digitally modeling and manipulating these natural systems, which is a difficult method where one is left "guessing" at the laws that control observed behaviors, the biological simulation

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[164] Behnaz Farahi, ‘Alloplastic Adaptation’.

[165] Behnaz Farahi, ‘Alloplastic Adaptation’.

uses the computational-like features in natural systems in an analog simulation process.

By returning to the source of adaptability, this type of organic computation can produce unexpected or formerly unattainable results.

4.2.1. Managing information through Biolearning

A good example of the exploration of this idea resides within “The Primitive Hut” concept, which investigates the anthropological interaction between humans and the natural environment as the essential premise for architectural construction. The concept asserts that the ideal architectural form expresses what is natural and inherent. The Primitive Hut as an architectural philosophy was developed from the mid-1700s to the mid-1800s, primarily by Marc-Antoine Laugier. In An Essay on Architecture, Laugier gave a metaphor of a man in nature and his desire for protection, which constituted an essential framework and approach to architecture and its application. This method has been investigated in architectural theory in order to hypothesize on a possible future for architecture as a discipline.[166]

Thus, the approach of learning from nature has always been part of the development of efficiency within architecture, offering more than enough information for future adaptive developments that have been tested through time. Climate data is one of the starting points in this transfer from biology to architecture since we aspire to attain specific types of adaptive behaviors in different kinds of environments.

a. Biomimicry in Architecture

The terms "Biomimetics" and "Biomimicry" derive from the Ancient Greek words “bios” (which translates as “life”), and “mīmēsis” (implying imitation), stemming from “mimos” (which translates as “actor”).[167]

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[166] Marc-Antoine Laugier, *An Essay on Architecture* (London: T. Osbourne and Shipton, 1755).

[167] AGE, ‘Biomimetics: Conception and Strategy Differences between Bionic and Conventional Methods/Products.’, *Guideline*, 6220, 2012, 6.

Otto Schmitt coined the words "biomimetic" and "biomimesis" in the 1960s. The idea of biomimicry is often distorted as designing edifices that resemble organisms, for example, structures modeled like shells, that represents another design technique known as Biomorphology. Imitating natural systems or processes will affect morphology, but that is not the main point of biomimicry.[168]

Biomimetics represents a field that seeks to move knowledge from biology to technical applications that aid in the delivery of a nonspecific frame of reference and procedure for creating relevant equivalences between various domains. Biomimetics, described through innovation methodologies, entails elementary research, rule abstractions, and conversion of fundamentals into an application development. This involves systems, structures, and materials, but it usually derives information about functions, mechanisms, or principles, which are then implemented or interpreted by architects or engineers. Furthermore, the interdisciplinarity used embraces the promise of innovation by creating sustainable goods and technologies.[169]

Biomimetic principles were widely investigated by ICD and ITKE, both from a morphological and a procedural point of view. Easy-to-clean or self-cleaning coatings on metals and glass, as well as façade finishes, are examples of biomimetic applications at the material and surface scale.[170]

Structures and edifices influenced by biology, particularly plant structures, are studied in prototype edifices such as the ICD/ITKE pavilion (2014-2015), as well as systems such as flectofin (visible on the Thematic Pavilion), an innovative façade-shading based on a flexible mechanism inspired by the bird-of-paradise flower's opening system (Strelitzia Reginae).[171]

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[168] Ilaria Mazzoleni and Shauna Price, *Architecture Follows Nature: Biomimetic Principles for Innovative Design*, ed. by Ilaria Mazzoleni and Shauna Price, 1st edn (Taylor & Francis), p. xix.

[169] AGE, 'Biomimetics: Conception and Strategy Differences between Bionic and Conventional Methods/Products.', pp. 4–5.

[170] Jan Knippers and Achim Menges, 'Buga Fibre Pavilion', *Ubiquity and Autonomy - Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, October, 2019, 140–49 (p. 141) <https://doi.org/10.1515/9783035620405-031>.

[171] Petra Gruber, Tim McGinley, and Manuel Muehlbauer, 'Towards an Agile Biodigital Architecture: Supporting a Dynamic Evolutionary and Developmental View of Architecture', in

Fig. 4.3 - CD/ITKE Research Pavilion 2014-15 (author: ICD/ITKE Stuttgart)[172]

As a result, biomimesis is not simply the impersonation of nature, neither in artistic regard nor in function and material, but rather the comprehension of natural concepts.

This helps with the understanding of comparable, technical issues, which will subsequently be addressed through the implementation of optimized technologies. Biomimesis represents the process of learning from nature in order to develop technology. Biomimetic applications are considered to be a three-step process: Research, Abstraction, and Implementation.[173]

A small investigation within already built structures can be made to contrast the correct and incorrect approaches for said biomimicry and biomimetics.

Interdisciplinary Expansions in Engineering and Design With the Power of Biomimicry (INTECH, 2018), p. 3 <https://doi.org/10.5772/intechopen.72916>.

[172] Image Source: https://www.archdaily.com/770516/icd-itke-research-pavilion-2014-15-icd-itke-university-of-stuttgart

[173] Gulay Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', *Alam Cripta, International Journal of Sustainable Tropical Design Research and Practice*, 7.2 (2014), 29–36 (p. 30).

Thus, looking at the “Golden Fish” sculpture, envisioned by Frank Gehry in 1992, honoring the Olympic Sports of Barcelona. The design objective was to portray the dynamic movement of a fish in water in its purest form. Its curved surface is wrapped in a woven stainless-steel lattice that hovers over a bare steel framework.[174]

In this case, the architectural abstraction was aimed at the overall shape and dynamism of a fish, including the scales’ properties in terms of light reflection and refraction.

Fig. 4.4 – “Golden Fish” Sculpture seen from the Hotel Arts Barcelona pool alongside a closeup of the metal lattice (authors: Mohammed Alam and BarcelonaYellow)[175]

As opposed to Frank Gehry’s design approach, the National Fisheries Development Board in Hyderabad, India, represents the total opposite of how biomimicry and mimetics should be applied. The study of the shape was not abstracted in any way to attain neither architectural nor functional value.

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[174] Youngjin Yoo, Richard J. Boland, and Kalle Lyytinen, ‘From Organization Design to Organization Designing’, *Organization Science*, 17.2 (2006), 215–29 (p. 222) <https://doi.org/10.1287/orsc.1050.0168>.

[175] Image sources: https://barcelonayellow.com/bcn-photos/129-pictures-patterns-barcelona, https://www.facebook.com/113860766987064/photos/a.113860810320393/242665110773295/

Fig. 4.5 - National Fisheries Development Board office in Hyderabad, India (author: @6milesup)[176]

In biomimicry, the key methodologies for design development are represented by problem-based and solution-based approaches. “Design to Biology” is known as the problem-solving approach. It is rendered on the identification of priorities and design limitations. In this method, the designer begins by defining the problem and then searches for solutions in natural species. The method known as the “Challenge to Biology” seeks solutions for human problems in nature, by having designers and biologists compare the issue to an organism that has answered a similar dilemma in the past. By experimenting and looking into nature, the designer improves a particular “design or solves a design” problem. Solution-based approaches are a “Biology to Design” type, that is used when biological principles are the basis of design concepts.[177]

Until identifying the goal of the design, the designer outlines a beneficial feature from nature that is abstracted and converted to a technical sense. In relation to

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[176] Image source: https://twitter.com/6milesup/status/1038612595513544704/photo/1

[177] Nihal Amer, ‘Biomimetic Approach in Architectural Education: Case Study of “Biomimicry in Architecture” Course’, *Ain Shams Engineering Journal*, 10.3 (2019), 499–506 (p. 500) <https://doi.org/10.1016/j.asej.2018.11.005>.

context, environmental considerations are critical in designing sustainable buildings.

Climate change is causing turmoil in the world as a result of greenhouse gas pollution. Designers will benefit from looking to nature for solutions as it is a massive provider that is both robust and aesthetically pleasing by using the appropriate “construction materials” while accounting for recycling and solutions based on local conditions. Processes that apply biological concepts that underpin the functionality, structures, and morphology of biological organisms to human-made design are what should be considered as being biomimesis.[178]

b. Levels of Biomimicry

Biomimicry is classified into three tiers: organism, behavior, and ecosystem. Buildings can mimic the characteristics of individual organisms at the organism level, while on a behavioral tier, the design can be influenced by in what way the organism behaves or interacts with its surroundings. On the ecosystem level, the development can draw from an organism's whole ecosystem including its surroundings. It focuses on the natural processes and cycles of its medium.[179]

Within each of these stages, there are five additional dimensions of biomimicry. The design may be biomimetic in terms of its shape and appearance, its material and composition, its structure and how it is created, its mechanism and how it functions, and its purpose and capabilities. The most visible aspect of biomimicry is the simulation of nature's work. On a process level, emulating nature entails learning about the way it’s evolving or propagating. Biomimicry explores nature's mechanism and how it manages waste and regeneration within closed-looped lifecycles.

[178] Amer, ‘Biomimetic Approach in Architectural Education: Case Study of “Biomimicry in Architecture” Course’, p. 503.

[179] Yedeki Arslan, ‘Biomimetic Architecture: A New Interdisciplinary Approach to Architecture’, p. 30.

Organism Level

This stage is concerned with mimicry of a single organism. In this case, looking at the subcategories and our main topic, we can see that if we create a structure only mimicking the organism tier, we can get generic results. In essence, it mimics the physical characteristics of an organism. Waterloo International Terminal (Fig. 4.4), designed by Nicolas Grimshaw & Partners, is an approach at this level based on mimicking of form and process.[180]

Fig. 4.6 - Waterloo International Terminal showing its glass panels that mimics a pangolin's scales (author: transformKC) [181]

Behavior Level

As we progress to the next step, we will see that the aspects change depending on how the organism's action relates in a broader context. This level may be understood by watching how an organism tends to behave in its environmental

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[180] Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', p. 32.

[181] Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', p. 33.

capability and under the constraints of energy and resources. The most typical example used to demonstrate this level is termites.[182]

Fig. 4.7 - biomimicry application of a termite mound to employ a natural ventilation system in Eastgate Center (authors: David Brazier, Daniel Gallant, Mick Pearce)[183]

Ecosystem Level

The ecosystem-level has a much larger horizon and can bind a large number of different species. It seeks to establish an entire ecosystem that encompasses the other two levels in order to create a sustainable environment. This necessitates a thorough understanding of ecology and natural restorative processes. This kind

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[182] Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', p. 33.

[183] Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', p. 34.

of conceptualization may begin on a local scale and progress to a larger size, such as green cities or eco-cities.[184]

Using biomimetic concepts in architectural design results in the creation of necessary and appealing building characteristics, i.e. adaptive architectural shells, optimal illumination, healthy environments as well as sustainable, and green surroundings.

c. From Biomimicry to Biolearning

The Institute for Biodigital Architecture and Genetics sets an excellent example when it comes to Biolearning, by encouraging research, design approaches, and theory for incorporating science and technology into advanced architecture. Researchers at the Institute, led by Alberto T. Estévez, are pondering the following questions:

> *"What role do biology, genetics, and computation play in developing forms and functions from nature for intelligent buildings?"*
>
> *"What role will AI and instrumented-assisted visualization take in future design studios? And, how do we begin to express genetic and metabolic potential in-studio projects?"*[185]

In this sense, we have looked into Biomimicry and Biomimetics in the form of Biolearning. Having such an abundant source of inspiration from nature's evolution in terms of adaptation, it is also a good template for shifting architecture. Biomimicry in architecture functions on developing how basic principles of organisms work and implementing them through new technology.

A close field in which biolearning was observed is that of Metabolic Architecture, in which architecture is not a static entity. It is viewed as a continuously changing

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[184] Yedeki Arslan, 'Biomimetic Architecture: A New Interdisciplinary Approach to Architecture', p. 34.

[185] Dennis Dollens, *Autopoietic Architecture : Can Buildings Think?* (Independently published, 2015) <exodesic.org>.

organism including a set metabolism. Buildings that facilitated population expansion were considered to have a finite lifespan and should have been developed to be replaced in a relatively short time.[186]

Metabolically developed architecture is envisioned using a spine infrastructure with prefabricated cell-like elements that can be easily added and removed when their life cycle is done. A good example is the Nakagin Capsule Tower, representing two interconnected concrete towers with prefabricated capsules; this is the metabolism idea since the 1960s. (Fig. 4.6) [187]

Fig. 4.8 - Nakagin Capsule Tower, 1972, Tokyo (image by author)

Around the same time, the concept of green building emerged, being recognized for reducing the impact it has on the natural environment and the wellbeing of its residents. Moving to sustainable architecture, the term "sustainability" in ecology denotes how biological systems preserve their productivity and diversity through time. It expresses the capacity for human health, which is dependent on the

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[186] Dollens, *Autopoietic Architecture : Can Buildings Think?*, p. 12.

[187] Francis D.K. Ching, *Architecture Form, Space, and Order*, 4th edn (Hoboken,: Wiley, 2015), LIII, p. 76.

natural environment wellbeing and the appropriate utilization of natural resources.

Focusing on how to approach nature, it is mandatory to involve a design strategy that incorporates natural growth, protection, and especially natural intelligence. To understand this, it is needed not just to observe through our eyes, tactile systems, and sensory abilities, but also to weave in new technologies that reach beyond our perceptions and decode a mixed intelligence system.

d. Interpreting Natural Intelligence

To start defining natural intelligence, we have to first ask ourselves: what is intelligence, and what are the defining factors that prove it? To do so, looking at the general aspects of intelligence, consciousness and cognition would offer insight.

What is Intelligence?

The common skeptical imperative is to “define intelligence.”

Linda Gottfredson's concept of intelligence is often raised, stating that intelligence is a broad mental capacity that includes the potential for reasoning, planning, thinking abstractly, problem-solving, grasping complex ideas, and learning from experience. It does not pose a matter of rote memorization, a slim academic ability, or test-taking expertise. Rather than that, it represents a wider and more sophisticated capacity for understanding our environment: "making sense", "catching on” of things, or "figuring out" how to go about it.[188]

Some of the most popular definitions of intelligence are:

> *"...the resultant of the process of acquiring, storing in memory, retrieving, combining, comparing, and using in new contexts information and conceptual skills" (Lloyd Humphreys)*[189]

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[188] Linda S. Gottfredson, ‘Mainstream Science on Intelligence’, *Wall Street Journal,* 1994, p. 13 <https://doi.org/10.1016/s0160-2896(97)90011-8>.

[189] Lloyd G. Humphreys, ‘The Construct of General Intelligence’, *Intelligence*, 3.2 (1979), 105–20 (p. 115) <https://doi.org/10.1016/0160-2896(79)90009-6>.

Goal-directed adaptive behavior. (Robert Sternberg & William Salter)[190]

The ability to deal with cognitive complexity. (Linda Gottfredson)[191]

What is Consciousness?

At its most basic level, consciousness is described as “sentience or awareness of internal or external existence”. Consciousness is the sensory perception of the information processed by the brain. According to one of the most current hypotheses, consciousness is the brain's imprecise representation of its own activity. In other words, the brain organizes and simplifies information in order to facilitate understanding of the surrounding environment.[192]

What is Cognition?

Cognition is described as the mental activity or process of understanding and knowledge acquisition via the use of reasoning, experience, and the senses.

Cognition engulfs a vast range of mental processes and functions, in particular: language comprehension and creation, attention, knowledge acquisition, memory, judgment, appraisal, reasoning, problem-solving, and decision making. Cognitive developments take advantage of previously acquired information whereas still generating novel knowledge.

Cognitive Science considers human cognition as information processing and therefore bridges disciplines such as informatics (e.g., artificial intelligence), cognitive psychology, anthropology, and neuroscience.[193]

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[190] Robert J. Sternberg, *The Cambridge Handbook of Intelligence*, 1st edn (Cambridge: Cambridge University Press, 2011).

[191] Linda S. Gottfredson, ‘The General Intelligence Factor’, 1998, p. 25.

[192] Michael S. A. Graziano, *Rethinking Consciousness : A Scientific Theory of Subjective Experience* (W. W. Norton & Company, 2019), p. 16 <LEIDO>.

[193] Cambridge Cognition, ‘What Is Cognition & Cognitive Behaviour’, *CANTAB*, 2015 <https://www.cambridgecognition.com/blog/entry/what-is-cognition> [accessed 19 January 2021].

Embodied Cognition

By considering how our brains perceive the world in which we act and interact, a new paradigm labeled embodied cognition was developed in terms of how we live and think in this particular environment.

One of the most counter-intuitive theories of cognitive science is that the mind is not related only to the body, but rather the body affects the mind. In comparison is dualism, a philosophy of mind popularized within the 17th century by Rene Descartes, who argued that:

> *"...there is a great difference between mind and body, in as much as the body is by nature always divisible, and the mind is entirely indivisible... the mind or soul of man is entirely different from the body."*[194]

Perceptions of the disembodied mind thrived in the decades that followed. It produced two fundamental concepts in western thought: reason is transcendent and universal, while rationality is disembodied because the mind is disembodied.[195]

Cognition in Nature and the Human Mind

Sophisticated building behavior is often predicated on a sequence of internalized mental maps. The most fundamental of these neural representations is that of the body. Typically, an animal "knows" the location of its tactile receptors, in the sense that it reacts correctly and appropriately to a specific stimulus. This is in contrast to the simple stimulus response (S → R) framework, which must have existed prior to anything more complex.[196]

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[194] Paul Dourish, *Where the Action Is: The Foundations of Embodied Interaction*, *Where the Action Is the Foundations of Embodied Interaction* (Cambridge: MIT Press, 2001), p. 105 <https://doi.org/10.1162/leon.2003.36.5.412>.

[195] Lucia Foglia and Robert A. Wilson, 'Embodied Cognition', *Wiley Interdisciplinary Reviews: Cognitive Science*, 2.3 (2013), 319–25 (p. 2) <https://doi.org/10.1002/wcs.1226>.

[196] James L. Gould and Carol Grant Gould, *Animal Architects: Building and the Evolution of Intelligence*, 1st Editio (New York: Basic Books, 2012), p. 28 <https://www.amazon.com/Animal-Architects-Building-Evolution-Intelligence/dp/0465028381>.

Each sensory ending or group of endings (such as tactile receptors) is connected to a response circuit in a S → R circuit. At the cellular level, the majority of neurons are composed of short information-collecting processes called dendrites, a cell body, and a long axon that terminates in synapses with the dendrites of other neurons or muscle cells.

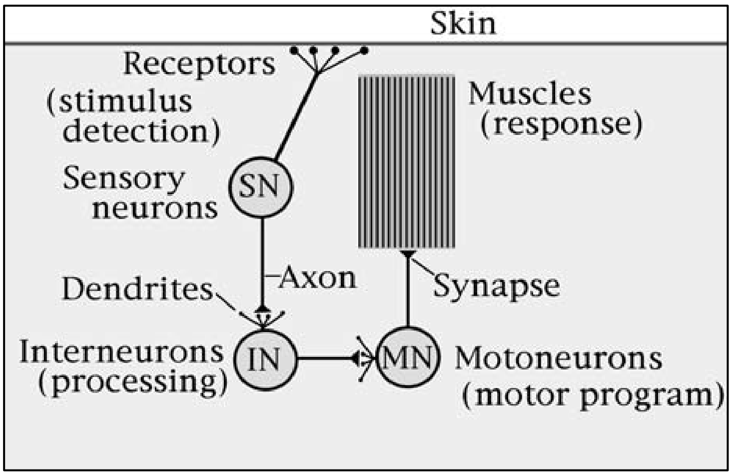

Fig. 4.9 - A basic neural circuit (James and Carol Grant Gould) [197]

The most basic circuits connect sensory organs to muscles. Sensory neurons gather information in a number of ways. In this case, the dendrites sense the stimulus and, if it is intense enough, cause the cell to send an impulse down the axon to intraneuronal synapses on the dendrites. If enough sensory neurons fire at the same time, the message is relayed to a motor-program circuit, where motor neurons coordinate muscle response.[198]

At the neural level, learning happens by wiring up other sensory inputs to drive the Response, ensuring that other (at first suppressed) sensory inputs must tap into the response circuit.

Learning occurs with the exception that only some sensory stimuli are available for each answer (accounting for selectivity of learning), while drive may also influence the process because it increases in intensity before the behavior is conducted, resulting in critical periods. Later-developing receptor axons may

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[197] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 29.

[198] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 28.

have reached the brain or sensory ganglia later, creating a linear map more or less automatically. Selection would have favored beings that excelled at incidental mapping. Tier–0 and Tier–1 levels of the neural organization are used to differentiate between the basic S → R system and later under-the-skin maps of sensory information.[199]

Tier–1 maps enable the animal to respond in a graded manner, possibly interpolating between various extremes. It is easier to imagine the evolution of an interpolation mechanism if selection begins early when there are few receptors to control (a low-resolution task) and only a few response motor systems to deal with the stimuli.

The next move is the conception of "personal-space" maps. An animal with this capacity will be able to interact with the environment just beyond its body with the same accuracy and sense of position that tactile feedback from below the skin provides. These Tier–2 maps are most likely duplicates of established Tier–1 tactile ones. For example, primate brains have at least a dozen visual grids, each designed for a specific set of information-processing tasks. [200]

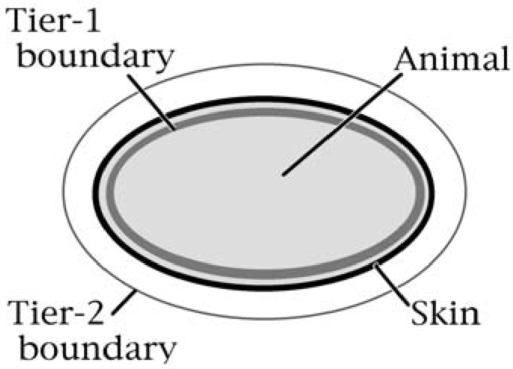

Fig. 4.10 - Representation of the first two Cognitive Tiers (James and Carol Grant Gould) [201]

Almost all species have a Tier–1 sensory map, which is an ordered projection of sensory receptors on and beneath the skin. A Tier–2 map is created by a creature probing and touching the outer world within its grasp. Such cognitive shortcuts

[199] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 31.

[200] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 32.

[201] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 33.

complicate our attempts to understand much of the building activity we observe in nature: what appears to be difficult may be trivial at the neural level, while what appears to be simple may necessitate intense concentration.

Mapping in Animals

- Tier 0 indicates that there is no spatial representation, having independent SR wiring for stimuli.
- Tier 1 is defined by an internal map, which generates a spatial representation of stimuli impinging on the body, most of which are tactile.
- Tier 2: is represented by a surround map, which generates a spatial representation of the objects and surfaces immediately surrounding the animal (within one body length, usually mapped by touching) and is generally tactile.
- Tier 3 is characterized by a local-area map, which provides a spatial representation of local objects (more than one body length) and allows for local navigation through interpolation and pattern matching. It is typically characterized by visual, tactile, olfactory, or auditory sensors.
- Tier 4 is defined by a Cognitive map, offering a spatial representation of the relative position of widely spaced objects or other landmarks, allowing home-range or nest-interior navigation based on a cognitive map. It is typically characterized by visual or tactile sensors.
- Network mapping defines Tier 5 as a multidimensional representation of the room, tool, and/or building equipment, priorities, and behavioral options; and the capacity for innovation.
- Concept mapping defines Tier 6: logical thinking, concept creation, capacity for understanding, and vocabulary.[202]

The evolutionary framework we have traced for the creation of cognitive abilities in animals has primarily centered on behavior building. Positive feedback motivates selection for greater analytical ability; new skills contribute to more resources and therefore to a competitive advantage for further cognitive capacity

[202] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 34.

and intellectual versatility. New mental abilities have evolved logically from previous ones, starting with basic body mapping and ending with the broadest sense of mental manipulation of tools. Selection has often favored increased facility in using any given degree of mapping, but it is the transitions from one sort mapping to the next more externalized and abstract kind that constitute the most noticeable directional changes.[203]

The morphological equipment of the species, such as the arrangement of onboard tools such as a beak and claws, or teeth and paws, or hands and a vocal apparatus capable of producing multiple consonants and vowels, is critical to what is possible at each stage of evolution. However, for the selection to have lasted more than 3 million years, there must have been several factors or one trigger that could have remained with us the whole time. The pressure driving the repetitive cycles of the social and traditional intelligence loops for the latter must have been other humans with whom we share the same niches.[204]

Evolution rewards innovation, the ability to quickly influence perspective, to perceive forces and deduce effects, minds that assume a cause-effect universe. The most complex reward we can assume was the mental technology that translates materials and tools into extensions of the hands in a species that is increasingly reliant on its brain, as well as the technology that its nervous system produces. Human hands, on the other end of the spectrum, are the most adaptable manipulators on the globe.[205]

Once competition became as much about social and conventional intelligence as it was about toughness, the cognitive escalations that resulted in expanded niches and new species in nest-building animals became, for ours, an accelerator that produced new incidental possibilities at the same rate as it exploited existing ones. Lewis Wolpert describes consciousness as an internal representation of our actions and the capacity to choose our conduct.

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[203] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 130.

[204] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 298.

[205] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 299.

Consciousness at this stage may have evolved most often in the widespread sense of construction, as a result of selection for increasing cognitive versatility in handling materials and using them as tools. The main element in our species that seems to be most emphasized is not consciousness in Wolpert's context, but rather intellect and imagination. The weaknesses over the last few decades have frequently been material related rather than imaginative, in terms of finding out how to build new tools rather than how to apply them.

Unfortunately, our current environment is one in which the majority of us may suffer if a critical piece of technology is lost, such as electricity. The innate need to control the world around us has bound us to certain artifacts in the same way that a robin's existence is inextricably linked to the species' nest. We are the prime inheritors of a billion-year-old drive to create, and thus take control of our immediate environment. This architectural push gradually developed the sort of mind that we now have.[206]

Unconventional, natural-inspired computing research aims to discover new concepts of efficient information processing and computation in biological, chemical, and physical systems. Thus, this leads to an establishment of new unique algorithms, computational architectures, and incorporates traditional algorithms to strive forward. As Stephen Hawking once said, “Intelligence is the ability to adapt to change”.[207]

Through biolearning, the idea of mimesis must be shifted as an imaginative act of assimilation, in which an individual should estimate and progressively integrate into a given system without ever being identical with it. Thus, the term mimesis enables us to comprehend not just how humans begin to identify with their surroundings, but also how they begin to incorporate those external forms into designs so that others can relate to them:

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[206] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*.

[207] Andrea Graziano and Alessio Erioli, *From Shaping to Informing Matter: Computation as Design Medium*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 35 <https://doi.org/10.1017/CBO9781107415324.004>.

Humans absorb external forms through mimetic impulses, integrating them symbolically within their self-expression, after which they rearticulate them in the objects they create. As a result, within the process of mimesis, architecture (like other visual-arts) can be regarded as a viable possible source. [208]

The architect can express the relational association with the world which is incorporated in the principle of mimesis, within the design of buildings. Those who encounter these forms may perceive them similarly, given that the process by which we become comfortable in the built environment may likewise be viewed as mimetic.[209]

Why Animals Build?

Asking this question, we can unveil how nature's architectural marvels address the ecological problems faced by each animal's habitat and niche, as well as how decision making and obvious planning play a role in construction and the continuing evolution of organisms. This also demonstrates how construction activity affects both the mind and the niche, thus influencing behavioral evolution.[210]

To start to comprehend what happens as animals build, we must first be conscious of the obstacles the creatures are attempting to overcome. We need to know what resources and constraints they face, as well as what onboard equipment evolution has developed. To understand why animals build and what mental capacities they have, we must acknowledge the idea that animals can use some level of creativity and insight in their design process.

Life is about survival and reproduction from a biological standpoint. This includes locating and obtaining food, preventing an early death due to predation, exposure to the elements, locating and attracting partners, and, in some cases, protecting and tending to the young.

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[208] Leach, *ADAPTATION*, p. 134.

[209] Leach, *ADAPTATION*, p. 135.

[210] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, p. 1.

Instinct or Learning?

Given the immense complexity of structures, such as bird nests and beaver dams, early animal behavior experts believed that elaborate construction behavior had to be studied. Naturalists, on the other hand, never really bought into this explanation since they saw nests being constructed by novice first-timers and found that, despite deficiencies, they had much of the features seen in mature adult designs. Until now, neither the neural systems of instinct nor the intricate and enigmatic laws of conditioning were fully understood.[211]

But, without a doubt, learning is involved, as an example, any hunting wasp must recall the location of its nest because it has to return many times during construction.

4.3. Adaptation in the Built Environment

> *¨Accepting the dynamics of buildings and cities…can turn architectural change into an ecologically efficient process as well as a new urban experience¨. (Ed Van Hinte et al)*[212]

It's self-evident that concepts like adaptive, kinetic, dynamic, and responsive architecture (among others) are all about transformation, which in turn all take into consideration the concept of time. However, changes in architecture have not been thoroughly addressed. Some essential concerns remain unanswered, such as what kind of changes could occur in structures, and for what purposes. We must analyze which changes are meaningful, helpful, or necessary, as well as the many scales of change (physical and temporal) and the varying rates at which they occur. Then there's the matter of whether certain things actually need to change.[213]

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[211] Gould and Gould, *Animal Architects: Building and the Evolution of Intelligence*, pp. 4–5.

[212] Ed Van Hinte and others, *Smart Architecture*, *010 Publisher* (Rotterdam: 010 Publishers, 2003).

[213] Branko Kolarevic, *BUILDING DYNAMICS: TOWARDS ARCHITECTURE OF CHANGE*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 138 <https://doi.org/10.1017/CBO9781107415324.004>.

While some resolutions to these queries can be found, no thorough assessments of adaptive architectural change exist. For instance, whereas Phillip Beesley and his colleagues assert that *"the next generation of architecture will be able to sense, change, and transform itself"*, they do not specify how. While they raise what might be the most critical inquiry, *"how responsive systems influence us?"*, they make no clear effort to address it. Likewise, Michael Fox and Miles Kemp avoid fully explaining why interactive systems are meaningful, required, or even useful in their "Interactive Architecture" book, instead stating that *"the motivation to create these systems is found in the desire to create spaces and objects that can adapt to evolving individual, social and environmental demands"*.[214]

The pursuit of an adaptive-enabled architecture is a reflection of the environment in which we live and work since contemporary existence is defined by an ever-increasing rate of change. The socioeconomic, political, cultural, and, particularly, technical circumstances are gradually shifting, changing conventions, practices, and expectations, as well as how we utilize and interact with space. Buildings that can change fast are required in such a dynamic environment and the type of change determines how structures may adapt and respond to it.[215]

This type of architectural flexibility entails several factors, including awareness, which enables an edifice to respond more effectively to a variety of functions, uses, and demands: transformation (which is characterized as changes in the morphology or aesthetics) and interaction along movability (that refers to both the inner and outer environments of an edifice).[216]

These capabilities ought to be supplied by "intelligent" building systems that will be influenced by a variety of elements. These range from environmental variables such as energy management to modifying the aesthetic of the structure through various projections and patterns. The systems may be considered automatic or

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[214] Michael Fox and Miles Kemp, *Interactive Architecture*, ed. by Lauren Nelson Packard (New York: Princeton architectural Press, 2009).

[215] Kolarevic, *BUILDING DYNAMICS: TOWARDS ARCHITECTURE OF CHANGE*, p. 139.

[216] Robert Kronenburg, 'Fabric Architecture and Flexible Design', *Architectural Design*, 76.6 (2006), 75–79.

"intuitive," implying that they may derive an acceptable set of responses from the context without overly specific inputs.

As stated before, adaptation takes place over time and generations, with continuous changes, feedback assessments, as well as implying the survival of the fittest theory, founded on specific fitness requirements. Alongside this resemblance, we will look within the built environment from the perspectives of the natural one, by judging the main factors: Intelligence, Consciousness, and Cognition.

4.3.1. Intelligence in Architecture

Architectural intelligence represents a worldwide drive that encompasses all aspects of intelligence associated with the development and use of the built environment. It bridges the gap between practice and theory, between material and immaterial, between academia and the profession, as well as between architecture and urbanism. The essence and way in which intelligence is conveyed — for example as connectors, skins/membranes, or communication networks makes us think, about how nature's sensory perceptions conduct various intelligent acts that can be carried out through the physical and morphological form (for example, in pursuit of light or nourishment).[217]

The above-mentioned query set a framework where spatial formations and material performance started to be examined, and AI and intelligence systems began to be considered. Alongside the advancement of further sophisticated forms of AI, like deep learning, we observe a revolution within digital-design methods, such as Generative Adversarial Networks, which converts artificial intelligence from an analytical method into a generative agent. [218]

Plants have evolved adaptation strategies for thermal comfort conservation, water management, air exchange with no external energy source and no mechanical or electronic power.

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[217] Yuan, Xie, and Leach, *Architectural Intelligence*, pp. 2–4.

[218] Yuan, Xie, and Leach, *Architectural Intelligence*, p. 5.

The translation of these techniques into technological resolutions to serve adaptive architectural applications necessitates numerous experiments with emerging technologies (i.e. cross-material 3D printing), material science developments, and studies.[219]

A good example is material intelligence. Materials are part of the physical universe, while computing is immaterial. For instance, a sand dune represents a material intelligence expression. Also, we have to keep in mind that, in addition to digital computation, we also have material computation. Wind interaction with sand particles causes the sand dune to "compute" or "recompute" its shape. The sand dune will appear to be beautiful, however, its shape is essentially a product of material processes.[220]

Hydrogels, thermo-expansive polymers, and photochromic polymers are examples of active materials that have aptitudes such as programmable actuation, self-transformation, and sensing. In summary, these actions translate to taking intelligence from one medium (natural) and applying it to another (artificial).[221]

In addition to material intelligence, we also have digital intelligence. There are several forms of it, i.e. swarm intelligence, which is a methodology implying multi-agent systems that can be thought of as an initial form of AI.

Swarm intelligence is defined as a formation of collective behavior which is exemplified by the intricate aerial choreography that emerges via the movements of bird flocks. Underpinning the flock's coherence and fluidity proves an extremely

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[219] Marlén López and others, 'How Plants Inspire Façades. From Plants to Architecture: Biomimetic Principles for the Development of Adaptive Architectural Envelopes', *Renewable and Sustainable Energy Reviews*, 67 (2017), 692–703 (p. 9) <https://doi.org/10.1016/j.rser.2016.09.018>.

[220] Feng Yuan, Shuyi Huang, and Tong Xiao, 'Physical and Numerical Simulation as a Generative Design Tool : Formation of a High-Rise Typology Using Wind Tunnel Testing and CFD Simulation', *CAADRIA 2016, 21st International Conference on Computer-Aided Architectural Design Research in Asia - Living Systems and Micro-Utopias: Towards Continuous Designing*, 2016, 353–62 (p. 354).

[221] Marlén López and others, 'Adaptive Architectural Envelopes for Temperature, Humidity, Carbon Dioxide and Light Control', *10th Conference on Advanced Building Skins*, November, 2015, 1206–15 (p. 1206).

complex type of swarm intelligence based on the immediate interaction of individual agents that results in increasingly complex actions. The resulting order is not imposed from the top but arises from the bottom-up interplay of the swarm's agents.[222]

The paradigm of complexity is progressively recognized as the logic underlying systems as varied as insect colonies, flocks of birds, human social networks, and also city operations. This dispersed mode of development is also emerging as the conceptual and methodological foundation for a variety of architectural generative design approaches.[223]

Other approaches regarding intelligence in architecture can be devised through the perspective of consciousness and cognition. These are briefly presented in Appendices: B.1 and B.2

4.4. Characteristics of Adaptive Architecture

Hearing the term Adaptive Architecture, the thoughts guide us directly to kinetics and dynamism, thus both being mainly described by a form of animation.

The architectural field has a close and complex relationship with the topic of animation as it attempts to animate matter in order to approach humans as though it were about to communicate. Traditionally, ornamentation was entrusted with this expressive ability. However, ornamentation was not the only way to fulfill this purpose, composition playing a main role in architecture's ability to appeal to people.[224]

Adaptivity in architecture can be more easily observed in large urban scales. Cities expand due to the interactive complexity between their multiple heterogeneous components, making urban growth prediction imprecise. Since the many physical and behavioral elements of cities are entangled, they cannot

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[222] Neil Leach and Roland Snooks, *Swarm Intelligence Architectures of Multi-Agent Systems*, 1st edn (Shanghai, 2010), p. 61.

[223] Leach and Snooks, *Swarm Intelligence Architectures of Multi-Agent Systems*, p. 1.

[224] Yuan, Xie, and Leach, *Architectural Intelligence*, p. 18.

be extensively accounted for using existing digital modeling methods, limiting the predictive efficiency of urban planning.

Although big data sets and fractal growth have been used to digitally model the dynamic creation of urban areas, these findings have been compiled using algorithms and abstracted databases that miss direct interaction with the materiality of cities. While urban development cannot be anticipated, more general concepts such as trends and patterns in urban expanse propagation can be calculated and provide navigational guidance for urban planners, architects, and developers. Since Aristotle's era, the total growth of a city has been compared to the growth of an organism.[225]

A feedback mechanism is at the center of modification that allows systems to change their behavior in response to changing environmental conditions. Feedback also allows systems to become aware of their surroundings by generating an implicit model of the environment that drives adaptation. In this sense, adaptation can be viewed as a feedback loop between the cause and effect of changes within the surrounding environment.[226]

Many adaptive architecture projects can be classified as interactive, dynamic, kinetic, or responsive architecture as stated by Sushant Verma & Pradeep Devadass in their adaptive[skins] project. Adaptation has been conceptualized as a method in a variety of disciplines with common approaches and objectives. This term translates directly into architectural conceptualization. We may think of the building as a device that adapts its actions based on information gathered regarding its users. [227]

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[225] Rachel Armstrong and Andrew Adamatzky, *CITIES AS ORGANISMS: FROM METAPHOR TO SLIME MOULD*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 16 <https://doi.org/10.1017/CBO9781107415324.004>.

[226] Peter Suen, *BIOLOGICAL SIMULATION: AN ANALOG APPROACH TO DESIGNING ADAPTABLE SYSTEMS*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 24 <https://doi.org/10.1017/CBO9781107415324.004>.

[227] Sushant Verma and Pradeep Devadass, 'Adaptive[Skins]', 2014 <www.adaptiveskins.com>.

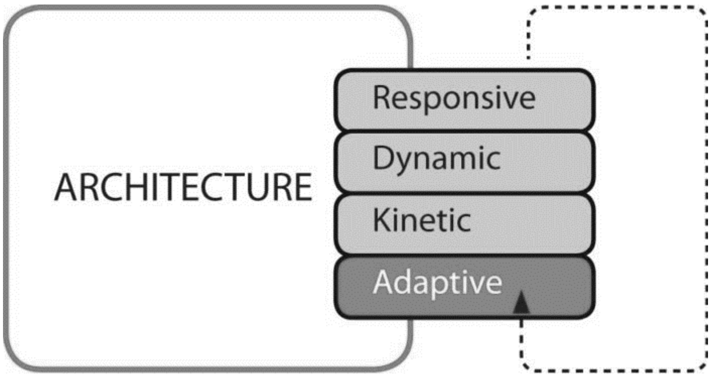

Fig. 4.11 – Adaptive Architecture cycle and stages (author: Sushant Verna)[228]

Data from outside the edifice may also be incorporated into the procedure. This implies weather data, energy prices, demands regarding neighboring structures, and so on. As a result, adaptive architecture offers the potential to react to a variety of parameters over time, this being a major factor in architectural adaptation.

4.4.1. Adaptivity and Materialism

The materials utilized may very much dictate the sort of adaptability that the built environment employs. Until recently, typical materials such as concrete, ceramic, metal, and glass have been industrially processed to meet the standards of the construction industry, thus most materials are uniform in structure and have equal or nearly identical qualities in all directions.

To produce any type of adaptive systems, manufacturing procedures and conventional materials produce inert solutions, static outcomes, or complicated high-technology equipment. Some approaches within kinetic architecture are constructed using electrical and mechanical sensing, activating and regulating components, usually generating inefficient designs in terms of energy use.

The subject of smart materials experienced substantial development in the twentieth century. The many distinct roles that smart materials may perform have resulted in the creation of smart material systems. These systems are comprised

[228] Verma and Devadass, 'Adaptive[Skins]'.

of a diversity of dedicated materials and can accomplish a range of functions in addition to detecting the change which causes the actuation.[229]

a. Smart Material Definitions

> *"A material which has built-in or intrinsic sensor(s), actuator(s) and control mechanism(s) whereby it is capable of sensing a stimulus, responding to it in a predetermined manner and extent, in a short appropriate time and reverting to its original state as soon as the stimulus is removed" (Ahmad I.)*[230]

Categorizations of smart materials were developed since it became impossible to organize materials using conventional systems because of the advancements in technological materiality. As a result, in 2005, a new system that categorizes materials based on how they function was introduced by Addington and Shodek, dividing them into two types: Property Change Materials and Energy Exchange Materials.[231]

Materials with property changes

Such material types are represented by the characteristic of changing at least one of their characteristics as a result of direct extraneous stimuli. Such direct modifications that can be reversed, without the need for an auxiliary controller to manage them. A photochromic material, for example, bears the capacity to shift color once in contact with UV radiation. Most frequently material changing properties are known as electrochromic, thermotropic, phototropic, mechanochromic, chemochromic, thermochromic alongside shape-memory and phase-changing materials.[232]

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[229] Yahya S. Abdullah and Hoda A.S. Al-Alwan, 'Smart Material Systems and Adaptiveness in Architecture', *Ain Shams Engineering Journal*, 10.3 (2019), 623–38 (p. 623) <https://doi.org/10.1016/j.asej.2019.02.002>.

[230] I. Ahmad, 'Smart Structures and Materials', in *Rogers CA (Ed) Proceedings of U.S. Army Research Office Workshop on Smart Materials, Structures and Mathematical Issues* (Technomic Publishing Co., 1988), pp. 13–16.

[231] Abdullah and Al-Alwan, 'Smart Material Systems and Adaptiveness in Architecture', p. 624.

[232] Abdullah and Al-Alwan, 'Smart Material Systems and Adaptiveness in Architecture', p. 624.

Material types for energy exchange

This category comprises smart-materials that have the capacity to transform energy from an input's form to another form's output energy, and its functions are performed in both a direct and revocable manner. Electro-restrictive materials are an example of this, as they convert electric energy into mechanical energy, resulting in a shape modification. This is easily reversible to its initial state by the use of the same process.[233]

Thermoelectric, photovoltaic, light emitting, piezoelectric, shape memory alloys, and LEDs are just a few examples of energy-exchange materials.[234]

The categorization of smart-materials is considered to be multi-layered, in which the first one indicates the material's physical behavior (what it accomplishes), while the second layer indicates the phenomenological behavior (the effect it has) of the material.

Smart-materials exhibit a variety of qualities that set them apart from more conventional ones, either in singularity or as a system, tiny as a speck or as large as a construction envelope, it would exhibit the following properties:

- Immediacy: the property of reacting in real time to stimuli.
- Transiency: the capability of answering to many inputs or environmental influences.
- Self-actuation: what governs the smart-material's reaction is internal to the material itself, rather than external.
- Selectivity: the behavior is unique and expectable.
- Directness: the reaction of the material is restricted to the 'activation' event.[235]

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[233] d. Michelle Addington and Daaniel L.shock, 'Smart Materials and New Technologies For the Architecture and Design Professions', *Elsevier*, 1 (2005), 225 (p. 17).

[234] Addington and L.shock, 'Smart Materials and New Technologies For the Architecture and Design Professions', p. 30.

[235] Addington and L.shock, 'Smart Materials and New Technologies For the Architecture and Design Professions', p. 10.

b. Smart material system types

A smart material can only perform one dedicated operation, yet, through material compositions, a network that can carry out a diversity of functions (in addition to sensing the change that causes the actuation) is created. Classifications of smart-material systems are founded on how that network replies to stimuli. There are three systems that can be identified: active, passive, and hybrid.[236]

Passive smart-material systems

When a material system detects any changes in stimuli and reacts directly by actuation or action, it is considered a passive system. The energy needed by the system to undergo this action is derived from the environment's resources. This system type cannot be interrupted and operates within closed loops.[237]

Active smart material systems

When the performance of a smart material system is managed and directed by an external system, it is considered active. This system includes a sensor that detects changes in the stimulus and transmits an impulse to the control unit, which responds appropriately by activating it. This system requires an energy source to function.[238]

Hybrid smart material systems

Hybrid systems combine advantages of both active and passive ones. Although the materials can function as a passive element, their execution could be controlled and monitored by an active system.

Active shading systems are one example of this. When actuated by the sunlight, it provides shading to the glazed surface of the building during the hot summer days, yet during cold seasons, its functions are overridden by the active system,

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[236] Abdullah and Al-Alwan, ‘Smart Material Systems and Adaptiveness in Architecture’, p. 624.

[237] Abdullah and Al-Alwan, ‘Smart Material Systems and Adaptiveness in Architecture’, p. 624.

[238] Marlén López and others, ‘Active Materials for Adaptive Architectural Envelopes Based on Plant Adaptation Principles’, *Journal of Facade Design and Engineering*, 3.1 (2015), 27–38 (p. 33) <https://doi.org/10.3233/fde-150026>.

to avoid shading and permit the required heat to flow inside. Superior performance and complexity are possible in hybrid systems.[239]

4.4.2. Adaptivity within Architectural Design and Morphologies

Recently, architectural study and practice have centered on developing buildings that are more responsive to external factors, particularly since the adoption of computation-based technologies enabled parametrically driven iterations including local differentiation. Architects strive to enhance buildings' "intelligence" by imbuing them with performance-driven morphogenetic characteristics, which could include the ability to quickly respond to environmental factors, with the goal of achieving real-time feedback.[240]

One of the premises within architectural intelligence consists in a conceptual reduction in which flexibility is limited to one feature of plasticity, that of being a reflecting representation of extrinsic conditions.

Architectural design aspires to be the practice, or art, of creating proactive open processes and plastic (rather than just responsive) artifacts as conduits between two closely intertwined realms: ourselves and the surrounding environment. Edifices must be equipped with a buffer that offers each user a type of "customized plasticity", allowing them to develop unique relationships with the environment based on each user's individual perception.[241]

The scope is to redirect our attention towards the self and the scales where the perceptual processes begin: at the boundary where biology and neuroscience meet technology. Some of the greatest recent advances in scientific study, such as synthetic biology, nanotechnology, neurology, robotics, and biocomputing, will have a profound impact on architecture and other design disciplines, if not entirely transform them. The momentum of the 3D printing revolution is undeniably

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[239] López and others, 'Active Materials for Adaptive Architectural Envelopes Based on Plant Adaptation Principles', p. 38.

[240] Graziano and Erioli, *From Shaping to Informing Matter: Computation as Design Medium*, p. 35.

[241] Graziano and Erioli, *From Shaping to Informing Matter: Computation as Design Medium*, p. 36.

significant for a variety of reasons, including closing the gap between concept and production as well as democratizing access to manufacturing with better access to resources and methods. However, its primary significance stems from the fact that it allows a low-cost approach to provide matter with a basic layer of information such as its position in space. Whether using G-codes or voxelizations, the goal is to provide the precise x, y and z coordinates wherein matter should be deposited. There is a fast advancement within this fundamental process, gaining the ability to add multiple layers of information at various scales and for multiple purposes and functions. 3D printing is a fantastic "learning by playing" method for comprehending that information, as John Archibald Wheeler postulated, lives at the heart of matter.[242]

In design, a paradigm shift is taking place, which implies shaping matter in order to imbue it with information. We are experiencing the growth of computation as a design medium for driving matter organization and formation processes. The first element that established computation as the universal field/feature in all processes was basically scientific research.

"Pattern Seeker" is a good example of this paradigm shift, representing a simple inquiry into how information may be stored and conveyed simultaneously via the data structure of a 3D model, manifesting through the created patterns. The generation of an information genotype, such as a binary sequence of variable length, and its application to a geometrical data structure is what defines the generated pattern, which could be represented as a mesh topology. The resulting morphologies are an explicit representation of an "information embodiment" process. The mismatch between both the genotype's information structure and the 3D model to which it is applied issues the cause of a rapid exploration of diverse epigenetic scenery. The results can then be analyzed and grouped into categories based on similarities in pattern features.[243]

[242] Graziano and Erioli, *From Shaping to Informing Matter: Computation as Design Medium*, p. 39.

[243] Graziano and Erioli, *From Shaping to Informing Matter: Computation as Design Medium*, p. 39.

Architecture is considered as a discipline in which unending assemblages of evidential scientific-speculated scenarios must converge, be evaluated, and frequently become constructive failures for additional studies. The knowledge, acquired via a combination of professional practice and academic theory, ranges from architecture to both landscape and urban design, defining a critical methodological approach. Comprehending the environment and its fundamental and emerging metabolic networks enables us to establish particular levels of intervention that span between natural/artificial and local/global narratives in order to imagine hybrid social compositions.

A good example of this type of convergence could be identified within the ICD/ITKE Research Pavilions. These researches, which are based on computational design, modeling, and robotic manufacturing, not only offer up a new approach to fiber-reinforced composite structures but also allow for the development of novel fibrous tectonics.[244]

Fig. 4.12 - ICD/ITKE Research Pavilion 2012 (author: Achim Menges, Jan Knippers)[245]

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[244] Achim Menges and Jan Knippers, 'Fibrous Tectonics', *Architectural Design*, 85.5 (2015), 40–47 (p. 42) <https://doi.org/10.1002/ad.1952>.

[245] Menges and Knippers, 'Fibrous Tectonics', p. 43.

The coreless filament wrapping process was then developed to manufacture highly distinct modules for the building of a segmented double-layered envelope employing just one variable toolset, culminating in the ICD/ITKE Research Pavilion 2013-14.[246]

Fig. 4.13 - ICD/ITKE Research Pavilion 2013-14 (author: ITKE Stuttgart)[247]

The fibrous system's design, engineering, and fabrication were all fluidly interconnected in a collaborative design method, rather than following a linear workflow. Module design, structural analysis, and manufacturing simulation were all done digitally in a feedback loop that was continually updated. The fiber configuration, density, and alignment of each component were optimized to meet stringent structural, architectural, and manufacturing criteria.[248] These aspects pushed forward towards the latest research pavilion: “The Buga Fiber Pavilion”.

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[246] Moritz Doerstelmann and others, ‘ICD/ITKE Research Pavilion 2013-14: Modular Coreless Filament Winding Based on Beetle Elytra’, *Architectural Design*, 85.5 (2015), 54–59 (p. 56) <https://doi.org/10.1002/ad.1954>.

[247] Image Source: https://www.itke.uni-stuttgart.de/research/icd-itke-research-pavilions/icd-itke-research-pavilion-2013-14/

[248] Knippers and Menges, ‘Buga Fibre Pavilion’, p. 141.

ICD and ITKE conducted extensive research into biomimetic concepts, both morphologically and procedurally. Principles of load adaptability and highly diversified fiber arrangement were transferred and implemented at an architectural scale. This bottom-up method was mixed with top-down decisions, which were required in this instance to adhere to the pavilion's program.[249]

Fig. 4.14 - Buga Fibre Pavilion (authors: Jan Knippers and Achim Menges)[250]

Thus, instead of pure technological experimentation, an ecosophical perspective based on new relational paradigms is suggested. The aim is to redefine and locally integrate both architecture and its residing landscape into a modern synthetic urban hybrid model, for establishing methodical control over the energy performance and the built environment's spatial qualities.[251]

A good approach might be derived from the concept of Landscape Urbanism, which is an urbanism theory that contends that landscape, instead of architecture, is capable of structuring a better city while improving the urban experience.[252] Landscape Urbanism applies landscape design-derived tools and approaches to the setting of urbanism, leading to a new spatial synthesis. Traditional urbanism

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[249] Knippers and Menges, 'Buga Fibre Pavilion', p. 141.

[250] Knippers and Menges, 'Buga Fibre Pavilion', p. 140.

[251] Bruno Latour, *We Have Never Been Modern* (Cambridge: Harvard University Press, 1993), p. 93 <https://linkinghub.elsevier.com/retrieve/pii/0956522196885046>.

[252] Allison Duncan and Ethan Seltzer, 'Landscape Urbanism : An Annotated Bibliography', 2010, 1–36 (p. 1) <http://www.terrafluxus.com/wp-content/uploads/2010/10/final-format-LU-bib-2.pdf>.

creates cities using static masterplans; in contrast, the idea is to create a dynamic relational system which adapts to changes in time, allowing for numerous alternative outputs as a result of process control.[253]

The methodology, which is founded on the structure produced by the Landscape Urbanism Master Program at the Architectural Association, is fundamentally divided into three steps: indexing, meshing, and prototyping.[254]

Indexing is the approach that enables us to read and analyze the hidden characteristics that shape and alter a site's functionality, as well as the layers that determine what we call a profound material structure. Indexing, as opposed to mapping, is a purposeful analysis that, though spatially descriptive, is molded by a design-oriented approach. Indexing aids in the discovery of complicated linkages between physical (ecological and infrastructural) and non-physical (economic, social, and political) conditions, as well as the establishment of variables that will inform design. Such a process is aided by metric operations and software, which enable the simultaneous integration of numerous layers in an objectified, quantifiable system.[255]

Meshing is the process of defining and connecting the site's future geometric structure, as well as structuring and linking all of the complicated interactions between the many components of the system. It enables the design of specific regions while maintaining overall formal and functional coherence. The mesh definition allows one to operate at both the local and general scales at the same time.

Prototyping characterizes a system by the various spatial configurations of all its parts and associated aggregation logic. A prototype approach allows for the

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[253] ArchitecturalAssosiation, 'AALU Landscape Urbanism' <http://landscapeurbanism.aaschool.ac.uk/> [accessed 27 May 2020].

[254] Federico Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge, 2013), p. 44 <https://doi.org/10.1017/CBO9781107415324.004>.

[255] Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, p. 44.

testing of multiple solutions, as well as visualizing, analyzing, and readjusting of design outputs in a continuous feedback loop, which enables greater flexibility within the design process.[256]

a. Form vs. Function

We see that fittingness allowed to overcome immediate utility or quantification as a result of this identification of a deep ecological dynamic. Such acknowledgment is fundamental to an exceptive architectural process, both as a desire to comprehend and engage with broader ecological horizons and as an awareness that a competent, ethical architectural practice should no longer disregard them.[257]

One of the issues we face is one of inclusion, thus expanding the scope of deep ecology to encompass the post-natural "worth" of our cultural and industrial byproducts. The methodology within the concept, indicates a potentially irreducible latency among form and function, striving to develop temporary material assemblages, such as groups of interacting components that may be separated from the whole, reconfigured, and recycled into new groups in adapting to shifting demands and dispositions.[258]

This emerging tendency is predicated on two erroneous premises: one believes that all subjects are equal or, at best, varied yet passive "users", while the other conflates plasticity (a vital idea for adaptability, resilience, and development) with flexibility, through which responsiveness emerges directly.

As a result of the first premise, all design work is directed away from the subject and toward the edifice and its environment. Thus, the building's "intelligence" is self-referential and self-directed. In this sense, even while the project allows for a spectrum of varied conditions, the interplay between this type of mapping and

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[256] Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, p. 44.

[257] Simone Ferracina, *EXAPTIVE ARCHITECTURES*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 62 <https://doi.org/10.1017/CBO9781107415324.004>.

[258] Ferracina, *EXAPTIVE ARCHITECTURES*, p. 65.

the myriad of different situations established by each interacting subject receives no consideration.

Although it is said that architecture has always been focused on human beings, little consideration is given to the reality that each individual is unique, in the sense that each of us experiences the surroundings differently as a result of our body shape, culture, belief, background, and behavior, to name a few. In summary, each individual develops a unique model of the environment.

The approach can be separated into two domains, natural and artificial. Afterward, it can be re-outlined as a unified system based on characteristic, quantity, and performance. Indexing is a crucial tool for producing a more comprehensive and holistic interpretation of the site's many layers and gaining a more adequate knowledge of the land.[259]

b. Active Shapes, a kinetic approach in architecture

During the design phase, it is usually difficult for designers to predict how their structure will move, fold, and rearrange into another shape. To define a methodology, we must question ourselves how we can develop and describe those unique motion behaviors, how we can anticipate them, and how can we construct the moving component. [260]

Unfortunately, no rules or frameworks exist to assist designers in crafting kinetic architectural structures. Herbert Simon claimed that designers begin by improving an already existing element and do not begin from scratch. Also, designers use "existing situations" or precedents to tweak them in order to create their own design, "the preferred one".[261]

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[259] Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, p. 48.

[260] Dina El-Zanfaly, *Active Shapes: Case Studies in Designing Kinetic Structures*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013), p. 146 <https://doi.org/10.1017/CBO9781107415324.004>.

[261] Herbert A. Simon, *The Sciences of the Artificial*, *Technology and Culture*, 3rd edn (Cambridge: The MIT Press, 1996) <https://doi.org/10.2307/3102825>.

This holds true for the design of kinetic architectural structures as well. The question is, what must designers do whenever they see a moving structure and are motivated to alter and add to it to integrate it into their own kinetic design? Our goal is to develop a set of principles for constructing kinetic architectural structures that employ motion capture and design rules based on shape grammars.[262]

c. The Active Rules

Active Shapes are defined by a physical shape that exhibits or creates motion. The design may consist of a single physical component or a collection of them combined into a single kinetic system.

Shape grammars enable the definition of shapes in a recursive fashion. The formalism is envisioned to be simple to use and understand by individuals while also being flexible for software application usages. Shape grammars are defined to phrase structural grammars, whereas a phrase structure grammar is determined through a symbol alphabet, and produces a language of symbol sequences. Thus, the shape grammar is based on an alphabet of forms and produces a language of morphologies.[263]

Based on this concept, we can implement a rule that could define the approach of the active shapes as a guideline within kinetic edifices. In this sense, we would have an initial factor defined by an active shape, upon which we can apply one or more transformations, resulting in a unique motion.

The rule can be transcribed as “A → t(A)”, whereas “A” is the initial active shape and “t(A)” is the resulting shape after the defined transformations.[264]

The transformations can be categorized into three defining aspects. The first would imply a transformation at the level of arrangement of the parts, the second

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[262] El-Zanfaly, *Active Shapes: Case Studies in Designing Kinetic Structures*, p. 157.

[263] Jams Gips and others, *Shape Grammars and Their Uses: Artificial Perception, Shape Generation and Computer Aesthetics*, ed. by Salamon Klaczko-Ryndziun (Springer Basel AG, 1975) <https://doi.org/10.1007/978-3-0348-5753-6>.

[264] El-Zanfaly, *Active Shapes: Case Studies in Designing Kinetic Structures*, p. 158.

would define the controlled motion (hinges, actuators, or connections), and the third records the transformations at the geometrical level of the Active Shape.

The arrangement aspects can be observed within modular components, in which the placement of each part can alter the final result. Applying control means to the design implies a motion that redefines the overall shape, without breaking the linkages of the initial rule. These types of controlled transformations could include gears, sliders, actuators, pneumatics et cetera. The final transformation relies on rethinking the geometrical aspects of the initial module to attain a dedicated effect of the overall motion.[265]

In terms of motion, we can observe another three aspects that define the kinetic applications. These are translated as Transition, Rotation, and a combination of the two. The transition effect is attained when an element is moved linearly on a dedicated rail, such as a slider, while the rotation implies a fixed point around which the parts revolve, such as a hinge. The combination of two or more of these different effects generates a more complex movement that increases the fluidity and range of the said motion.[266]

4.4.3. Adaptivity within Building Envelopes

Although the façade is perhaps the most visible feature of an edifice, modern architecture has always regarded the conscious design of the vertical surface as a doubtful endeavor.

According to this concept, if a building is rationally developed according to its internal demands, structure, and material, the façade will 'design itself.' As Le Corbusier famously stated, "the exterior is the result of the interior". The definition coined by Merriam Webster provides an additional cause to question the quality of the façade design, with two unique significances.

The first interpretation holds that the façade is the building's main surface, which uses architectural styling to highlight its importance, while the second describes

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[265] El-Zanfaly, *Active Shapes: Case Studies in Designing Kinetic Structures*, p. 158.

[266] El-Zanfaly, *Active Shapes: Case Studies in Designing Kinetic Structures*, pp. 158–59.

a derogatory, implying that the word "façade" refers to a "dissimulation" (an inaccurate front concealing doubtful or deficient reality). Furthermore, in the aftermath of post-modernism, the ideology that seemed to argue that architecture was nothing more than the façade discredited. As a result, the vertical surface design, over and above strict technological limitations, has become a notorious activity.[267]

Through this research' approach, we hope to demonstrate how a concentrated application of principles incorporated in a set of carefully crafted algorithms may be used to address both technical principles and compositional approaches in the design of the façade. Numerous studies, both speculative and accomplished, are seeking to utilize these potentially feasible applications of such systems on an architectural scale in order to redefine building fundamentals.[268]

Today's facade is transitioning into an intelligent medium that can dynamically address the foreseen and unforeseen eventualities while serving as a mechanical system for interactions with the intricacies of the ecosystem and climatic phenomena. A building's façade serves as the breathing and sensory elements of the building, providing contact with climatic conditions. It interacts with the viewer's senses and conveys the meaning and purpose of architecture in the context of the environment and beyond.[269]

As stated by the Maldegem Physical Institute, façades are accountable for more than 40% of energy losses during cold seasons and for the tendency of overheating during hot seasons, mandating the use of air conditioning systems to guarantee proper indoor well-being. Thus, the construction sector consumes

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[267] Douglas Noble, Karen Kensek, and Katie Gould, 'Face Time 2020 : Better Buildings through Better Skins', in *Facade Tectonics 2020 World Congress*, 2020, II, p. 114.

[268] Walter Haase and others, *ADAPTIVE FACADES: Towards Responsive Building Structures and Envelopes*, ed. by Karen Kensek, Douglas Noble, and Matt Elder, *Facade Tectonics - SKINS on Campus: Bridging Industry and Academia in Pursuit of Better Buildings and Urban Habitat*, 1st edn (Los Angeles: Tectonic Press, 2018).

[269] Mitra Kanaani, *The Routledge Companion to Paradigms of Performativity in Design and Architecture: Using Time to Craft an Enduring, Resilient and Relevant Architecture*, *The Routledge Companion to Paradigms of Performativity in Design and Architecture: Using Time to Craft an Enduring, Resilient and Relevant Architecture* (Taylor and Francis Inc., 2019) <https://doi.org/10.4324/9780429021640>.

the most energy, much more than industry and transportation combined. There are various terms for the distinction between architectural exterior and interior. The term façade typically refers to the edifice's vertical plane, whereas the term envelope, which has lately gained popularity, points out to the entire construction enclosure.

The concept of "building skin" was coined to emphasize the separation amid the coating and the structural components, but it is now more commonly connected with envisioning the envelope as a smart environmental system capable of exchanging energy and information.[270]

Wigginton and Harris state in the publication "Intelligent Skins" that, "the skin operates as a part of a holistic building metabolism and morphology, and will often be connected to other parts of the building, including sensors, actuators, and command wires from the building management system", which reinforces this tendency.[271]

Innovative façade designs that manage both the indoor environment quality of a room and the thermal efficiency of the whole structure are driven by the dynamic nature of light and energy. Moreover, pursuing a thermally efficient envelope in conjunction with optimal daylighting comfort is critical from an environmental aspect, as the deployment of advanced solutions would contribute to the building energy demand minimization.

Static and dynamic external shading systems have been effective in the domain of façade engineering. However, it is essential to employ alternative solutions, especially in the case of elevated or severely-loading buildings where typical sun control systems cannot be used. To address these problems, a prototype has

[270] Trubiano, *Design and Construction of High Performance Homes*, p. 76.

[271] Michael Wigginton and Jude Harris, *Intelligent Skins*, ed. by Michael Wigginton and Jude Harris, 1st edn (Oxford: Elsevier Architectural Press, 2002), p. 27.

been built for an adaptive, sub-structured programmable vitrification system with inbuilt sun and glare protection. [272]

The term that is tackled within this thesis is generally defined as “the ability to adjust and adapt to changing circumstances by itself”. Thus, adaptive envelopes are capable of altering their behavior, configurations, or characteristics in response to environmental alterations.[273]

Building skins are an important component in resolving architectural adaptivity concerns since they serve as a conduit for imparting information within the building system for it to react to environmental stimuli. Therefore, the ability of an actual intelligent edifice envelope to adjust energy fluxes via control, amplification, attenuation, rejection, or entrapment is a vital feature. This brings us to a complexity point in which control plays the main role.

To some extent, the degree of architectural complexity is a matter of perception and changes depending on which aspect is being explored. It can, for example, be analyzed in terms of form, method, and utility, as well as a whole, which includes all three. The exploration of complex systems and how they're being translated and decomposed into rules or simple elements and supplied into a system via a bottom-up process is prominent in current architectural research and practice.[274]

A controllability aspect comes into play here because the bottom-up design methodology consists of basic (or sometimes extremely complicated) sets of operations that function like a gene pool (genotype), leading to a complex architectural shape (phenotype), resulting in an outcome that can be difficult to

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[272] Karen Kensek, Douglas Noble, and Matt Elder, *FACADE TECTONICS*, ed. by Karen Kensek, Douglas Noble, and Matt Elder, *SKINS on Campus: Bridging Industry and Academia in Pursuit of Better Buildings and Urban Habitat*, 1st edn (Los Angeles: Tectonic Press, 2018), I.

[273] R. C.G.M. Loonen and others, ‘Climate Adaptive Building Shells: State-of-the-Art and Future Challenges’, *Renewable and Sustainable Energy Reviews*, 25 (2013), 483–93 (p. 353) <https://doi.org/10.1016/j.rser.2013.04.016>.

[274] Hanaa Dahy, Piotr Baszyński, and Jan Petrš, ‘Experimental Biocomposite Pavilion 1 Experimental Biocomposite Pavilion at Night’, *Ubiquity and Autonomy - Paper Proceedings of the 39th Annual Conference of the Association for Computer Aided Design in Architecture*, October, 2019, 156–65 (p. 163).

predict at times. Controlling the relationship between different levels of hierarchies grows difficult and crucial when using this technique to design.[275]

Simultaneously, the manner in which complexity is translated is essential. Because of the fabrication methods used within a project, the geometry's complexity must be split into simple sections. Genetic algorithms can be effective in this situation. Computation, with its vast range of tools such as scripting and programming, is now entrenched in this type of research.

This continuing experimentation involving the transdisciplinary exchange of architecture and computation is a broad topic with many possibilities for exploration and testing. Different areas of simplifying complexity can be investigated and critically studied, such as the fabrication process, network advancements, and even functional resolutions.

With the constant inflow of new fabrication technologies at all scales into the architectural industry, digital fabrication and material computation hold the promise of unexplored possibilities for experimentation. Today, the integration of cutting-edge tools and technology into the design process is an intriguing subject of study.[276]

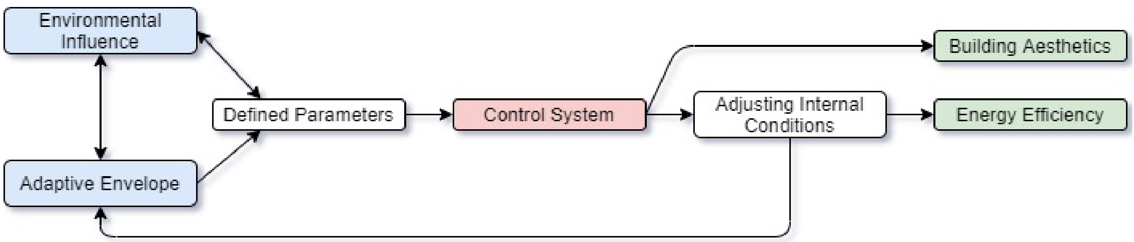

Fig. 4.15 - Complexity Schematic (image by author)

Bottom-up design, which reduces complexity by the use of basic sets of procedures, is a field of research that can aid in the solution of multiple

[275] Gruber, McGinley, and Muehlbauer, ‘Towards an Agile Biodigital Architecture: Supporting a Dynamic Evolutionary and Developmental View of Architecture’, p. 5.

[276] Verma and Devadass, ‘Adaptive[Skins]’.

complicated issues. The stacked system's feedback loop becomes crucial in this situation.

A design process in which simple geometrical operations are fed into a stacked system to generate successive generations of architectural form that can be reviewed according to specific parameters, such as structural optimization or fabrication suitability, is one area of research in the field of complex systems in architecture.

The input variables for a project, as well as a sequence of outputs generated by a specific script (such as genetic algorithms) and analyzed using the right tools, can be used to validate this process. This inquiry can be used to confirm the effectiveness of cross-disciplinary interactions involving genetic algorithms, computation, and architecture.

Additionally, the tool limitations can be assessed during the process, providing insight into future approaches essential to justify complexity in the vast field of architectural design.

Adaptive architectural envelopes could be classified into two categories, and the functions listed above indicate two types of adaptive behaviors, in terms of Activeness and Passiveness (Fig.4.7).

The active type entails the presence of noticeable motions (Folding, Expanding, Sliding, Rolling, Rotating Inflating, etc.) that result in changes within the envelope structure. These changes explicitly influence the internal structure of a material in the second type, which is based on material properties through static or passive strategies, and is expressed through variations in particular characteristics (reflections, absorptions, or energy transfers from one element to another).[277]

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[277] López and others, 'Adaptive Architectural Envelopes for Temperature, Humidity, Carbon Dioxide and Light Control'.

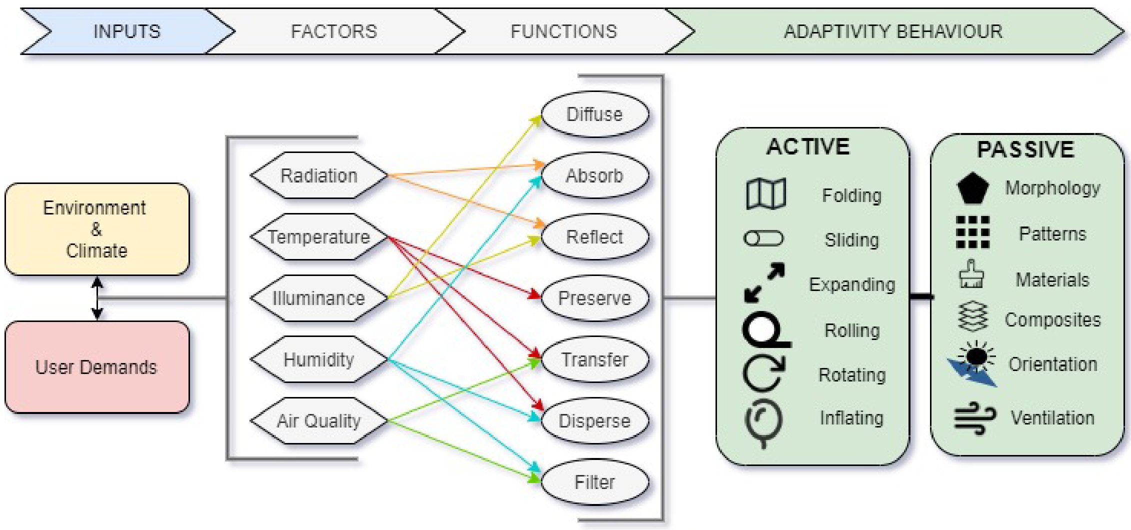

Fig. 4.16 - Adaptivity Behavior Diagram (image by author)

Light and heat are the main criteria within the regulation of internal environments, defining the optimum conditioning, efficiency, and ambiance effects, for both the interior and exterior. Smart systems that incorporate smart materials and geometries are used to produce passive and active skins, based on material intelligence and pneumatic actuation.

Genetic algorithms can be designed for system optimization, and adjusted via physical prototypes at different scales, to account for the complexities of the multi-parametric system. By integrating several digital applications to form a feedback and storage loop network, new tool sets will be generated during the process.

The project's parameters and sub-parameters are then implemented assets of "genes" in an algorithm that develops the "phenotype" as an actuated form, evaluates it in real time, and feeds the data back to the "genes" for improvements and alterations. To obtain the desired output/phenotype, it is required to run an iterative process for several generations to develop an initial population.[278]

[278] Verma, *SUPER-COMPLEXITY CONTROL*, p. 99.

When the envelope is curved or sophisticated, the transition between systems and materials is crucial. Systems that generate physically validating connections minimize risk and develop precedents for future projects.[279]

In all phases, parametric modeling provides holistic management for the design objects. Based on specific inputs, the algorithm employs its basic method of generation to create a sequence of complex morphologies and structures based on specific parameters, defined by static values, that are directly tied to actual data (such as weather patterns or solar radiation) and the digital input (which is produced from design process data).

If we accept that parametricism is a viable strategy for controlling and manipulating design objects at all scales at a holistic level, we must embrace the algorithmic methodology of generation to also develop complexity inside an element as little as a particle. One of the goals of this study is to use the advantages of parametricism to regulate environmental data inputs at any scale.[280]

There are fairly broad interpretations of adaptive systems. Research groups seem to incline towards establishing their own terminology to represent a specific sort of adaptive system approach. The adjectives kinetic, convertible, or plain adaptive are most typically used to define the nonstationary character of shading systems. Terms such as dynamic, performative, and responsive also define the functional relationship between the shading systems and their environment. Some research papers propose several definitions to enable a better understanding of the use of these concepts.

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[279] Alireza Jahanara and Negar Kalantar, *KINETIC SHADING SYSTEMS: A Parametric Approach to Optimizing Daylighting Performance*, ed. by Karen Kensek, Douglas Noble, and Matt Elder, *SKINS on Campus: Bridging Industry and Academia in Pursuit of Better Buildings and Urban Habitat*, 1st edn (Los Angeles: Tectonic Press, 2018).

[280] Danelle Briscoe and Reg Prentice, *RECONFIGURING FRIT: SERENDIPITY IN DIGITAL DESIGN PROCESSES*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013) <https://doi.org/10.1017/CBO9781107415324.004>.

Kinematics

Kinematics is a term that refers to the research of motion deprived of the regard for the mass or other factors that may induce it.[281] Kinematic systems analysis begins with a description of a system's morphology and its initial position values. Kinematics is a term used in engineering to define the movement principles of systems comprised of connected pieces and it is frequently denoted as "the geometry of motion".[282]

Kinetics

The study of movement principles concerning forces and masses implied defines the kinetics aspect. If an elastic deformation is the source of the system's motion, the system meets the definition of Elastic Kinetics.[283]

Dynamics

The term dynamics refers to the analysis of forces that operate on a subject and cause it to move. The phrase is frequently used to refer to movable building systems or envelopes.[284]

Retractable

This phrase is frequently encountered within architecture to refer to membrane coverings that are clustered or folded. Alternatively, such systems are referred to as moveable.

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[281] Marta Barozzi and others, 'The Sustainability of Adaptive Envelopes: Developments of Kinetic Architecture', *Procedia Engineering*, 155 (2016), 275–84 (p. 312) <https://doi.org/10.1016/j.proeng.2016.08.029>.

[282] James L. Meriam, Glenn L. Kraige, and Jeffery N. Bolton, *Engineering Mechanics: Dynamics*, ed. by Linda Ratts, *Angewandte Chemie International Edition, 6(11), 951–952.*, 9th edn (Austin: Wiley, 2018).

[283] Julian Lienhard, 'Bending Active Structures: Form-Finding Strategies Using Elastic Deformation in Static and Kinematic Systems and the Structural Potentials Therein' (Universität Stuttgart - Institut für Tragkonstruktionen und Konstruktives Entwerfen Herausgeber, 2014), p. 15.

[284] Lienhard, 'Bending Active Structures: Form-Finding Strategies Using Elastic Deformation in Static and Kinematic Systems and the Structural Potentials Therein', p. 15.

Convertible

Convertibility is one of the mechanisms of variability in structures, along with mobility, for adapting to varied roles. There are two forms of convertibility: external, which refers to the variability of the building's outer envelope, and internal, which refers to the inner spaces. Convertible structures are developed to shift their shape within a short period of time, depending on different needs.[285]

Transformable

As with convertible, the term transformable can be used for items or structures that exhibit an inherent quality of controllable modification. Foldable, retractable, or shape shifting bodies are all examples of transformable bodies.[286]

Performative

This capacity is the ability of the building skin to act as a buffer between the user's desired level of comfort and the surrounding environment. Envelopes that are considered performative employ abilities that influence external elements with respect to predetermined architectural performances.[287]

Responsive

Responsiveness denotes a reactive system, namely, one that moves, in contrast to manipulation, which denotes a system that is moved and controlled externally and is used to refer to passive settings. According to Nicholas Negroponte, “responsive” refers to an active environment, generating changes to a certain extent as a result of intricate or simplistic computations.[288]

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[285] Irene Meissner and Eberhard Möller, *Frei Otto: Forschen, Bauen, Inspirieren / a Life of Research, Construction and Inspiration*, ed. by Cornelia Hellstern, *Frei Otto*, 1st edn (Munchen: DETAIL, 2015), p. 69 <https://doi.org/10.11129/9783955532536>.

[286] Chuck Hoberman, *Transportable Environments*, ed. by Robert Kronenburg and Filiz Klassen, 3rd edn (London: Taylor & Francis, 2006), pp. 145–50.

[287] Michela Turrin and others, ‘Performative Skins for Passive Climatic Comfort: A Parametric Design Process’, in *Automation in Construction* (Elsevier, 2012), XXII, 36–50 (p. 36) <https://doi.org/10.1016/j.autcon.2011.08.001>.

[288] B. L.H. Hasselaar, ‘Climate Adaptive Skins: Towards the New Energy-Efficient Façade’, *WIT Transactions on Ecology and the Environment*, 99 (2006), 351–60 <https://doi.org/10.2495/RAV060351>.

4.4.4. Adaptivity within Interior Environments

Traditional architectural strategies for space creation, reorganization, and articulation expand beyond the physical limits of the environment. Spatial statements are built on the basis of cognitive human perception, emotion, and imagination in the intellectual, creative, aesthetic, and psychological domains, while the visual quality of space is determined by the aesthetic features of the architectural elements that make it up, as well as their complex relationships. Color, material, texture, size, and shape are examples of these characteristics.[289]

Architecture's interaction with science and technology is nothing new, part of which involves the post-Second World War period when swift technological breakthroughs fused with a generalized cultural attitude marked by themes of progress and futurism. The Industrial Revolution, and the rise of machine technology that accompanied it, resulted in a greater philosophical movement away from Newtonian physics certainty and toward growing contingency and probability.[290]

Within this movement, the concept of anticipatory architecture was developed by Reyner Banham and John Summerson.[291]

a. Anticipatory Architecture

Anticipatory architecture looks at the potential of space in both utilitarian and empirical design. Every space-defining component carries with it the potential for new places and functions to emerge. Throughout the design process of anticipatory architecture, certain uncertainty is acknowledged.

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[289] Ching, *Architecture Form, Space, and Order*, LIII, p. 312.

[290] Norbert Wiener, *The Human Use of Human Beings: Cybernetics and Society* (CAMBRIDGE: Houghton Mifflin Co., 1950), p. 56.

[291] Chris Perry, ‘Anticipatory Architecture | Extrapolative Design’, *Life In:Formation: On Responsive Information and Variations in Architecture - Proceedings of the 30th Annual Conference of the Association for Computer Aided Design in Architecture, ACADIA 2010*, 2010, 305–12 (p. 306).

Solutions for spatial transformations, layouts, and manifestations are presented to anticipate requirements that may occur as a result of changing environmental, social, cultural, economic, and technological circumstances.

Modularity, courtyard systems, and movable walls are among the features of traditional and vernacular architecture that allow for diurnal and seasonal home activities to be accommodated.[292]

In anticipatory architecture, the interplay of light, matter, and shape to possible spatial links is explored, which in turn generates sensory perceptive and aesthetically captivating spatial experiences. The Chapel of Ronchamp, designed by Le Corbusier, explores dynamically developing sensory spaces through formal manipulations and hybridization.

b. Human-Space Interactions and Interactive Spaces

To complete an interaction, an action or input must be returned by means of a conscious response or output. Human-space interactions occur in architecture once physical space morphs in response to a user's input or action. By adapting mobile partitions and changing their spatial qualities, an inhabitant can interact with a confined physical area. The user can customize his living space as an active participant in this relationship by developing aesthetic, physical, social, and emotional meanings.

Information technology has shifted in recent years to include artistic, cultural, and embodied human connections. Novel forms of human-space interaction have been made possible by technological advancements.[293]

Interactions among humans and the built environment are enabled through integrating or embedding computational technology under the form of sensors and microchips, defining the interactivity within architecture. Computing technology's "interactive essence" enables buildings or spaces to reflect the

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[292] Jeremy Till and Tatjana Schneider, 'Flexible Housing: The Means to the End', *Architectural Research Quarterly*, 9.3–4 (2005), 287–96 <https://doi.org/10.1017/S1359135505000345>.

[293] Joanne Jakovich and Kirsty Beilharz, 'Interaction as a Medium in Architectural Design', *Leonardo*, 40.4 (2007), 368–69 <https://doi.org/10.2307/20206449>.

gathered information by interconnecting its various sources, such as human and environmental inputs. [294]

Embedded computing has also enabled real-time "embodied" interactions between the physical world and social environments.[295] Over the last decade, there has been a surge of invention in interactive materials, which has led to the creation of a range of urban-scale spatial artworks, that use both of these computation forms.

Embedded sensors in different materials can alter brightness and color, shift, shrink or enlarge in reaction to presence or sound, textiles being the primary contenders in this sense. Such spatial studies observe how our bodies engage with space, and they challenge how we perceive, navigate and interact with it.[296]

These adaptations are well-suited for designs that include psychological and aesthetic demands that are part of everyday life. The goal of design is to create and promote sensations of safety, creativity, intimacy, serenity, introspection, or any other emotional states desired by the tenant, being evaluated and demonstrated in terms of its ability to establish possible spatial articulations to achieve its objective. As a result, such a design might envelop a single place with programmable, interactive planar surfaces. By altering the color, material, light, and texture of the enclosure, assigned sensors can follow user input and actuate the interior environment in real-time. In this way, the inhabitant bears the option to change whatever interior surfaces and personalize the living space in order to meet all psychological demands.[297]

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[294] Asma Naz, 'Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation', *Cognitive Systems Monographs*, 29.January 2016 (2015), 1–12 (p. 396) <https://doi.org/10.1007/978-3-319-22599-9_23>.

[295] Dourish, *Where the Action Is: The Foundations of Embodied Interaction*, p. 102.

[296] Lucy Bullivant, *4dsocial: Interactive Design Environments*, ed. by Lucy Bullivant, *Architectural Design* (London: Wiley, 2007), LXXVII, p. 62.

[297] Naz, 'Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation', p. 397.

The dwelling can also respond to external inputs by providing abstract representations of material, modulated light, color, and shadow, representing exterior weather conditions, diurnal and seasonal changes within the interior space to perceptually connect the inhabitant with the outdoor physical world. [298]

Fig. 4.17 - Modified interior spaces reflecting abstract representations of externa weather conditions and ambiances (author: Asma Naz)[299]

A great example of this type of adaptivity and interaction could have been observed within the DigitalFUTURES 2018 workshop series, “Cyborg Futures”. One of the studios used professional acoustic equipment alongside virtual reality equipment and projectors. The process was envisioning a collection of sound data in a space delimited by textiles, and processing that information to project visual immersive animations, transforming sound into a visual experience.

Through Fourier operations, the frequency change of sound can be intuitively analyzed within a period of time, similarly to spectrum analysis. Coloring the sounds of different frequency bands and drawing the sound spectrum can differentiate the nature of the sound in the space.[300]

So far, Rhino's Grasshopper has been able to collect sound data as well as processing it into the accompanying responsive morphological design.

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[298] Naz, ‘Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation’, p. 397.

[299] Naz, ‘Interactive Living Space Design for Neo-Nomads: Anticipation Through Spatial Articulation’, pp. 398–400.

[300] Fangshuo Mo, Philip F. Yuan, and Yao Zhao, ‘Sound Visualization’, *DigitalFUTURES 2018* (Shanghai: Tongji University, 2018), pp. 1–22 <https://mp.weixin.qq.com/s/hvGOpHhmCQ-gQMK1saYvhw>.

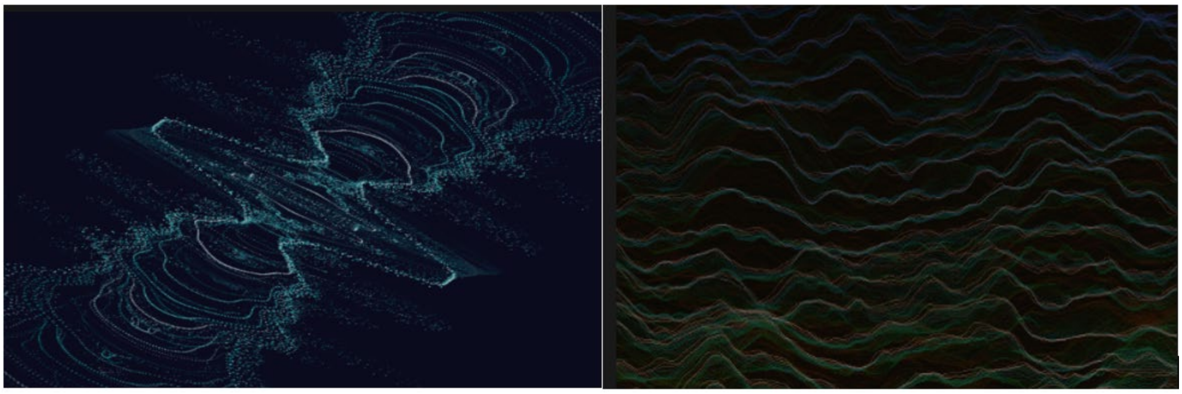

Fig. 4.18 - Processed Spectrogram Analysis (author: Mo Fangshuo)[301]

Through analysis and processing, we can create an intuitive visual interface that can intuitively represent the amplitude, frequency, timbre, warmth, clarity, and other aspects of the sound in real-time. Knowing that sound and music influence human behavior, it is interesting to see this interaction within a responsive environment.

The data collected by the acoustic sensors and the somatosensory data captured by the Kinect can be interlaced into a design algorithm that would generate a variety of immersive visualizations within the interactive spaces, emphasizing the integration of the viewer and the performer, thus creating a different audio-visual space experience.

Fig. 4.19 - Interaction within the audio-visual space ((author: Mo Fangshuo))[302]

[301] Mo, Yuan, and Zhao, 'Sound Visualization'.

[302] Mo, Yuan, and Zhao, 'Sound Visualization'.

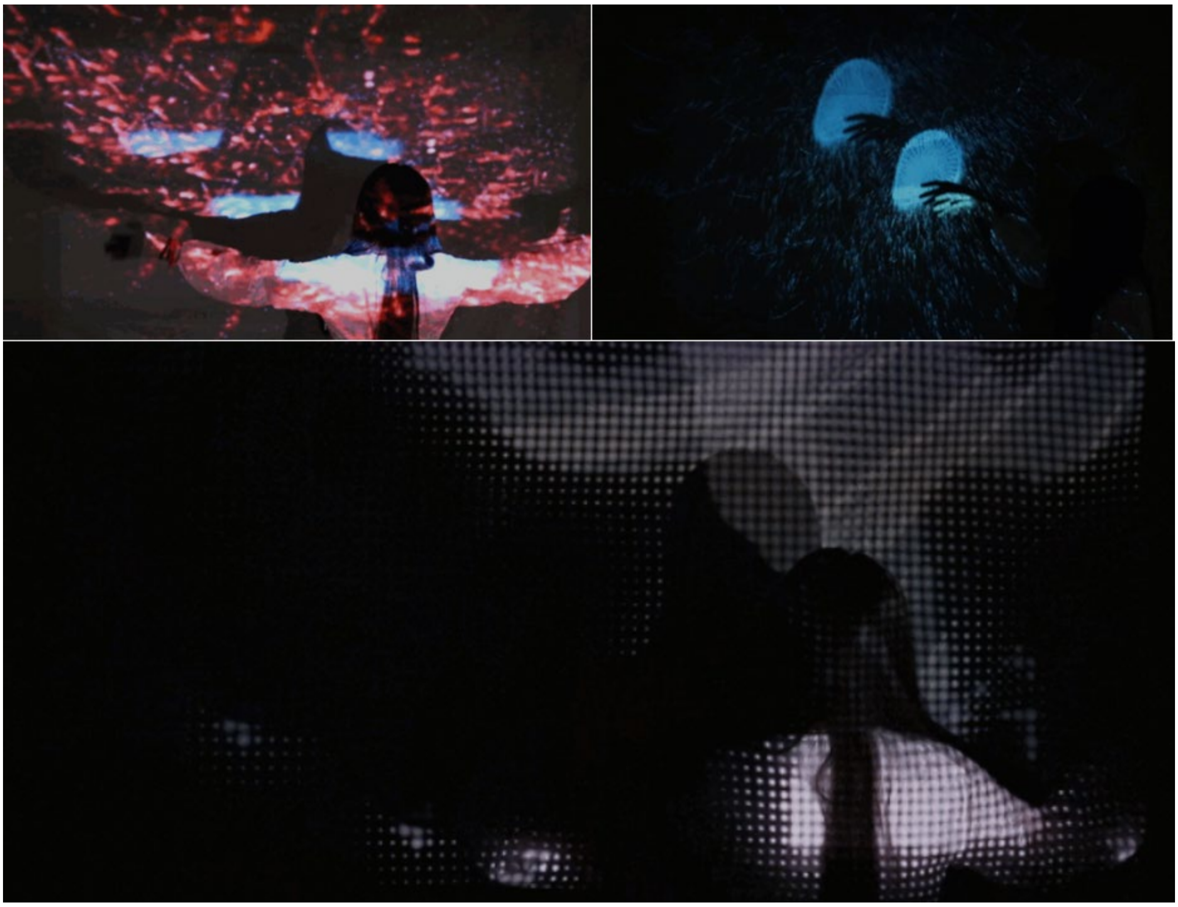

Fig. 4.20 - Variations of responsiveness (author: Mo Fangshuo)[303]

In the digital age, using data and programming languages that can transform intangible feelings into tangible and visible experiences, defines advanced technological prostheses that can expand the users' sensory perceptions.

[303] Mo, Yuan, and Zhao, 'Sound Visualization'.

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Procedural Architecture

5. Procedural Architecture

Form generating algorithms pose a controversial approach regarding the legitimacy of architectural design and approach, making people question the relationships between form and function alongside constructions systems and aesthetics, costs, user needs, and so on. Recently the software and technological advances have pushed us to develop an array of computational form-finding tools and techniques through which architectural and design production have been revolutionized.

These procedures can be encountered under the terms such as “parametric design”, “generative design” or “algorithmic modeling”. These have been enabling architects to develop computational generated complexities and develop new topologies out of the favor of the classical relationships between form and representation. This emphasis shift was defined by Branko Kolarevic as “form-finding” as a derivate of “form making”.

Today's designs are fairly sophisticated, necessitating multidisciplinary collaboration between separate domains of architecture, engineering, and computation in a cohesive system. As a result, a step-by-step approach that allows numerous disciplines to collaborate at various stages of a project, facilitating efficient and productive workflow and adding to the research and project's knowledge database, had to be developed. The main objective is to diminish the gap amid architecture and technology in relation to the design processes, methodology, and workflow for projects of all sizes and disciplines.

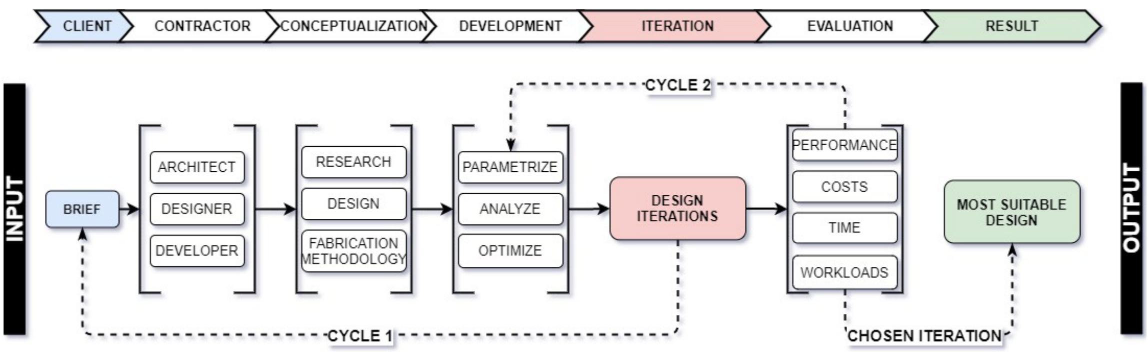

Fig. 5.1 - Procedural Architecture Workflow (image by author)

The main benefit of working through procedural architecture applications is that we enable the possibility of generative design that can be adapted and applied to about any project that we see fit.

5.1. Procedural Modeling

One of the most fundamental concerns in architectural education and practice is how to generate morphologies. The link connecting form and function, construction systems and aesthetics, edifice and context, user needs, and building costs, in all its permutations, is typically accompanied by discussions over the validity of architectural production.

Computational technologies have revolutionized architecture design and production in recent years by introducing novel form-finding approaches, giving architects additional design options by parting with traditional form-representation relationships in exchange for computationally generated complexity, allowing for the creation of new topologies.[304] These techniques shift the focus away from "form-making" and toward "form-finding".

Such design techniques, according to critics, isolate the architectural result from its surroundings and users, resulting in a reduction in spatial quality as well as a building's integration into the urban environment. Furthermore, it was stated that a completely computational method leads to a detachment from physical modelling and drafting processes, which were historically key aspects of architectural education, thus threatening material qualities, effects, and attributes.

Yet, long before the digital revolution, numerous generative form-finding methodologies were used in architecture. Many creative architects, engineers, and designers, including Frederick Kiesler and Frei Otto, had used design processes that were very close to today's computational approach around the end of the twentieth century. In this sense, today's new computational design methodologies appear to be neither as revolutionary nor as difficult to apply without the aid of computational tools. Therefore, should critics of so-called digital

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[304] Branko Kolarevic, *Architecture in the Digital Age: Design and Manufacturing* (Taylor & Francis, 2003), p. 57.

architecture focus on the tools or the design process? The following will attempt to shed some insight on what seems a never-ending dispute.[305]

So, what exactly does "generative design" imply? There are no definitive explanations, but rather a set of complementary definitions that point to a process in which form is generated using a set of rules or algorithms derived from computer software such as "Rhinoceros," "Grasshopper," "Processing," and other scripting platforms.[306]

Generative modeling techniques have grown in popularity, and many designers have adopted procedural modeling research intending to speed up the design process. This method produced well-organized structures that, in many situations, outperform their conventional equivalents by allowing for a greater degree of control and manipulation of the end result.[307]

The advantage of the method can be found in its concise description, which is based on the model's complexity rather than solving problems on a small scale.

The efficiency with which a project is developed is not dependent on its scale in this regard. The clear analogy between its 3D modeling and programming is one of the major aspects of generative modeling. The only shortcoming of this method is that it requires the use of a programming language, which most architects and designers avoid due to the level of intricacy involved.

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[305] Asterios Agkathidis, ‘Generative Design: Form-Finding Techniques in Architecture’, *Form + Technique*, 2016, 161 (p. 9).

[306] Agkathidis, ‘Generative Design: Form-Finding Techniques in Architecture’, p. 14.

[307] T. Ullrich, C. Schinko, and D. W. Fellner, ‘Procedural Modeling in Theory and Practice’, *18th International Conference in Central Europe on Computer Graphics, Visualization and Computer Vision, WSCG 2010 - In Co-Operation with EUROGRAPHICS, Full Papers Proceedings*, 2010, 5–8.

5.2. From Building Information Modelling (BIM) to Building Procedural Modelling (BPM)

5.2.1. Defining the Building Information Modelling

The concept of Building Information Modelling has been coined in the 1970s and was firstly published in a publication by G.A. van Nederveen and F. P. Tolman in 1992.[308]

The BIM has been made to cover more than just geometry, but likewise spatial geographic information, spatial relations, light, and shading analysis, material quantities, and details specific to building components, such as manufacturers' details. Based on these approaches we can assume that the concept represents the designs as a combination of "objects" with certain specific properties.

In terms of information extractions, BIM software offers the possibility of choosing specific views of the models to capture elevations and sections to ease the drawing production while keeping the whole model in sync throughout the workspace. Another benefit of BIM software is that it defines certain objects parametrically, by offering access to the fundamental properties that define them, thus making it easy to adjust them based on your needs. A good example of these objects is windows and doors that are easily defined by introducing the height width alongside other attributes that they might come along with such as numbering and material tracking.[309]

Within big architectural offices, BIM software applications offer a variety of means through which a whole team can work on a single project from different computers based on their specific sections, allowing for concomitant contributions within a single shared model. This eliminates the chances of information loss and provides more extensive information to coordinators of complex projects.

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[308] G. A. van Nederveen and F. P. Tolman, 'Modelling Multiple Views on Buildings', *Automation in Construction*, 1.3 (1992), 215–24 (p. 216) <https://doi.org/10.1016/0926-5805(92)90014-B>.

[309] Wikipedia, 'Building Information Modeling - Wikipedia', 2020 <https://en.wikipedia.org/wiki/Building_information_modeling> [accessed 20 February 2020].

The ease of management and access to information enables BIM platforms to be optimal within the development of green buildings, keeping track of all the important aspects of building performances as well as material provenance and construction efficiency enabling the possibility of data storage and interoperability between design and analysis tools such as solar, shadow and sustainability analysis through universal file extensions such as IFC (Industry Foundation Classes).[310]

The inclusion of energy simulation engines within BIM software helps designers to quickly and accurately calculate energy consumption levels whilst choosing the appropriate materials and keeping track of all requirements in order to eliminate as much waste as possible. The most renowned rating strategies such as LEED, BREAM, and Green Star offer integration possibilities within most BIM software.

Another useful integration that contributes to the growth of green buildings is the implementation of GIS (geographic information system) that can help estimate the progress of construction for every stage while regulating the site preparation procedures. This aids in the simplification of the whole approach alongside maximizing the site use whilst shortening the construction periods.

5.2.2. Defining the BPM (Building Procedural Modelling)

Building Procedural Modeling can be defined as a process to obtain a result through the usage of well-defined steps through which we manipulate digital objects. Procedural modeling is better known as algorithmic aided design.

Within architecture and design, this type of approach became more accessible through visual programming, a way of creating algorithms using script lines under the form of components on a canvas. This software was developed by David

[310] Jill Fehrenbacher and Autodesk, 'How Building Information Modeling (BIM) Helps Buildings Go Green', *Autodesk - Accelerating Better Design*, 2011 <https://inhabitat.com/building-information-modeling/> [accessed 11 February 2020].

Rutten at Robert McNeel & Associates, a company that specializes in 3D modelling software programs.[311]

5.2.3. Algorithmic Modelling in Rhino and Grasshopper

An algorithm is a procedure used to perform a particular task through a list of well-defined instructions. Based on human abilities to split problems into simple steps to process them easily, the algorithms are designed the same way. A fairly good example of how it works is to compare it with a cooking recipe; you mix the ingredients, put them in a pan, cook them, plate them and serve them.

Obviously, each step needs to be well defined, have a precise list of components that go "in the mix" and have a precise set of instructions, in order to form a proper algorithm. Also, the inputs could be different for type and quantity, each component requiring a specific value for a specific task.[312]

Algorithms can be categorized within different classes such as computation procedure algorithms (an algorithm that leads to a number), decision procedure algorithms (an algorithm that generates a true or false statement), geometric algorithms (an algorithm that leads to a geometric form), etc.

Within algorithmic modelling, objects are no longer manipulated through a mouse or keyboard; instead, they are defined by procedures expressed in the embedded editors provided by the software program (Grasshopper, RhinoScript, AutoLisp, etc.) or other cross platforms (Python). These approaches are often referred to as scripting, which contains two working environments, the editor and the 3D modelling environment. The final result is not just an output of a 3D model but also an interactive digital model corresponding to the values of the inputs, offering flexibility throughout the entire system.

> *"A process is more important than the outcome. When the outcome drives the process, we will only ever go to where we've*

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[311] Arturo Tedeschi, 'Intervista a David Rutten', *MixExperience Tools 1* (Naples, February 2011), pp. 28–29.

[312] Arturo Tedeschi, *AAD Algorithms-Aided Design: Parametric Strategies Using Grasshopper*, *Le Penseur Publisher*, 2014, p. 23 <http://www.arturotedeschi.com/wordpress/?page_id=6691>.

already been. If the process drives the outcome, we may not know where we're going, but we will know we want to be there." (Bruce Mau)[313]

Mau describes the concept of algorithmic design as offering the capability to generate and also control design-complexity beyond human capabilities. Algorithmic design allows designers to develop new solutions and bypass the limitation of traditional CAD and 3D software programs.

Lately, many software producers have developed visual tools in order to make scripting more accessible and user-friendly for users that are unfamiliar with programming skills. Due to this approach, associative rules and components were integrated into a graphical method based on node diagrams.[314]

Visual scripting, as well as regular scripting, is based on two working environments, a visual editor and a 3D modelling environment. Having two environments, the process generates two outputs: the parametric diagram (also known as node diagram or visual algorithm) and a parametric 2D or 3D geometry.[315]

5.3. Computational Evaluation

The general area's various environmental and climatic features are represented by inconstant parameters, whereas those regarding interior comfort in constructions are relatively static.

As a result, we use a lot of energy to cool, heat, ventilate and light our structures within fairly clear boundaries, while external environmental variables can change dramatically. Current solutions to these issues typically feature a static edifice shell and dynamic building services. As a result, traditional façade designs are not intended to respond optimally to contextual challenges and demands.

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[313] Tedeschi, *AAD Algorithms-Aided Design: Parametric Strategies Using Grasshopper*, p. 25.

[314] Tedeschi, *AAD Algorithms-Aided Design: Parametric Strategies Using Grasshopper*, p. 27.

[315] Tedeschi, *AAD Algorithms-Aided Design: Parametric Strategies Using Grasshopper*, p. 35.

The way we approach the design process massively influences the outcome of building performance. Approaching the solutions by using the environment as the first step would imply identifying the critical factors that would influence the building performance and aspect, thus highly increasing the accuracy of the final variant of the edifice from the early stages of design.[316]

5.3.1. Rhino & Grasshopper Medium - Ladybug Tools

The Ladybug Tools represents a collection of software applications, under the form of a plugin for Rhino's Grasshopper software, that supports environmental design and education. Its specific trait is that out of the most available environmental design software applications it is the most complete, connecting 3D interfaces to a mass of authenticated simulation engines such as EnergyPlus, Radiance, OpenFOAM, OpenStudio, and Therm.

One of the main characteristics of this plugin is the fact that it is available for free and also open-source (the only one out of the bunch), allowing everyone in the community to benefit from it as well as contribute to the project. Through the modular components of the Ladybug Tools, a high rate of flexibility is achieved across all the stages of the design.[317]

Being built specifically for Grasshopper implies the parametric visual scripting interfaces which enable the evaluation of highly complex structures, offering ease of exploration as well as automating certain tasks through 3D graphics, animations, and data visualizations. If the designer has experience within Python scripting, he can easily customize the plugin components since the source codes are available.

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[316] Mostapha Sadeghipour Roudsari and Michelle Pak, 'Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design', *Proceedings of BS 2013: 13th Conference of the International Building Performance Simulation Association*, 2013, 3128–35 (p. 3128).

[317] Roudsari and Pak, 'Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design', p. 3134.

The main applications within the Ladybug Tools are:

- "Ladybug", which executes comprehensive analysis based on climate data to generate personalized and interactive visualizations for a development that is environmentally-informed.
- "Honeybee", an approach towards creating and visualizing daylight simulations through the use of Radiance, generating energy models using OpenStudio, as well as thermal envelope heat flow evaluations using Therm.
- "Butterfly", takes the form of a plugin that helps the designer to generate advanced computational fluid dynamic (CFD) simulations through the use of OpenFOAM
- "Dragonfly", the latest contribution to the array, analyses, models, and estimates scenarios best on large-scale climate phenomena, for example, urban heat-island analysis, possible upcoming climatic changes, and the impact of the local climate factors. [318]

The foremost application is the one that we use for our applications in this thesis application since it is meant to use the very thing we are looking for, EnergyPlus Weather files (*.epw), which contains hourly recorded weather data. With this information, the plugin delivers 2D and 3D interactive weather graphics that aid the design process during its early stages. During the course of project developments, Ladybug can support assessments of solar radiation studies, sunlight-hour modeling, and many other functions, and with the integration, through a visual programming environment, the user gets instant feedback on design adjustments along with a high grade of customization.

5.3.2. Some of Ladybug's most valuable characteristics include:

- Climate Data Plots through a variety of 2d and 3d charts.
- Sun Path Graphics using variable diagrams.
- Shadow Studies

[318] Roudsari, 'Ladybug Tools | Home Page'.

- Solar Fan and Envelope to figure out how the volume can be developed while still allowing for solar access.
- Radiation Studies, which enable us to quantify the sun energy incident on our geometry.
- Conducting View Studies to ascertain the visual connection to the outdoors.
- Psychrometric Charts that allow us to adjust our graphics for thermal comfort.
- Adaptive Comfort Charts for evaluating our passive designs' thermal comfort.
- Outdoor Thermal Comfort analyses that take into account heat exchange with the sky
- Local Thermal Comfort features that simulate radiant asymmetry and discomfort caused by downdrafts, among other things.
- Shade Benefit Analysis that enables us to visualize which shaded patches are more beneficial or detrimental to thermal comfort.
- Shadow Masks that help us to observe areas of the sky obscured by hues and context.
- A renewable energy study that calculates the amount of energy generated by photovoltaics and solar hot water. [319]

5.3.3. Existing limitation: Data-Design Disconnection

For several years, the attempt to construct a unique platform for design and simulation at various phases of the design process was a persistent focus of development. According to a recent study, designers and architects agreed that integrating analytic tools within the design application facilitated the environmental design process.[320]

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[319] Roudsari, 'Ladybug Tools | Ladybug'.

[320] Lieve Weytjens, Vincent Macris, and G. Verbeeck, 'User Preferences for a Simple Energy Design Tool: Capturing Information through Focus Groups with Architects', in *28th International PLEA Conference on Sustainable Architecture Urban Design: Opportunities, Limits and Needs - Towards an Environmentally Responsible Architecture \ PLEA 2012*, 2012.

Numerous platforms for simulation and design not just slow down the process, but also pose interoperability concerns, such as the usage of numerous models and interfaces. Other challenges include unfamiliar working methods for developing simulation software, complexity in geometry development, and demanding input data. Because of this, several modeling systems try to combine conceptual massing and environmental analysis into a single platform, such as Vasari by Autodesk, which merges conceptual massing and environmental analysis. However, being a Revit-based application, the production of sophisticated geometry is constrained, and data representation is limited to the software parameters. In addition, Revit has taken measures to incorporate conceptual massing components within its existing architecture. However, like with Vasari, modeling complex geometry has limitations, and the program is often not utilized for advanced form investigations.[321]

Designing large-scale projects, such as master plans, have constraints as well. Furthermore, incorporating environmental simulation into architectural designs requires an integrative graphical visualization result. The outcomes are normally delivered in the form of reports and/or spreadsheets, apart from daylighting and radiation studies, which frequently overlay the data onto the geometry.

Whereas simulation professionals may easily understand this type of information, it typically does not appeal to the graphic character of a designer's train of thought. The format of data presentation is determined by application settings that cannot be modified for the majority of characteristics. Therefore, with the exclusion of a few applications, simulation data can’t be employed to produce subsequent design iterations. [322]

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[321] Brady Peters and Terri Peters, ‘Computing the Environment: Digital Design Tools for Simulation and Visualisation of Sustainable Architecture’, *AD Smart*, 6 (2018), 68–70 (pp. 76–77).

[322] Roudsari and Pak, ‘Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design’, p. 3129.

5.3.4. Ladybug's Approach: Design and Analysis Integration in a Parametric Environment

Parametric modeling tools, which were brought to the architectural community quite recently, introduced a new method for modeling and design. By definition, parametric modeling is data-driven, enabling connections and changes across various layers of information to be immediate.

This system offers numerous advantages for merging design and analysis, enabling designers to establish a clear bridge amid data analysis and design by being able to overlay environmental data analysis throughout the design platform. Building features developed from the reference geometry are retained as levels of the base data within the Grasshopper parametric platform. Once the reference geometry that is suited for environmental analysis is optimized, the parametrically related features automatically update.

Thus, only one model is being used for both the design as well as the analysis, allowing for an extra fluidity, integrated and efficient approach. Meaningful data visualization can help designers make better design decisions, in which sophisticated studies can be applied during the design development phase to improve conceptual environmentally-conscious design strategies.

5.3.5. Ladybug Applications

a. Weather Data Visualization and Analysis

To interpret any data, it is important to have means of visualizing it. The 3D chart is a component that could be used to create a line chart of any data within the Rhino scene. A colored mesh is created as a 3D plot of the input data.

For several input data streams or graph scales, multiple meshes will be generated. The 3D chart component can also be projected onto a plane offering a simple 2D view. [323]

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[323] Mostapha Sadeghipour Roudsari, '3D_Chart · Ladybug Primer' <https://mostapharoudsari.gitbooks.io/ladybug-primer/content/text/components/3D_Chart.html> [accessed 11 June 2018].

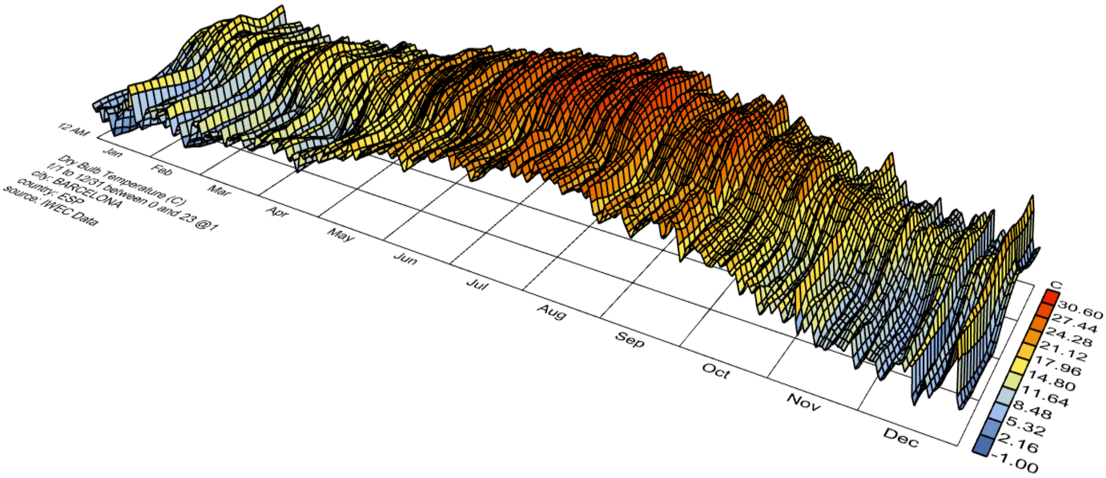

Fig. 5.2 - a 3D Plot generated based on the annual temperature in Barcelona (image by Author)

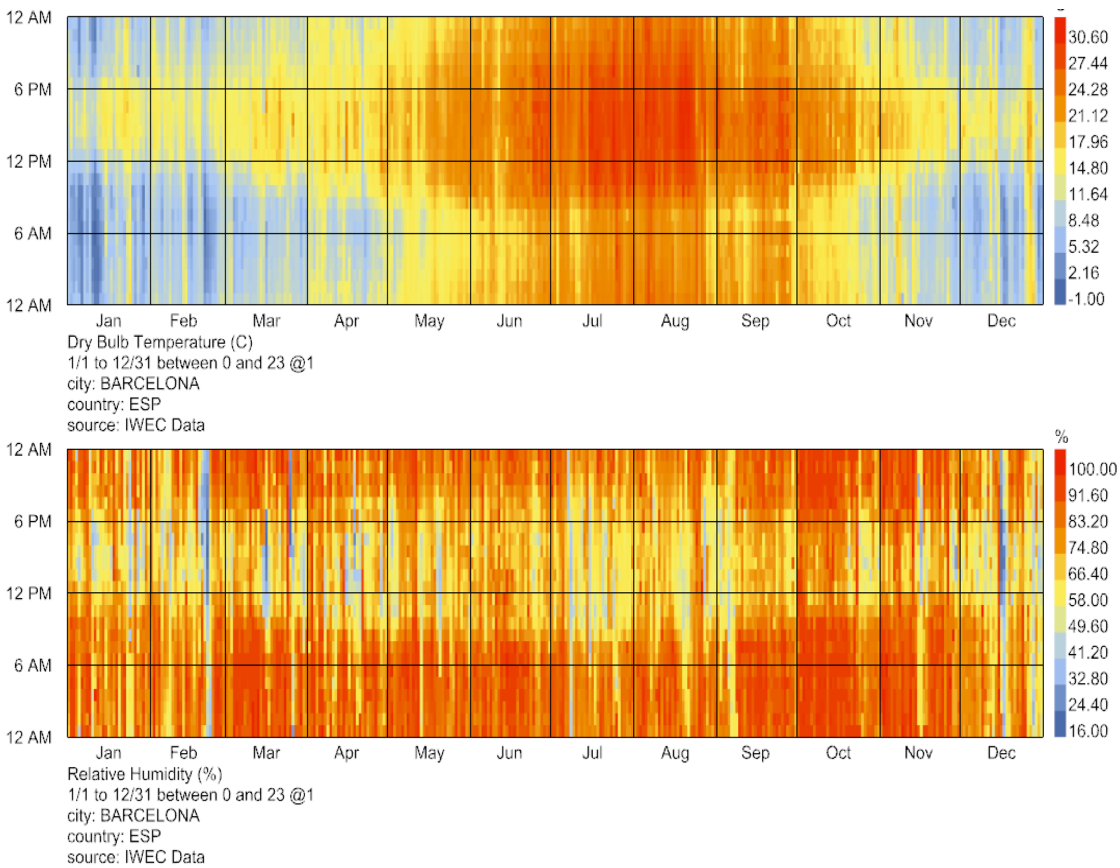

Fig. 5.3 - 2D plot of the Relative Humidity and Dry Bulb Temperature data throughout the year for Barcelona (Image by Author)

The grasshopper definition for this application can be found in Appendix C.1.

b. Wind rose

The wind rose is a graphical representation that meteorologists use to offer an understanding of the typical distribution of wind speed and direction at a certain place. Each wedge in the rose graph reflects the percentage of time throughout the analysis period in which the wind came from, and it is colored as well (corresponding to the legend on the right), expressing the frequency and speed of the wind. The chart can be customized with any other data besides the wind direction, such as relative humidity or temperature. This method anticipates how the weather feels in windy conditions.

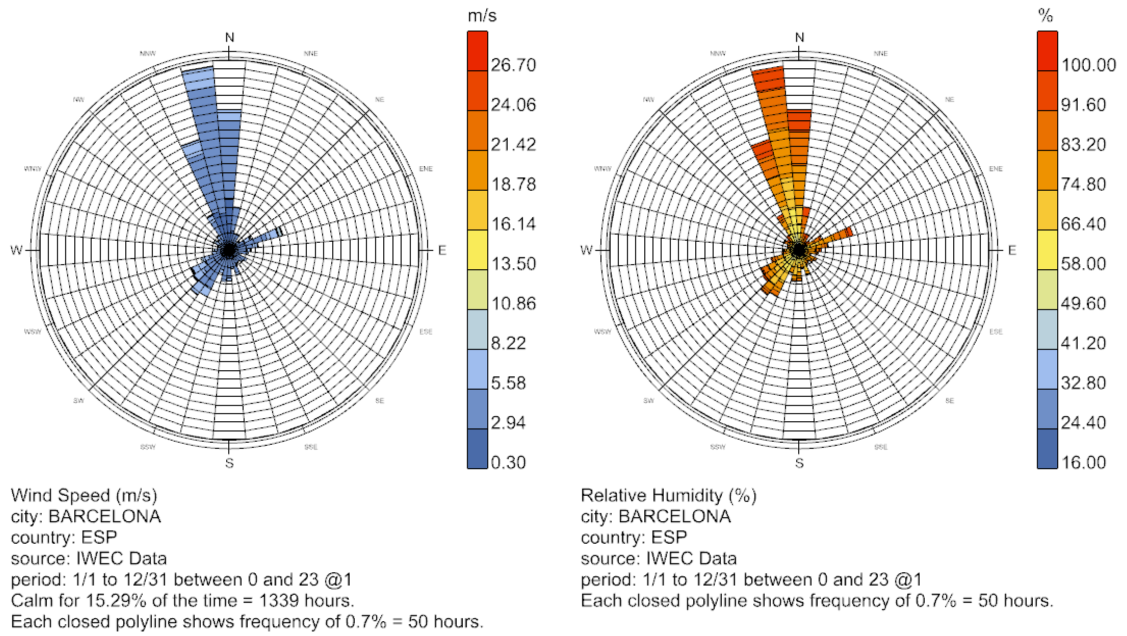

Fig. 5.4 - Windrose comparison showing wind speed (left) and relative humidity (right) [324]

The grasshopper definition for this application can be found in Appendix C.1.2.

c. Radiation Studies

Radiation is a critical aspect to consider when determining the thermal comfort of occupants in addition to the structures' energy consumption. Despite the fact that the amount of radiation received by a surface is directly proportional to its orientation and vertical angle, many visualization approaches ignore this correlation. Radiation data is typically presented as tabulated 2D graphs that are

[324] Image by Author

averaged weekly or monthly, or 3D graphs that solely display the amount of radiation for a single time period. To address this issue, Ladybug offers distinct radiation diagrams such as the Sky Dome and the Radiation Rose.

The “Sky Dome” enables us to envision a dedicated sky matrix so as to see regions of the sky from which radiation is originating. By default, the component generates three variations: one that shows total radiation, one that shows only direct radiation, and one that shows only diffuse radiation.[325]

The plug-in computes the quantity of radiation for various Skydome patches and colors them based on the results, thus the graphic provides the viewer with a general view of the sky state. The user can visualize the sky dome at any time of year by selecting a season. There are three ways to display the dome: a 3D Hemisphere, an orthographic projection, and a stereographic projection, both in a 2D plane.

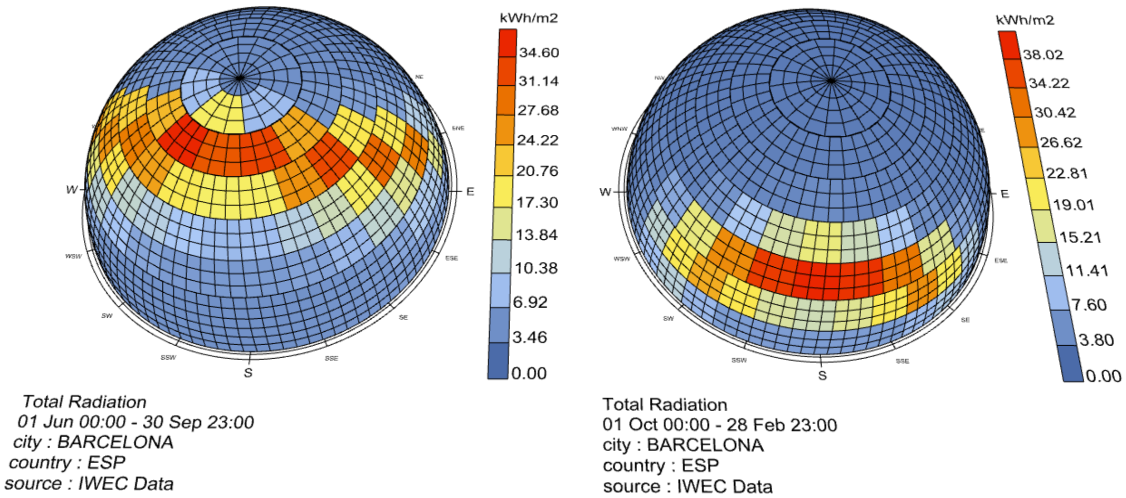

Fig. 5.5 - Sky condition for Barcelona during the months of June to September (known as a cooling period) against the months of November to February (Heating Period) – Image by Author

The grasshopper definition for this application can be found in Appendix C.1.3a.

325 Mostapha Sadeghipour Roudsari, ‘Sky_Dome · Ladybug Primer’ <https://mostapharoudsari.gitbooks.io/ladybug-primer/content/text/components/Sky_Dome.html> [accessed 11 June 2018].

Radiation roses show how much radiation comes from each cardinal direction, which can help determine where glazing should be avoided, shade should be provided, or solar panels should be installed.[326]

The Radiation-Rose ("radRose" component) is a graph similar to the wind-rose that depicts the magnitude of radiation emitted from various angles (horizontal directions). The user can alter the vertical angle of the surfaces as well as the time range. Unfortunately, the Radiation Rose is only available in the legacy variant of the Ladybug plug-in.

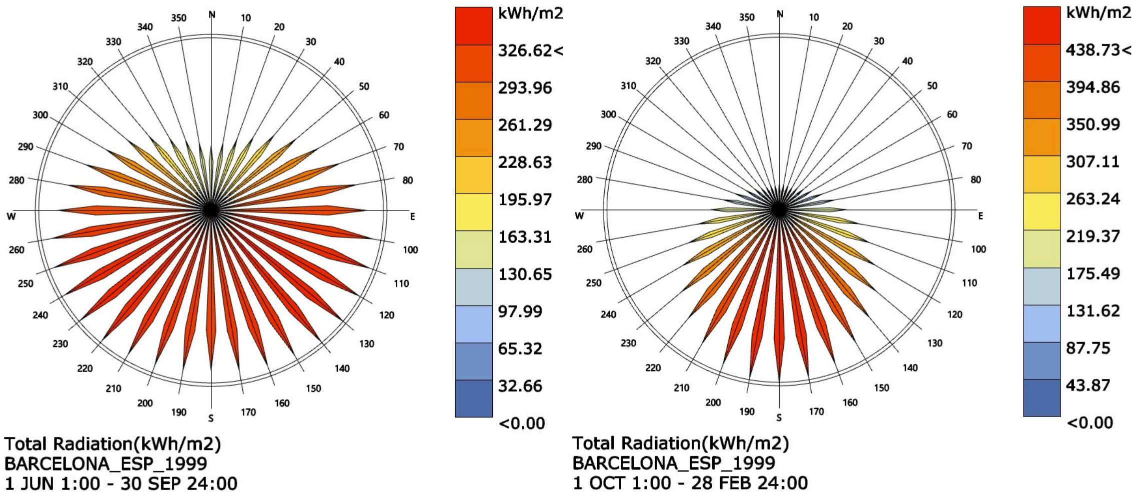

Fig. 5.6 - Radiation rose Showing the difference between the cooling Period and the Heating Period in Barcelona

The grasshopper definition for this application can be found in Appendix C.1.3b.

The Radiation Analysis (identified as Incident Radiation within the plug-in) allows you to calculate the radiation falling on a selected geometry. This form of radiation analysis is beneficial for building surfaces such as glazing, where solar heat gain is a concern, or solar panels, where the amount of energy gathered has to be taken into consideration. This approach is also useful for surfaces that depict outside environments (such as parks or seating areas), where radiation may have an impact on thermal comfort or vegetation growth.

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[326] Mostapha Sadeghipour Roudsari, 'Radiation_Rose · Ladybug Primer' <https://mostapharoudsari.gitbooks.io/ladybug-primer/content/text/components/Radiation_Rose.html> [accessed 11 June 2018].

This analysis does not account for sunlight reflection in the radiation study; hence it should not be utilized for indoor daylight studies, complex geometries, or materials with high reflectivity.

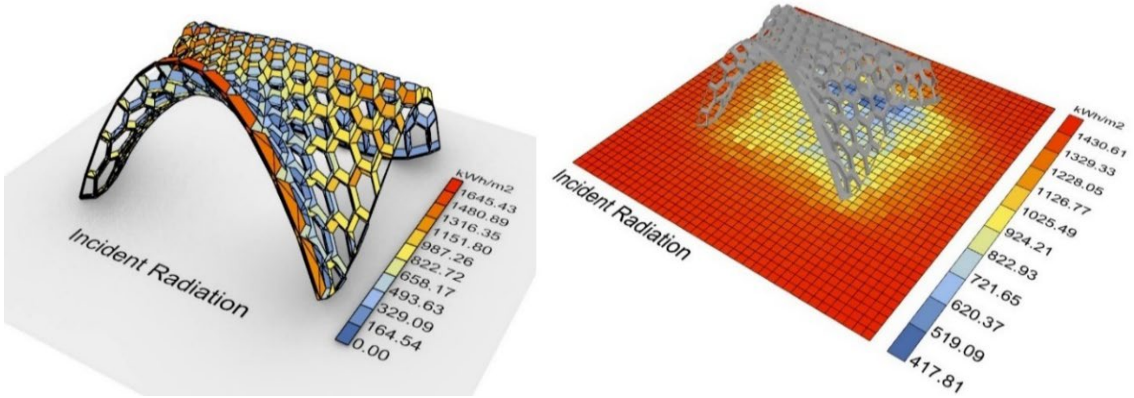

Fig. 5.7 - Incident Radiation comparison between the surfaces of a pavilion and the ground underneath (Image by Author)

The grasshopper definition for this application can be found in Appendix C.1.3c.

d. Illumination Studies

The sun-path component is one of the most important and instructive diagrams for environmental analysis that has been used for numerous years, yet it is mostly represented as a self-contained visual. Ladybug creates a link between both the sun-path and hourly weather data by allowing the operator to overlap them for a clearer understanding of any given situation.

Furthermore, this study enables us to filter the sun locations for the overlaid data based on any desired criteria. The user can, for example, trace the sun's path for certain hourly intervals of the year when the temperatures are above 24°C, and at the same time, when the direct horizontal radiation is greater than 600 Wh/m^2 (Fig. 5.8). As an example, this feature can make the process of shading design easier and faster. A typical strategy would be to:

- Determine the cutting days using temperature, heating, cooling degree, or any other shading design index.
- Determine the sun's position for the cutting days.
- Determine the horizontal and vertical shadow angles.
- Figure out the shading geometry.

By merging the first three processes stated above, the sun-path component in Ladybug speeds up the process by simply connecting the hourly data and constructing a conditional statement.

The output of the sun-path component is the generated sun-vectors that can be used to create shading morphologies in Grasshopper. Because the type of hourly data input is unrestricted, the user can experiment with a variety of shading possibilities based on various approaches. [327]

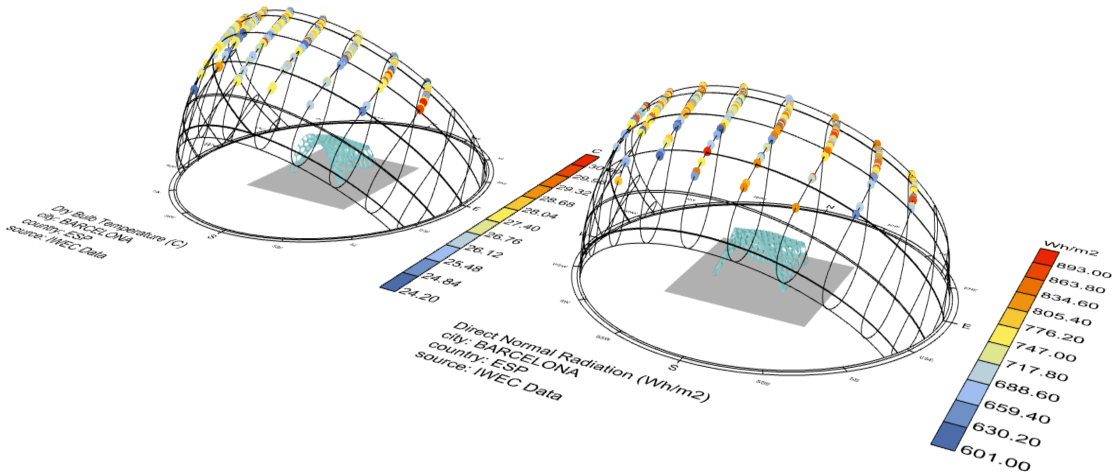

Fig. 5.8 - Sun path Analysis showing the sun positions and the corresponding data - dry bulb temperature in the left and direct normal radiation in the right (Image by Author)

The grasshopper definition for this application can be found in Appendix C.1.4a.

Using the sun path, we can also calculate the amount of direct sun hours we have on a certain geometry. This analysis could be used to measure how many hours of direct light vegetation receives in a park or when the direct sunlight may render some areas pleasant or uneasy. In the Rhino scene, it can also be employed for coarsely-gridded shadow analyses.

[327] Roudsari and Pak, 'Ladybug: A Parametric Environmental Plugin for Grasshopper to Help Designers Create an Environmentally-Conscious Design'.

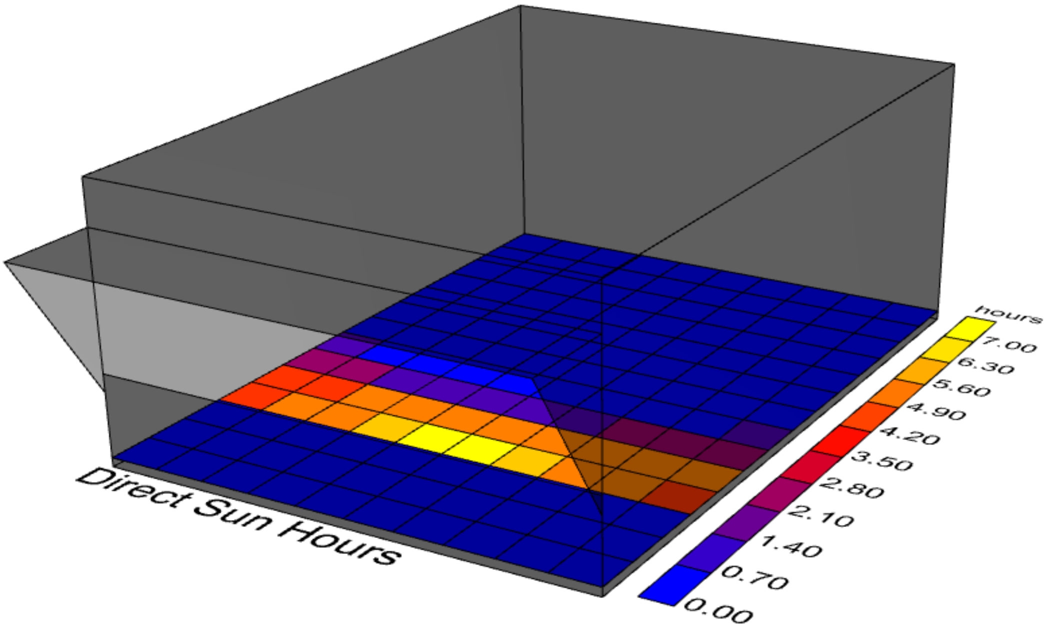

Fig. 5.9 - Example of the amount of direct sunlight passes through a window upon the floor (Image by Author)

The grasshopper definition for this application can be found in Appendix C.1.4b.

e. Orientation Studies

Multi-Objective optimization ought to be employed to discover the best solar orientation. These are some of the major benefits of developing in Grasshopper or Rhino, having the potential to benefit a number of other projects in the community. Galapagos, for example, is a Grasshopper multiple-goal evolutionary algorithm, in which users may quickly set up and run a multi-objective performance form optimization by combining it with Ladybug. Even recently, it could take a great amount of programming to connect different platforms in order to undertake a performance-driven optimization study.

A good example of form optimization would be to increase sun radiation during winter (heating period) and limit it during summer (cooling period). The user can study the various options and select the best trade-off. Because optimization studies generally involve several simulations, Ladybug was designed to benefit from many CPUs executing the analyses, allowing intensive studies to be completed in a reasonable amount of time.

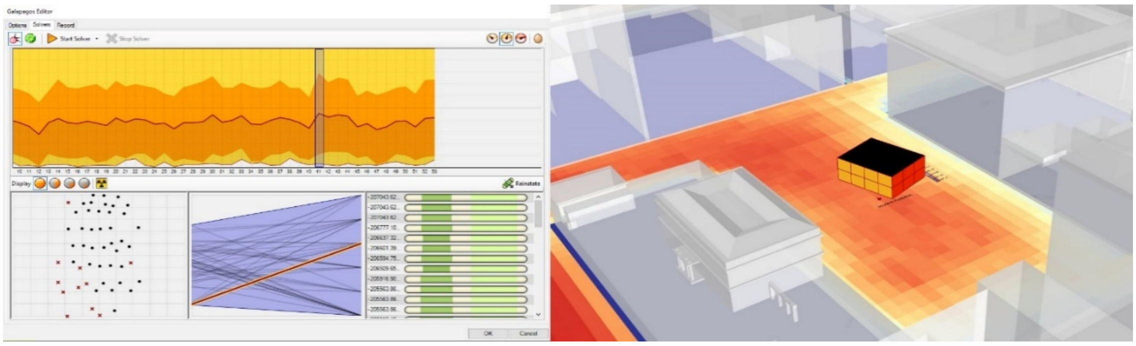

Fig. 5.10 - Galapagos Interface (left) and Mass Orientation Optimization (right) – Image by Author

The grasshopper definition for this application can be found in Appendix C.1.5.

In the shown exercise we placed the generic mass on the site and optimized its orientation and size based on the amount of beneficial irradiance hitting its sides. The geometry rotates around a set axis and changes its width depending on the recorded irradiance. The size optimization is based on a defined total surface area (the total area of the ground floor) and the length of the entire shape. If the length changes, the width will be adjusted to maintain the total surface area initially set. Galapagos ran a total of 50 iterations showcasing the best possible outcomes.

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Informational Prototyping

6. Informational Prototyping

Within the 1800s, Immanuel Kant claimed that “we can never have access to the unfiltered thing-in-itself of objective reality”.[328] This points out the fact that the way we experience the surrounding environment heavily depends on our perception and past recorded interactions. Because of this, we can easily observe situations when our senses are limited and easily deceived, especially when analyzing elements with and without their context.

Another good example of this can be observed within the perception of color, where our brain interprets the result differently based on the context in which they are placed. Based on these premises we can deduce that our perception is basically a construction of the brain.[329]

Instead of relying heavily on information going towards the mind from the outer world, perception relies equally, if not more, on intuitive predictions streaming the other way around. This is because we do not merely or passively observe the world, we actively create it. What we envision on the inside shapes the world we live in just as much as what we see on the outside. [330]

One way of equalizing the perception of information is to simplify it through means that will always offer the same type of result, scalable and comparable. In this sense, we can use all our gathered ideas and information from the previous chapters and bring them to a quantifiable state that is easy to interpret. One way to do so is to digitalize everything within a computational framework through the means of electronics and robotics.

The field of robotics has been of keen interest in architecture ever since systems theory and cybernetics became popular in the 1960s and 1970s. These practices

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[328] Beau Lotto, *Deviate: The Science of Seeing Differently*, *Journal of Chemical Information and Modeling*, 1st edn (New York: Hachette Books, 2017), LIII, p. 13.

[329] Colin Ware, *Information Visualization / Perception for Design*, *Interactive Technologies*, 3 edition (Morgan Kaufmann, 2013), pp. 96–98.

[330] Anil Seth, *30-Second Brain : The 50 Most Mind-Blowing Ideas in Neuroscience, Each Explained in Half a Minute*, ed. by Anil Seth (Sterling, 2014), p. 33.

quickly advanced to computational and digital methodologies that are now definitely implemented, both in theory and practice, within the architectural field.[331]

The human brain's ability to perceive and comprehend everything around us is limited. However, as new advancements occur, these limitations have been repeatedly stretched, therefore our "perception bubble" has continued to expand. Anything outside of this perception bubble is considered to be complex. The way people perceive things differs from person to person, therefore the level of complexity is unique for everybody. Decrypting this complexity either stretches the limitations of human perception or streamlines it for human comprehension. Systems that exist outside of this bubble and are difficult to comprehend or decode are defined as super-complex, and can be characterized as systems (or wholes) made up of numerous complex systems that interact and operate at different scales. When seen on a micro-scale, each component might be considered complex in and of itself.[332]

This is where our ability to perceive things comes into effect. It's all about zooming in and out to comprehend systems and classifying them as simple, complex, or super-complex. In an urban situation, for instance, the system can be classified as a complex, with emergent behavior, if it is analyzed in terms of many layers: such as people (agents), infrastructure, and the physical environment, alongside the interplay between these three components. From the same circumstance, if the interactions between individual city agents, sub-layers of infrastructure, and individual-built elements are accounted for, the system is regarded as a super-complex, and emerging behavior characteristics change dramatically. [333]

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[331] Akshay Goyal, *ROBOTIC FIELD LANDSCAPES*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013) <https://doi.org/10.1017/CBO9781107415324.004>.

[332] Verma, *SUPER-COMPLEXITY CONTROL*, p. 97.

[333] Verma, *SUPER-COMPLEXITY CONTROL*, p. 98.

This basically would become a question of human perception boundaries. The goal is to break down the complexities into basic bits that fit within the human perceptual bubble.

6.1. Defining the Informational Prototyping

The term of Informational Prototyping resumes the practices of robotics implementation within a concentrated area of sensor and data collection that would be especially used in relation with interactive architectural design development, having the type of sensor used as an indicator that dictates the target within the spectrum of the concept that would be followed.

A good methodology of approaching sensor usage would be that used within the "Landscape Urbanism" programs, developed by the Architectural Association in London, that implies a structure made of three steps: Indexing, Meshing, and Prototyping.[334] Based on these approaches we can reduce the scale of the Landscape Urbanism approach, to a smaller variant that would involve only the building site and its surroundings.

Indexing would be the tool through which we would be able to read and analyze the hidden data available on the destined site and its afferent surroundings. Being inspired by the process of mapping, the indexing process is an intentional reading that would be defined by a design-oriented focus instead of focusing on space descriptions. The method helps us uncover complex relationships between physical aspects (such as the surrounding building influence on the microclimate of the site) and non-physical ones (such as an economical approach relying on that microclimate) that would help establish parameters that will influence and define the final design. The procedural modeling approach is perfectly suited for this process, enabling synchronized integration of multiple layers of data within a quantifiable system.[335]

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[334] Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, p. 43.

[335] Ruberto, *MATERIAL TACTICS: COMPUTATIONAL TECHNIQUES FOR A TACTICAL RESISTANCE*, p. 44.

The technique of Meshing would be the process through which we can define the future edifice's geometrical boundaries and its efficiency functions, based on the indexed data. This will allow the development of specific aspects by taking into account an overall formal and functional consistency.

The final process would be that of Prototyping, which is composed of a system that connects the multitude of spatial configurations to their actuating counterparts for the purpose of achieving the desired result. The prototypical approach could be enabled through a computational plugin for Grasshopper, named "Firefly", that allows us to test different solutions by visualizing, evaluating, and adjusting the design.

The firefly plug-in expands geometrical control outside the virtual procedural model into the physical world, through electronics and mechanisms. Firefly also allows information to flow in the opposite direction, permitting virtual building representations to be influenced by, and interact with real-world data.[336]

This approach is categorized as "Interactive Prototyping". The normal design process for interactive prototypes frequently necessitates the use of many software tools and computer languages, as well as a wide range of highly specialized skill sets. A new integrated approach to design and prototyping was clearly necessary. Thus, the Firefly plugin emerged as a visually focused "Interactive Prototyping Environment".[337]

This toolkit enables the user to manage digital prototypes through real-time data (building 'live models' where parameters may be iteratively evaluated until a desirable range of outputs is attained). Firefly closes the information feedback loop by enabling designers to send data from Grasshopper back to hardware devices to trigger real-world actions (controlling motors, LEDs, valves, etc.). It uses Grasshopper's medium to provide a new framework for microcontroller programming, rendering it perfect for visually oriented professions like architects

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[336] O'Payne and Johnson, 'FireFly: Interactive Prototypes for Architectural Design', p. 144.

[337] O'Payne and Johnson, 'FireFly: Interactive Prototypes for Architectural Design', p. 147.

and designers that prefer generating scripts by manipulating things graphically instead of textually.[338]

Fig. 6.1 depicts a double-skin facade installation; additional design changes featured prototypes for both a single-skin ventilation system, as well as a roof outlet. While the initial design objective was for these prototypes to be completely self-regulating, they may now respond to various environmental stimuli (light, movement, wind) when linked to other sensors via Firefly's IPE.[339]

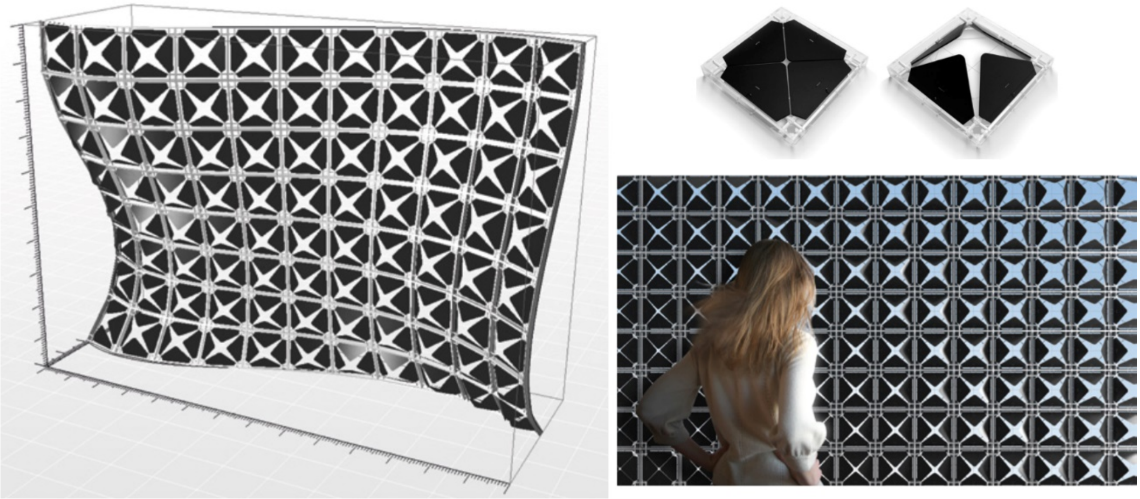

Fig. 6.1 - A double-skin facade application, prototyped using Firefly (image authors: Andrew O'Payne)[340]

6.2. Immersive Technologies

Geometric shape, mass customization, and performative computational analysis together gave rise to innovative envelope designs as well as the genesis of unique iconic façade manifestations such as the ones developed by Frank Gehry and Zaha Hadid.[341]

Architects embraced the computer not only as a tool for design and analysis but also as a critical component of architectural theory and practice as a whole. This

[338] O'Payne and Johnson, 'FireFly: Interactive Prototypes for Architectural Design', p. 47.

[339] O'Payne and Johnson, 'FireFly: Interactive Prototypes for Architectural Design', p. 145.

[340] O'Payne and Johnson, 'FireFly: Interactive Prototypes for Architectural Design', pp. 144–45.

[341] Bianconi and Filippucci, *Digital Wood Design: Innovative Techniques of Representation in Architectural Design*, p. 223.

enables them to significantly integrate architectural education with a renewed emphasis on both the building envelope, as well as interior ambiance, as the destination of innovation and conceptual interaction.

As we enter a new technological era characterized by immersive and omnipresent computing, how will this new batch of available digital tools (specifically mixed reality technologies that include both virtual reality and augmented reality) re-inform the development design process and product?

Traditional representations, such as drawings, renderings, physical models, and animations, are all being replaced by technologies with the potential to replace them, especially in terms of production. Interactive design, simulation, analysis, and construction are more easily managed when both virtual and physical worlds are integrated.

To illustrate, examples could be encountered within several domains within the architectural realm, spreading from research-conducted applications, art manifestations, all the way to interactive teaching exercises done in the classroom.

6.2.1. Immersive Environments

As previously presented within chapter 4.4.4 (Adaptivity within interior environments) immersive environments could be represented as an effective form of adaptation, by projecting the inhabitant within a specific setting that would account for his needs. In this sense, immersive environments represent the overall aspect of this application, by recreating a selected setting through projections, visual technology, and sound into a real-world experience. These settings are envisioned to be applied equally for both interior and exterior environments.

Architecture and media arts are becoming inextricably linked disciplines since the advent of computational technology in the early twenty-first century. Architecture as a discipline is at a turning point, presently broadening the concept and design of 'space' to incorporate realities that are often alternative or virtual, thanks to the use of digital technology and machine intelligence. In this spirit, material logics like steel, wood, and concrete aren't necessarily the only elements that make up a structure. Rather, the media is beginning to think of a building's facade as a canvas that may be enhanced, instead of merely physical elements and structure. Media arts, and therefore media facades, give unique options for engagement in urban public places in direct correlation to these themes.[342]

Architecture is being turned towards intelligent aspects of technology capable of conversing with and responding autonomously to human perception, the built environment, as well as other physical or perceptual characteristics. Vast flows of environmental information are exchanged between the architecture and the public, resulting in sensorial extensions of the urban world.[343]

An effective example of this manifestation can be identified within the centenary anniversary of the Los Angeles Philharmonic, exhibited on Frank Gehry's Walt Disney Concert Hall.

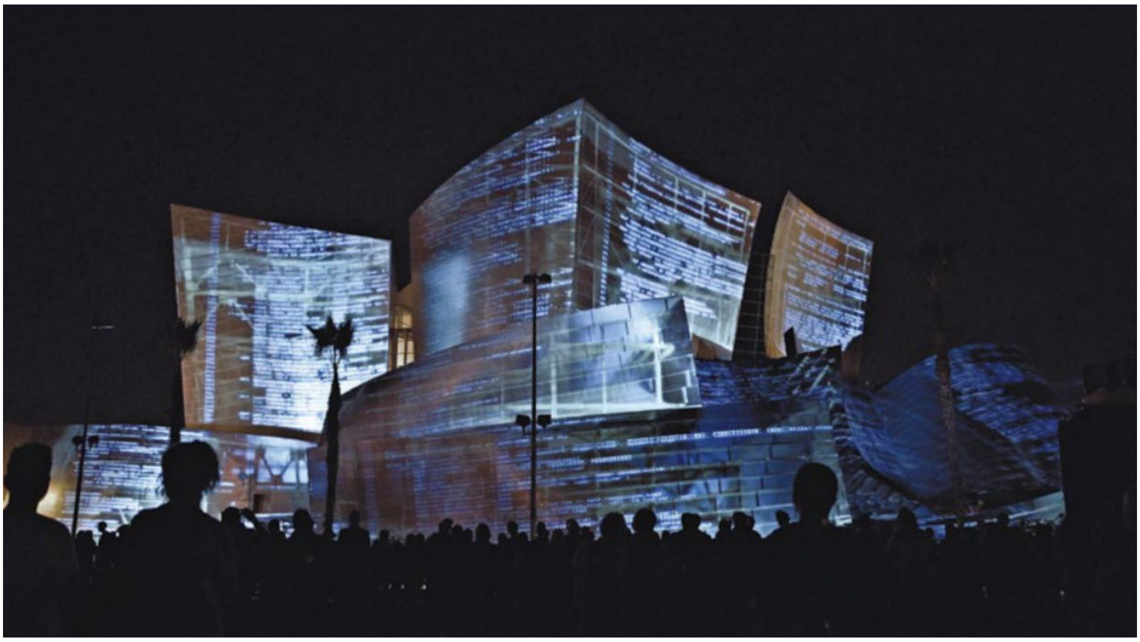

Fig. 6.2 - Walt Disney Hall immersive projection (author: Refik Anadol) [344]

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[342] Refik Anadol, 'Synaesthetic Architecture', *Architectural Design*, 90.3 (2020), 76–85 (p. 78) <https://doi.org/https://doi.org/10.1002/ad.2572>.

[343] Anadol, 'Synaesthetic Architecture', p. 78.

[344] Anadol, 'Synaesthetic Architecture', p. 79.

If a structure like the Walt Disney Concert Hall might communicate its memories (if its "consciousness" came to life) we would be able to conceive a new path for architecture altogether. To commemorate this special occasion, the studio of Refik Anadol collaborated with Google Arts & Culture's Artists and Machine Intelligence (AMI) program, as well as Google's open research project Magenta to investigate this concept. This was done by laying claim towards the past while employing the structure's skin to 'dream' about what is to come.[345]

Anadol's material is represented by his "data universe", and machine intelligence is his artistic accomplice. By waking the figurative "consciousness" of the Walt Disney Concert Hall, they generated something fresh in vision and sound. The outcome is a radical portrayal of the institution's first century, as well as an investigation of synergies between art and technology, along with architectural and institutional memory.

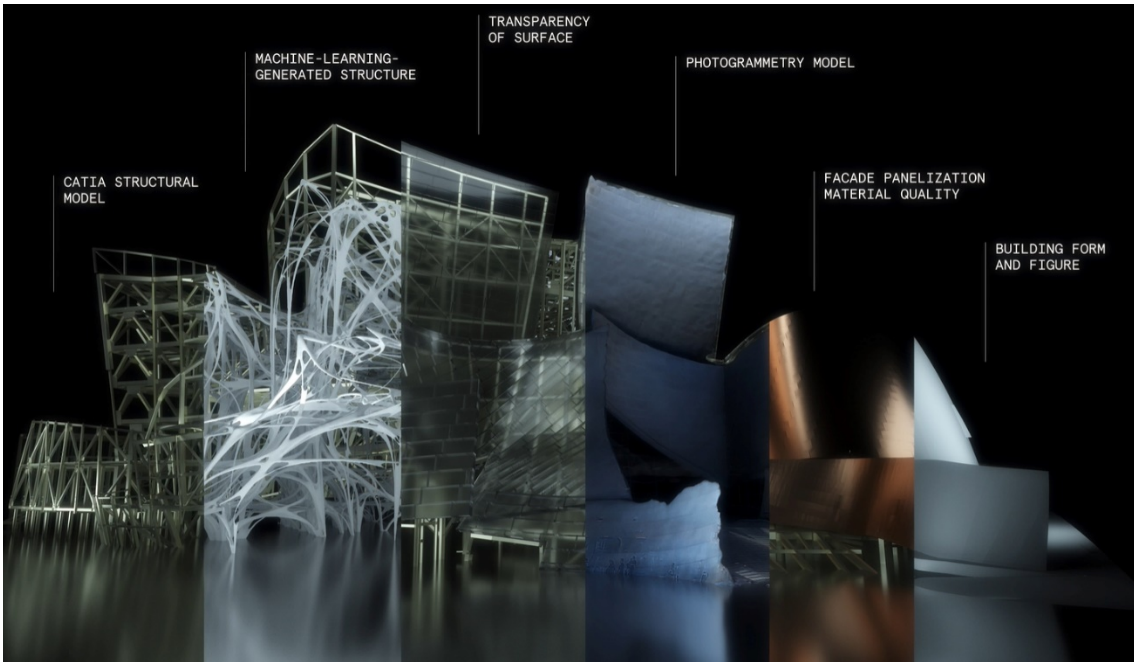

Fig. 6.3 - A sequence from the last stage of the public Audio/Visual (AN) display, which includes projections of the Generative Adversarial Network (GAN) outcomes from the archive data processing (author: Refik Anadol)[346]

[345] Anadol, 'Synaesthetic Architecture', pp. 78–79.

[346] Anadol, 'Synaesthetic Architecture', pp. 80–81.

The development's principles form the foundation of an emerging topic known as "synaesthetic architecture", which asserts that architecture has the ability to empower perception on a plane transcending vision, by generating a spatial experience based on multidimensional media. With the introduction of machine learning, participants are being pushed to widen their sense of space to incorporate 3D environments, time-based '4D' media interactions, and depictions of greater, hidden dimensionality. This discipline's basis is founded on three sorts of spaces that modern architects could construct: material, simulated, and latent (the space in a machine's "mind").[347]

Through physical performances, enhanced architectural settings, and sculptures, media arts may depict all aspects of the built environment and delve into making the unseen conduits of data apparent.

This necessitates an extensive multidisciplinary approach to better investigate the relationships between art, technology, and architecture, as well as how they interact with environmental or cultural memory. It is the role of designers and artists to generate insights into critical and radical possibilities, as well as to visualize contemporary cultural consciousness. It is vital to visualize this fluidity when advocating synaesthetic architecture so that it may draw together scientists, artists, educators, urban planners, architects, and legislators to construct future platforms that allow all participants to opt-in.[348]

Immersive environments could also be achieved through independent installations that protrude within the fabric of reality. A good example of this approach would be the "Virtual Depictions: San Francisco" art installation by Refik Anadol. The setting's major aim was to offer a 21st-century focus on public art by defining new spatial poetics via media arts and architecture, as well as to build a distinctive parametric data sculpture with intelligence, memory, and culture. The major objective for this seminal media architecture concept is to contextualize this experience with a rigorously abstract and cinematic site-specific data-driven

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[347] Anadol, 'Synaesthetic Architecture', pp. 80–81.

[348] Anadol, 'Synaesthetic Architecture', p. 85.

storytelling via architectural alterations of the media wall positioned in the building's lobby. As a consequence, through concurrent compositions, this media wall transforms into a magnificent public event, creating direct and phantasmagorical linkages to its surroundings.[349]

Fig. 6.4 – Virtual Depictions art installation, San Francisco (author: Refik Anadol)[350]

The degree to which an installation can be more or less immersive depends on its scale and its ability to influence the environment. In this sense, if the installation itself surrounds the audience, offering both visual and auditory experiences, it could be considered as fully immersive. Another example of Refik Anadol's approach, "Machine Hallucination" at the A/V Performance Exhibition in New York, points out this fact.

The project is a 30-minute experimental film in 16K resolution which follows the story of New York through the city's collective memories, which form its profoundly buried consciousness. The display does not serve as a reminder of

[349] Refik Anadol, 'Virtual Depictions' (San Francisco, 2015) <https://refikanadol.com/works/virtual-depictions-san-francisco/> [accessed 9 February 2021].

[350] Anadol, 'Virtual Depictions'.

today's New York but rather envisions what could happen in the future, thanks to machine intelligence's ability to make a connection between the present and a projection of the near future. This is a positive view of the emerging interaction among man and machine that stands in opposition to the mainstream narrative of a catastrophic future. Machine Hallucination provides us with a unique setting in which to investigate an alternate universe. This can increase our capacity to dream and assist us to envisage sights we would not otherwise be able to see or envision, making it both an enjoyable and intriguing experience.[351]

Fig. 6.5 - Machine Hallucination (author: Refik Anadol Studio)[352]

Architectural education is growing and improving. In addition to comprehending the historical and critical features of architectural objects and their interrelationship with the urban landscape, the field of architecture ought to be prepared to receive feedback from urban and cultural awareness.

[351] Refik Anadol, 'Machine Hallucination', 2019 <https://refikanadol.com/works/machine-hallucination/> [accessed 9 February 2020].

[352] Refik Anadol, 'Machine Hallucination'.

6.2.2. Immersive Educational Experiments

Teaching exercises can demonstrate the use of immersive portrayal to visualize and test dynamic façade performance on a full scale, with the use of virtual reality as a connecting medium for hand-to-hand interactions, and the utility of the digital as a virtual building material overlay. [353]

Due to computer processing speed, programming, and three-dimensional modeling, the concept of formal experimentation has now become an accepted practice in the field. Rendering farms' fly-through videos and BIM (building integrated modeling) standards have become standard outputs in business practice. While some academics have rejected the prevalence of computers as design tools by ranting against the digital and turning to collage and hand drawing, others in academia embrace computers as design tools.

How can we fully benefit from the aspects of design where the computer is more capable, such as in calculating, pattern discovery, and comparative analysis, in the coming period while keeping the humanistic considerations that are fundamental to architecture?

The interaction between algorithmic configurations and architectural production using hybrid reality technologies is already accessible, thus we should only evaluate how to use these tools to transform our understanding of the environment, by bringing it within the virtual and augmented reality realms.

Virtualization has always been a feature of architecture. Structures begin as architectural visions visible only to the designer, even if they are made of actual materials like steel, concrete, and glass. Architecture is as much as a communication of an idea as it is a livable structure, relying primarily on the building's front for interaction and using form and material as its language. [354]

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[353] Phillip Anzalone and Amber Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, ed. by Douglas Noble, Karen Kensek, and Katie Gould, *FACADE TECTONICS: World Congress Los Angeles 2016 Conference Proceedings*, 1st edn (Los Angeles: Tectonic Press, 2020), p. 141.

[354] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 142.

Furthermore, today's building "façades" are just as much skin as they are visage, and they are expected to function as an environmental barrier with growing efficiency while also meeting aesthetic goals. As a result, the building façade must integrate emerging technologies to help with this quest, whether it's to increase the envelope's performance or to add iconic elements. Because of their ability to portray the façade experientially from both the interior and exterior and at numerous scales, it makes sense that the building façade is one of the characteristics of a building where the deployment of mixed reality visualization tools would be most effective.

The difficulty of the tools, particularly for non-programmers, and the cost of the equipment may be linked to the barriers to the growth and implementation of MR's usage in architecture, both in practice and education. In 2013, Oculus, a Kickstarter-funded company, released the Rift DK1, which significantly enhanced the head-mounted display technology and increased developer accessibility. Users could have a full "room-scale experience" with the launch of HTC Vive in 2015. [355]

This capability allowed users at the consumer level to walk, sit, and move about freely in both physical and virtual surroundings. This widespread adoption of a consumer-friendly product reignited flagging interest in virtual reality in a variety of areas, resulting in an increase in the use of VR as an instrument in design studios and academic institutions around the world.

Contemporary AR tools are largely available as mobile apps that are simple to use but difficult to alter beyond their intended use, or as head-mounted displays (HMDs) that are effective but require significant investment and development capacity to activate.[356]

Previous approaches towards integrating immersive technologies into design education have differed in terms of methodologies, expectations, evaluation, and

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[355] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*.

[356] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 143.

equipment. Even with the latency between conception and representation, as well as the early VR's need for abstraction, it benefited from the ability to "walk-through" the scene. The advancement of VR hardware and software that connects it to digital modeling tools has greatly increased the exploratory capability of VR in the design process, and more recent design studio implementations have assimilated additional objectives or technologies like agent-based modelling techniques and biometric feedback.[357] The examples below show how mixed reality tools can be used to expand the design process from conception to data visualization, all the way to production.

The streamlined outcome of software to a 3D simulated environment is not by itself sufficient for experimentation. We are interested in using MR tools as a means to interactively engage the data representation and modification of the architectural model, as well as evaluating its relation to the physical creation of prototypes. Customized software modifications via plug-ins and programming provide better control of the environment's interaction, comparable to gaming scenarios where user action triggers a pre-programmed response within the simulation.

This is a crucial aspect of the idea that the virtual environment is more than just a new representation of modeling data, but as a platform for designing, analyzing, and studying how to create the physically built environment.

There have been a variety of approaches to using mixed reality as a design tool, such as using a painting software like Google's "Tilt Brush", which allows users to make broad outlines with the controller to create rough 3D sketches inside the virtual environment that can be outsourced into traditional modeling software for further modification and enhancement. This method creates an environment for full-scale design simulation, but it still requires the user to digitally transfer the sketch into more traditional tools. [358]

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[357] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 143.

[358] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 144.

A direct workflow between digital modeling applications and virtual reality is possible thanks to a variety of software options. Because the targeted goal of these software programs is to smoothen the transition between traditional modeling tools and the VR view, it makes them the favored method for most practices to incorporate the technology.

6.3. Mixed Reality for Data Visualization

The students in Phillip Anzalone and Amber Bartosh's "Mediated Environments" workshop were required to expand the digital model-to-VR process to include architecture-centric environmental data generated through simulations such as acoustics, daylighting, and ventilation.

This extra step frequently required students to convert 2D software output, which is often represented in plans or graphs, into 3D information for the VR model. Other spatial translation technologies translated data from spreadsheets or databases into geometry that could be accessed by software and hardware. A major part of this investigation was determining the readability, correctness, and architectural design utility of the embedded data in the virtual model.

Fig. 6.6 - Interactive visualization of air circulation resulting from operable windows in the virtual environment (image authors: Anzalone Phillip and Bartosh Amber)[359]

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[359] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies.*

Because acoustic information is such an important part of the immersive experience, the readability of the data was improved even more when audio components supplemented the visualization. Finally, the user interface, which was often a dashboard-style pop-up menu, was essential in complementing the geometric elements with instructions, legends, and explanatory text. [360]

Despite the ease with which speech instructions may be written in Unity, students generally used visual instructions, which may reflect the preference for creating graphic material over sound. As immersive representation becomes more common, students and professionals in architecture are increasingly likely to grasp the necessity to tackle the aural element of design directly.

Another course established by Phillip Anzalone and Amber Bartosh, titled "Assembly Analysis," places a premium on performative design, detailing, and construction processes in fabrication, as well as analysis and building system integration. Students had to create a custom curtain wall system and a specific glazing system in a widespread urban project, with emphasis on the building skin as a high-performance interconnected system.[361]

The integration of virtual reality equipment into the method enabled students to not only study the assembly of the components in 3D but also sequence the construction using programmed animations to gain a better comprehension of how the structure would be constructed.

A study of the method and sequence of assembly, as well as the material and geometric aspects of detailing, becomes an invaluable component of the building envelope design process. The digital and virtual component of the study of the building envelope assembly process is supplemented by active learning initiatives such as field trips to construction sites, visits to façade manufacturers,

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[360] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 146.

[361] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 146.

and consultants to examine samples and design processes in order to practice assembling full-scale building components.

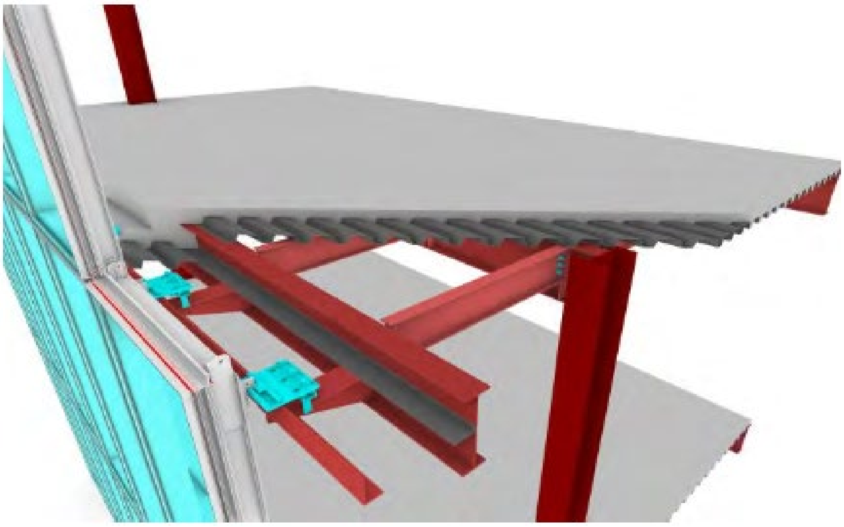

Fig. 6.7 - A digital model of a student project demonstrating the integration of structural and building exterior details was created for VR representation in order to examine the construction sequence (image authors: Anzalone Phillip and Bartosh Amber).[362]

Bartosh created a shifting virtual façade in partnership with a multidisciplinary team of architects and material researchers to assess the user experience of a self-shading façade system made of a thermally activated smart material that contracts when the temperature rises. Due to manufacturing constraints, samples of this material were tough to obtain and were just a few centimeters wide. At various temperatures, the system's ability to diminish solar gain was digitally simulated. This information influenced the physical prototypes' and virtual model's design iterations. The information from the analysis was incorporated into the VR experience, having the range of insolation values across the space represented by color, while energy data units existed as a grid within the interior.[363]

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[362] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 147.

[363] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 148.

Within the VR experience, the user could manipulate the visualized temperature and witness how the smart material façade system changed the pattern on the glaze, the shadows projected on the floor, and the illumination values within the space. The VR allowed a comprehensive immersive prototype of a system that was otherwise limited by expense and material, which was key to this expansion of standard product development processes. This enabled them early design feedback on actual user responses, which could then be fed back into the physical prototype.

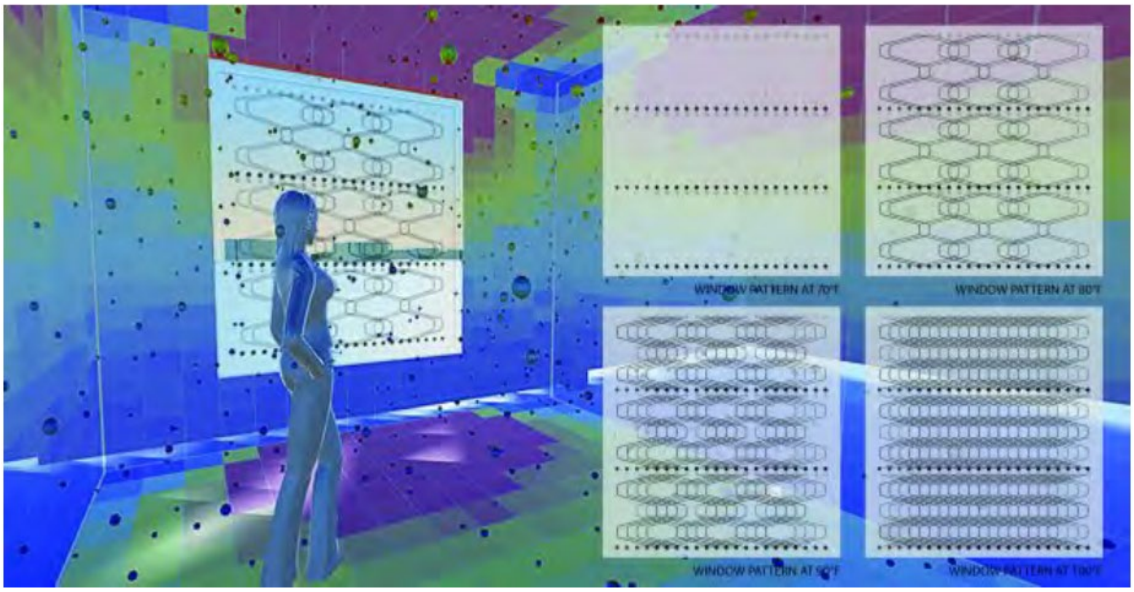

Fig. 6.8 - Visualization of thermally-active shading within the VR design area. When the virtual temperature of the room rises, the window pattern and insolation mapping shift.[364]

Today's software and technology enable designers to handle tasks that need difficult calculations such as structural analyses, even while they don't experience the conditions they are designing in, just by using local information. The same may be said about using a virtual interface to design, study, and coordinate assembly.

The methodology offers a parallel pathway that incorporates virtual tools while also working with the actual materials, lighting, urban contexts, and so on. The

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[364] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 148.

point is that getting closer to simulating the real environment, the more vital it is to be accurate about what reality actually is.

We noticed there was a spectrum of accessibility when using mixed reality as a tool. Starting with AR programs that can be simply downloaded to smartphones and provide some model and tracker customization and moving on to hi-end VR headsets, such as the HTC Vive or Oculus Rift, brings a benefit from being linked to a computer with a presumably high-end graphics card and processor, either by wires or Bluetooth. This connection accelerates the translation and testing process while also improving image quality.[365]

Despite the fact that these devices are marketed to be cheap to consumers, the tailored experiences necessary to export the data and load it to the device to accurately test the VR experience brings some degree of difficulty. Although a model can be run on a computer screen, the rendering quality is inferior to that of the application, and the hand controller can only be simulated with the mouse and keyboard.

AR devices with a head-mounted display (HMD) that project images onto a lens in front of the user's eyes without impeding their view of their surroundings are becoming more widely available. Both the "Microsoft HoloLens" as well as the "Magic Leap One" have made significant progress in terms of developer tools. The cost of the gadget, as well as the shortage of available devices, may be the biggest impediment for head-mounted AR devices right now.

Furthermore, this sort of AR differs from VR in that it combines the real world with the virtual, providing both advantages and restrictions for the representation of creative projects.

The relevance of exploring this topic should be considered as a rich field for taking advantage of the expertise given by the immersive and interactive virtual world itself, rather than just as a next step in normal visualization techniques. The ability of this new technology to connect to the physical built environment via data

[365] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 149.

acquisition and analysis, control of automated manufacturing equipment, the collaboration of workers and researchers, as well as artificial intelligence agents, expands exponentially the possibilities of the designer to engage in the creative and productive process in multiple trajectories.[366]

[366] Anzalone and Bartosh, *Mixed Reality in Facade Education: Expanding the Application of Immersive Technologies*, p. 150.

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EDIS

Environmental Data Indexing system

7. Environmental Data Indexing System (EDIS)

This is one of the main chapters of the thesis in which the solution for the lacking and management of data is addressed. This would enable the adaptive efficient behavior of future architectures. As presented in the introduction (Chapter 2.2.1), the existing means of attaining reliable data are rather inconsistent, either from the perspective of its integrity (Fig. 7.1), date (Fig. 7.2), and Location (Fig. 7.3)

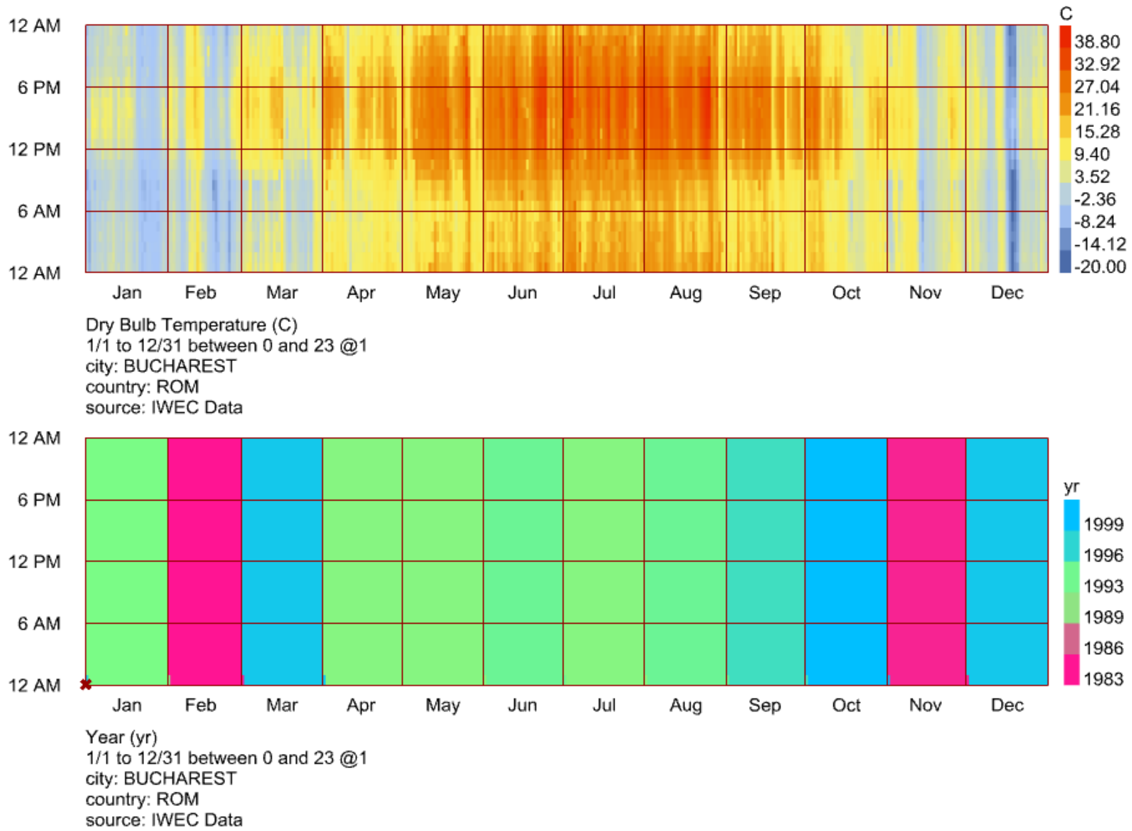

Fig. 7.1 - Top: Hourly Data Plot / Bottom: Year Model Data Plot for Bucharest (Image by author)

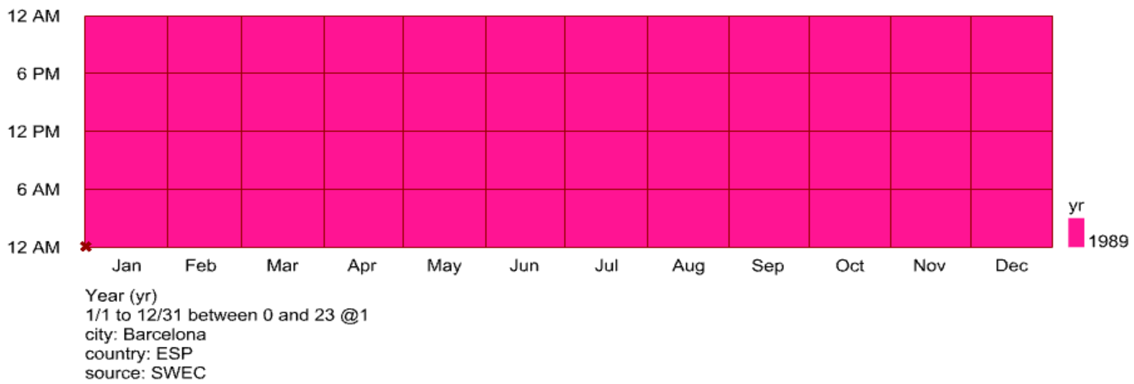

Fig. 7.2 - Year Model Data Plot for Barcelona (Image by author)

Fig. 7.3 – Barcelona data collection point (blue) in relation to the city (image by author) [367]

The first step is to develop means by collecting the necessary environmental data in real-time and recording it for further use, under the form of an energy plus weather file format ("*.epw"). These files are meant to be shared through a dedicated website fully available to the public, with no restrictions.

The EDIS is a conglomerate of sensors that, similarly to a weather station, collects environmental data at an hourly rate, but offers a direct connection through our procedural environment through specific communication devices, such as Wireless, Ethernet, or GSM modules. The main intention of the prototype is to be used in an assembly system scattered through various sectors of a city to generate a complete environmental map that would offer exact onsite climate, geographic and air-quality data.

The part of the prototype that we will be focusing on in this article is the climate indexing cluster that translates all the data directly within an "*.epw" file format that will be used in relation to the Ladybug Tools.

[367] Image Source: https://energyplus.net/weather

The cluster is defined by an Arduino board to which we will connect a variety of sensors that help us gather the following data: exact date and time, dry bulb temperature, relative humidity, calculated dew point temperature, atmospheric pressure, geographic coordinates, global horizontal radiation, direct normal radiation, diffuse horizontal radiation, global horizontal illuminance, direct normal illuminance, diffuse horizontal illuminance, wind speed, wind direction, and precipitable water.

a. Measurement descriptions and components

Types of measurements included within the EDIS: rainfall measurement, wind speed and wind direction, illuminance, temperature and humidity, atmospheric pressure, geographic coordinates, and irradiance.

b. Rainfall Measurements

Rainfall is the main force behind the urban hydrological cycle. As a result, it's critical to have as much precise rainfall data as possible when constructing, modeling, or managing sewer systems. Two typical rainfall measurement methods, the tipping bucket rain gauge, and optical infrared sensor are examined in this chapter, along with their potential sources of inaccuracy. [368]

After all, though measuring rainfall looks to be an easy activity at first, it quickly becomes a difficult effort. As a result, strategies that have the potential to increase the accuracy of rainfall readings should be explored. TBRs, or tipping bucket rain gauges, are commonly used to measure rainfall rates. The principle is described in Fig. 7.4. Rainfall is collected by a funnel with a receiving area (marked as 1), after which the gathered rainwater pours from the funnel into a bucket via a spout (2).

The bucket will tip when a particular volume is achieved. This tipping allows the bucket to discharge its contents and the other bucket to move below the spout, allowing it to be filled. The level at which a bucket will tip is determined by the

[368] Toon Goormans, *Analysis of Local Weather Radar Data in Support of Sewer System Modelling*, *Katholieke Universiteit Leuven, Department of Civil Engineering*, 2017, I, p. 7 <https://www.researchgate.net/publication/318108618_Analysis_of_local_weather_radar_data_in_support_of_sewer_system_modelling>.

adjustment screws (3). Higher rainfall rates will result in more tips per unit of time. The rainfall index can be measured using this number of tips.[369]

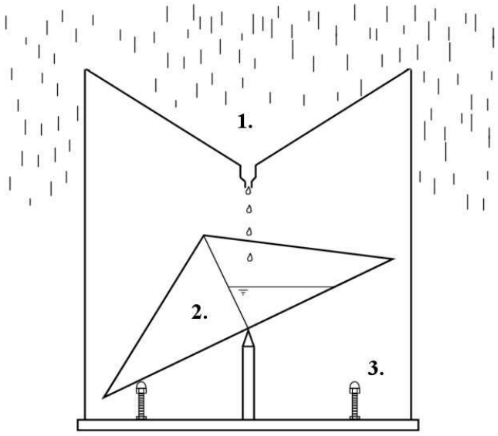

Fig. 7.4 - The operation of a tipping bucket rain gauge: 1) funnel; 2) tipping bucket; 3) adjustment screws (image author: Toon Groomans).[370]

Uncertainties caused by the surrounding environment

Wind effects. The existence of a rain gauge at that site will usually alter the wind flow pattern. After all, the gauge is a stumbling block that causes an increase in wind speed directly over the immediate receiving region (Fig.7.2). This acceleration might sweep away rain drops that aren't caught by the funnel, causing the rainfall rate to be underestimated.

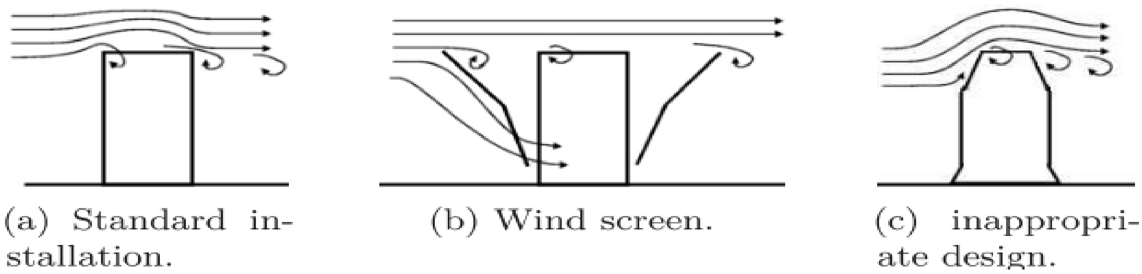

Fig. 7.5 - Aerodynamics of a rain gauge (image author: Toon Groomans)[371]

[369] Goormans, *Analysis of Local Weather Radar Data in Support of Sewer System Modelling*, I, p. 8.

[370] Goormans, *Analysis of Local Weather Radar Data in Support of Sewer System Modelling*, I, p. 8.

[371] Goormans, *Analysis of Local Weather Radar Data in Support of Sewer System Modelling*, I, p. 11.

An alternative for Rain Gauges – Optical Rain Sensors

A good alternative to the tipping bucket is an optical rain sensor. The Optical Rain Gauge uses infrared light beams to detect water striking its exterior surface, similar to how rain-sensing windshield wiper controls work in cars.

The optical gauge reflects infrared rays inside the sensor lens, and infrared light exits as raindrops hit the surface. The size of the raindrop is directly proportional to changes in the strength of the infrared beams during rainfall. The technology compensates for humidity and very small drips automatically, being able to detect rain drops as small as half a millimeter.

Many of the drawbacks of traditional tipping bucket rain gauges are addressed by optical sensor technology. The sensor works in mobile surroundings, has no collecting funnel that is prone to clogging, and is fundamentally self-cleaning because of its circular form, being perfect for wet weather report systems or distant recordings where regular servicing is impossible.

The sensor measures the state of the lens' surface, which might be affected by dirt, pollutants, deterioration, and other variables. It compensates for these elements properly, making the gadget almost immune to ambient influences. Individual raindrops are analyzed by hardware and sophisticated software, which then applies a correct control strategy for the specified mode.[372]

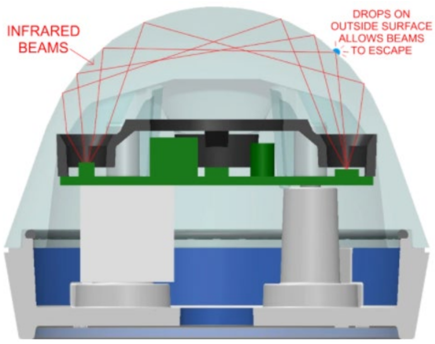

Fig. 7.6 - Hydreon Optical Solid State Rain Sensor (image author: Hydreon)[373]

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[372] Hydreon, 'Hydreon Optical Rain Sensor' <https://rainsensors.com/> [accessed 1 February 2020].

[373] Hydreon, 'Hydreon Optical Rain Sensor'.

c. Wind Speed and Wind Direction Measurements

Wind direction can be measured with a variety of equipment, including the windsock and wind vane. Both of these instruments function by moving to reduce air resistance. The direction from which the wind is blowing is indicated by the way a weather vane is directed by prevailing winds. The bigger aperture of a windsock faces the direction in which the wind is blowing, while the smaller opening on its tail points in the same direction.[374]

Anemometers and wind vanes are modern equipment that is meant to measure wind direction and speed. The wind energy sector employs these types of equipment for both wind resource evaluation and turbine control.

Wind measurements can be achieved through the use of two types of devices. A switch-based device, which would calculate rotations in a certain amount of time and a resistance system type, which is based on the speed at which ultrasonic signals propagate or the impact of ventilation on the resistance of a heated wire (when a high measurement frequency is required, such as in research applications).[375]

Pitot tubes are another type of anemometer that employs the pressure difference among an inner and an outer tube subjected to the wind to measure dynamic pressures, which are then utilized to find out how intense the wind is.[376]

d. Illuminance Measurements

Within the field of photometry, the total light flux received on a surface per unit area is referred to as illuminance. It is defined as a wavelength-weighted measurement of how much incident light touches an area, that correlates with the perception of brightness.

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[374] Myer Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, ed. by Myer Kutz, 1st edn (New Jersey: John Wiley & Sons, 2013), pp. 733–37.

[375] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 562.

[376] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 563.

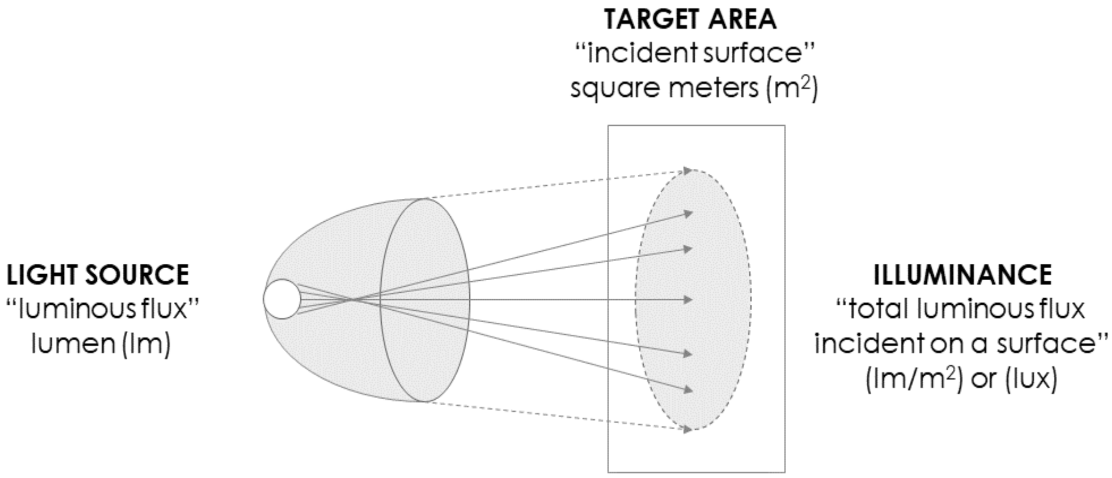

Fig. 7.7 - Illuminance Diagram[377]

An example would be the usage of the foot-candle, as a non-metric illuminance unit in photography.

At the same time, the luminous flux per unit area emitted from a surface is referred to as luminous emittance. In international system terms, lux (lx) is the unit of measurement, or correspondingly, lumens per square meter ($lm*m^2$).[378]

This is used in photometry to describe the intensity of light that strikes or travels through a surface, as perceived by the human eye. Also, the centimeter-gram-second system (CGS) uses the phot as the unit of illuminance, that equivalates to 10000 lux.

Previously, illuminance was frequently referred to as brightness, although this causes misunderstanding with other meanings of the term, such as luminance. The term "brightness" must never be used quantitatively, but solely to relate to physiological experiences and discernment of light.[379]

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[377] Image Source: https://en.wikipedia.org/wiki/Illuminance#/media/File:Illuminance_Diagram.tif

[378] Kane Borg, 'Lighting Investigation for Computational Design', 2010, p. 6.

[379] Alex Ryer, *Light Measurement Handbook*, ed. by Alex Ryer, 2nd edn (Newburyport: International Light, 1998) <http://www.intl-light.com>.

Lighting Condition	Lux
Full daylight	10,000
Overcast day	1,000
Very dark day	100
Twilight	10
Deep twilight	1
Full moon	0.1
Quarter moon	0.01
Starlight	0.001

Table 7.1 - Common Illuminance Levels [380]

e. Irradiance Measurements

Irradiance, when it comes to radiometry, is the amount of radiant flux (power) absorbed by a surface per unit area. In the international system of units, radiance is measured as a watt per square meter (Wm^2). Irradiance is often denoted as intensity, although in radiometry, this term is avoided since it can be confused with radiant intensity. Radiant flux is the term used in astronomy to describe irradiance.[381]

According to the World Meteorological Organization:

> *"Sunshine duration during a given period is defined as the sum of that sub-period for which the direct solar irradiance exceeds 120W/m^2" (WMO, 2003).*[382]

f. Temperature and Humidity Measurements

Temperature is a physical quantity that expresses the sensations of hotness and coolness. The manifestation of thermal energy, which exists in all matter and is the source of heat, represents a movement of energy that occurs when one body comes into touch with another that is colder or hotter. A thermometer is used to measure temperature.

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[380] Table Source: https://en.wikipedia.org/wiki/Illuminance

[381] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 695.

[382] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 701.

Thermometers are calibrated in a variety of scales that have traditionally defined different reference points of the behavior of substances. The Celsius scale (formerly known as centigrade, defined by the symbol °C), the Fahrenheit scale (defined by the symbol °F), and the Kelvin scale (defined by the symbol °K) are the most commonly used scales. [383]

Humidity refers to the quantity of water vapor within the air. Water vapor, described as the gaseous form of water, is generally undetectable to the human eye. The relative humidity of the atmosphere specifies the presence of precipitation, dew, or fog.

Humidity is determined by the system's temperature and pressure. Cool air has higher humidity than warm air when the same amount of water vapor is present. The dew point is a related metric, justifying that the amount of water vapor required to attain saturation increases as the temperature rises. Once the temperature of a volume of air falls below a specific level, it will eventually approach saturation, neither adding nor losing water mass.[384]

The amount of water vapor in a given volume of air can vary dramatically. For example, at 30°C, a parcel of near-saturated air may contain 28g of water per m^3 of air, but only 8g of water per m^3 of air at 8°C.

g. Atmospheric Pressure Measurements

The pressure within Earth's atmosphere is known as atmospheric pressure, or barometric pressure (after the barometer). The typical atmosphere is determined as a pressure unit of 101,325 Pa, or 760 mm Hg. The atmospheric unit roughly corresponds to the Earth's mean sea-level atmospheric pressure, recording at about 1 atm.

Most of the time, the hydrostatic pressure induced by the weight of air above the measuring location closely approximates atmospheric pressure. Because there is a reduction in overlaying atmospheric mass per height, atmospheric pressure

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[383] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 738.

[384] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 739.

falls as elevation rises. By SI units of pascals (1 Pa = 1 N/m^2), pressure measures force per unit area.

An air column with a cross-sectional range of 1cm^2 consists of a mass of around 1.03 kilograms and produces a force or "weight" of around 10.1N (Newtons), resulting in a pressure of 10.1 N/cm^2 or 101 kN/m^2 measured from the average sea level to the top of Earth's atmosphere (101 kilopascals, kPa).[385]

h. GPS – Latitude and Longitude Location Indexing

GPS location indexing is required to accurately assign the recorded data to a certain area. Having a dedicated GPS module, we can easily reposition the station on different sites, making data sorting easier. [386]

7.2. Initial Approach – Arduino Based Indexing System

The initial approach for the development of the EDIS was based on an Arduino microcontroller, equipped with a data logger and a variety of sensors. The main operation of the indexing system had envisioned a real-time communication with the procedural domain through Firefly, a computational tool that offers access to a series of comprehensive software tools that are devoted to closing the gap between Grasshopper and an Arduino micro-controller.

Through these means a near-instantaneous data flow between our digital and physical mediums can be attained, enabling fluid management of our prototype. This brings us features that enable the use of real-world data, acquired through indexing sensors, and use it to explicitly define parametric connections with a Grasshopper model.

The aforementioned micro-controller, Arduino, is represented by an open-source physical computing platform alongside a dedicated environment for developing applications for it. The Arduino may be employed to create interactive systems,

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[385] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*.

[386] Kutz, *Handbook of Measurement in Science and Engineering Volume 1*, p. 9.

tanking input from a variety of sources, such as sensors, cameras, and switches, and controlling a set of actuators based on our set instructions.[387]

Unfortunately, due to the complexity that needed to be achieved, it was decided to replace the Arduino with a Raspberry Pi, in order to have better control and control and access to the station. The main disadvantage of the Arduino platform was that it proved to be difficult to process the collected data within an energy plus weather file (*epw), demanding an external connection to a computer. Also, we had to add an irradiance sensor to the system (requiring extra serial components for it to work), as well as better connectivity modules.

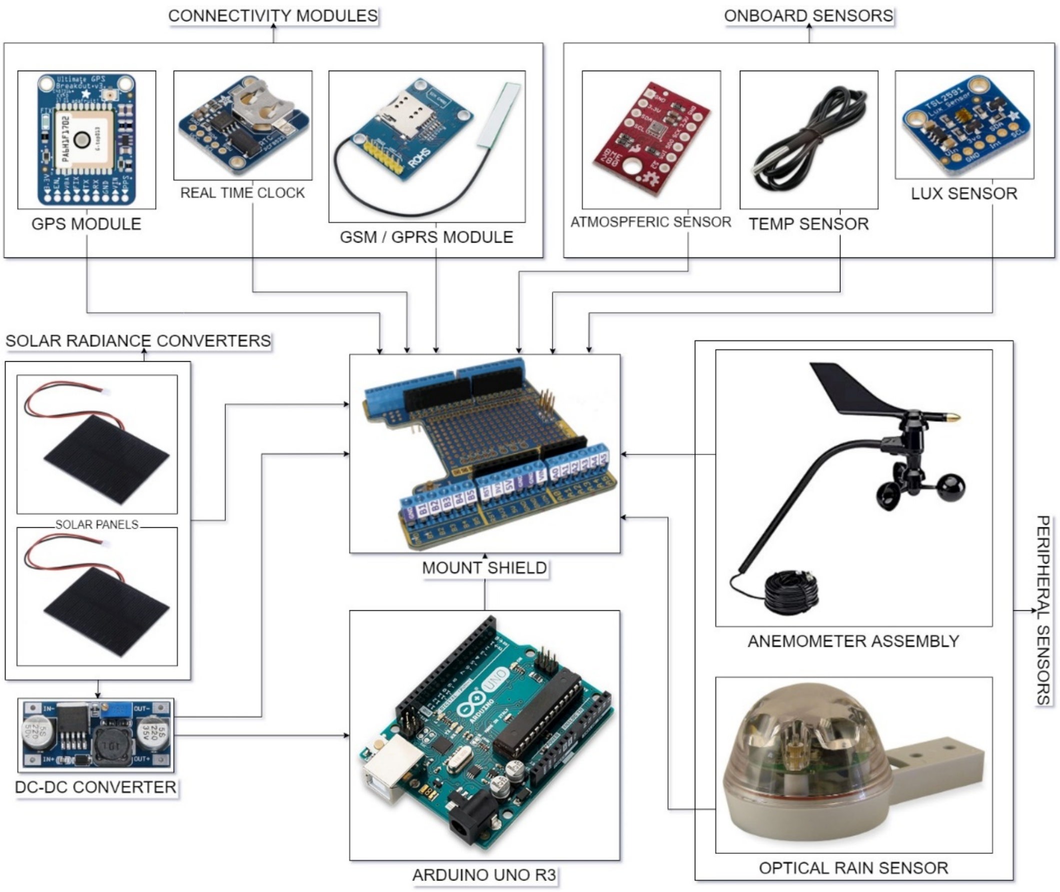

Fig. 7.8 - EDIS sensor layout (Image by Author)

Further details regarding the system components of the initial approach can be found in Appendix D.1.

[387] Payne, *Interactive Prototyping*.

7.3. Final Approach – EDIS – Raspberry Pi Indexing System

Fig. 7.9 - EDIS Assembly[388]

The new layout for the EDIS comes with a lot of improvements. The system is designed to be stand-alone without the need for external connections to other computers, and also with an online feed of the data that it records. The Pi comes equipped with onboard Wi-Fi and proprietary ethernet and USB connectivity.

[388] Image by Author

7.3.1. Component List

For the Raspberry Pi based system we considered the following components:

a. Raspberry Pi

The Pi is an ultra-compact, low-cost computer, yet powerful enough to be used to code, construct robots, and a number of other peculiar and intriguing developments.

The Raspberry Pi can do everything you would imagine a computer to do, including internet browsing, gaming, viewing, and listening to media. On the other hand, is much more than a modern computer, offering the chance to create your own operating system and directly connecting circuits to the board's pins.

The Pi was created to train people on how to write programs in languages such as Python and Scratch, and it comes with all of the main languages pre-installed.[389]

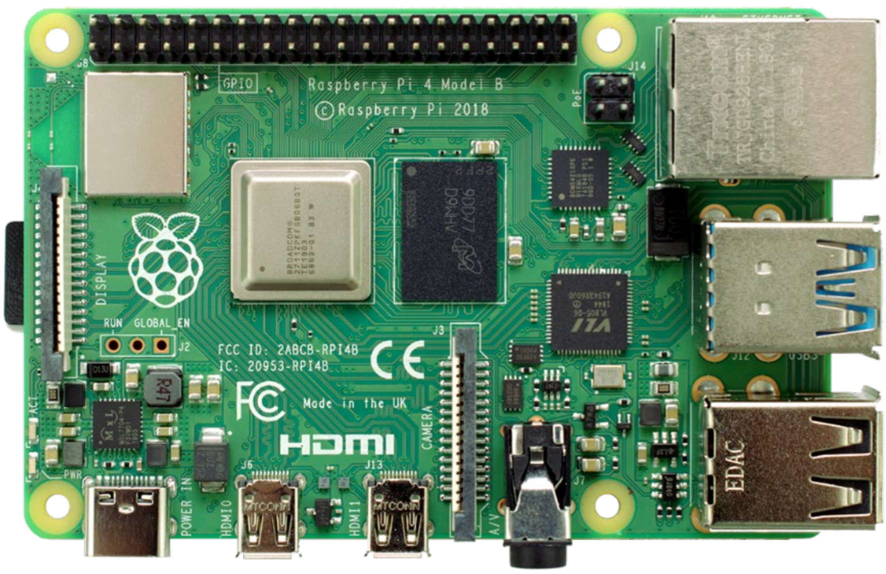

Fig. 7.10 - Raspberry Pi 4 (image author: Gareth Halfacree)[390]

[389] Halfacree, 'The Official Raspberry Pi Beginner's Guide'.

[390] Halfacree, 'The Official Raspberry Pi Beginner's Guide'.

b. SwitchDoc Pi2Grover

The Pi2Grover boards enable Digital, Serial, and I2C interfaces for Internet of Things (IoT) experimentation. It comes with fifteen Grove connectors for prototyping purposes out of which ten are Digital, four I2C, and one UART. Grove devices come in a variety of sizes and shapes, allowing for quick prototyping. There are no software drivers needed and it connects to the Raspberry Pi via a specific connector that allows for the attachment of additional boards or hats to the Grove board.[391]

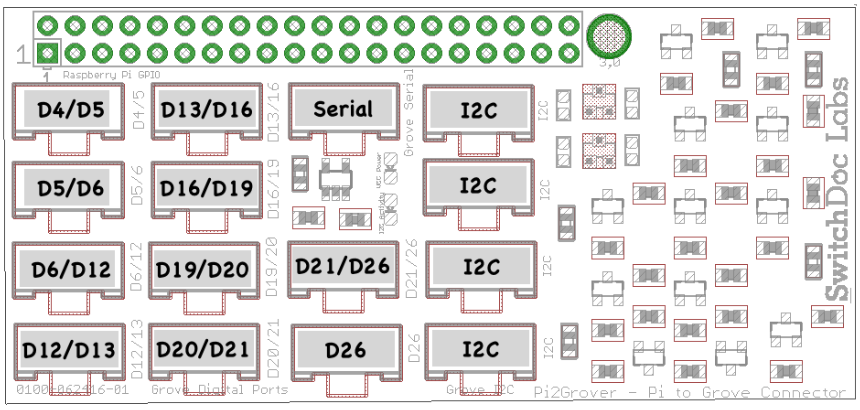

Fig. 7.11 - Pi2Grover Schematic (image author: SwitchDoc Labs)[392]

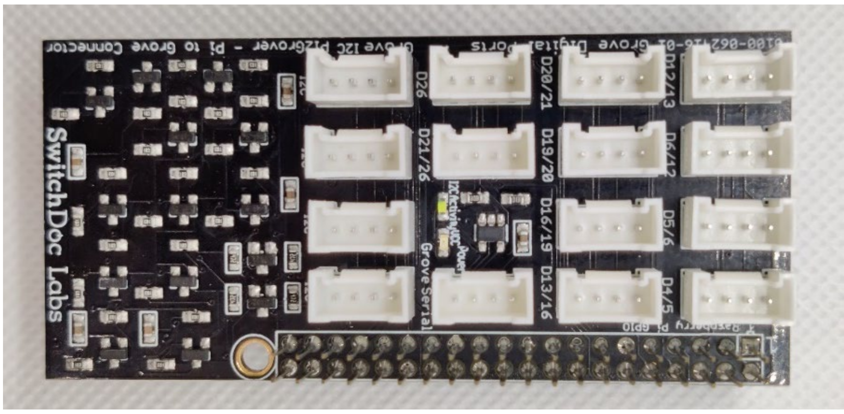

Fig. 7.12 - Pi2Grover (Image by author)

[391] SwitchDocLabs, 'Pi2Grover Grove / Pi Interface Theory of Operation The Four Types of Grove Connectors' (Washington: SwitchDoc Labs, 2018), pp. 1–11 <https://shop.switchdoc.com/products/pi2grover-raspberry-pi-to-grove-connector-interface-board>.

[392] SwitchDocLabs, 'Pi2Grover Grove / Pi Interface Theory of Operation The Four Types of Grove Connectors'.

c. PiWeather Connection Board

The PiWeather Board is a controller board for weather stations that interfaces to Arduino microcontrollers and Raspberry Pi computers. The board is designed by SwitchDoc Labs and allows users to simply build a fully functional Weather Station while allowing for feature customization.[393]

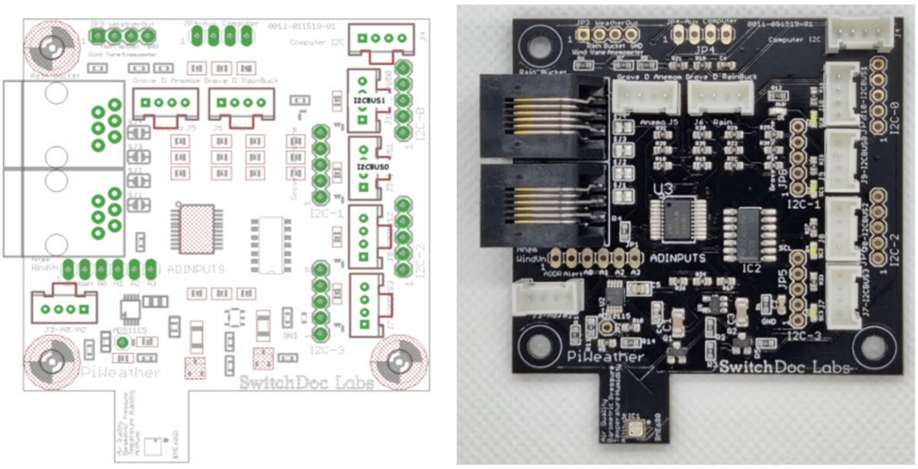

Fig. 7.13 - PiWeather Board Schematic (left)[394], PiWeather Board (right) – image by author[395]

d. SunControl – Solar Power Controller Board

SwitchDoc Labs developed SunControl, a solar power controller, sun tracker, and power supply system for Arduino and Raspberry Pi-based systems. Solar panel charge control, a voltage booster, an A/D system data collecting monitor, USB solid state relay, and a hysteresis-based power control system are all included on the board.

This board can be used to power, measure, and control solar power projects. It combines a variety of exceptional features into a very small, low-cost single completely manufactured and certified PC Board.[396]

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[393] SwitchDocLabs, 'PiWeather Board' (Washington: SwitchDoc Labs, 2018), pp. 1–19 <https://shop.switchdoc.com/products/piweather-interface-board-for-raspberry-pi-arduino-weather-stations>.

[394] SwitchDocLabs, 'PiWeather Board'.

[395] Image by Author

[396] SwicthDocLabs, 'SunControl Solar Power Controller' (Washington: SwitchDoc Labs, 2017), p. 28 <https://shop.switchdoc.com/products/suncontrol-advanced-solar-controller-charger-sun-tracker-data-gathering-grove-header>.

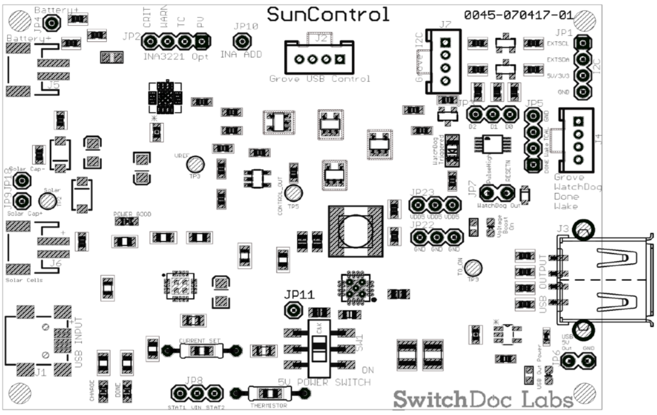

Fig. 7.14 - SunControl Board Schematic[397]

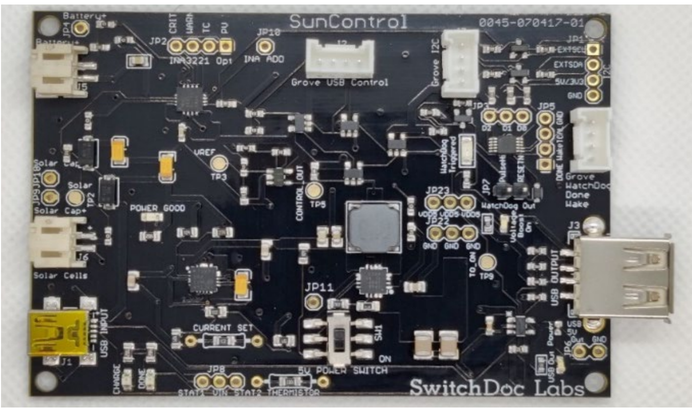

Fig. 7.15 - SunControl Board (image by author)

e. GrovePowerSave Board

Using the GrovePowerSave board we can control the activity of the connected devices, such as shutting them down to save power and rebooting them whenever needed log data. The board is 3.3V and 5V compatible.

GrovePowerSave toggles the VDD line of the Grove device connected to the Out Port. This disconnects the attached device from the power supply, lowering the gadget's power consumption. Grove Connections are used to regulate the GrovePowerSave, which is controlled via a GPIO line from the Raspberry Pi or Arduino device.[398]

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[397] SwicthDocLabs, 'SunControl Solar Power Controller'.

[398] SwitchDocLabs, 'GrovePowerSave / USB PowerControl to Reduce Solar Power Requirements' (Washington: SwitchDoc Labs, 2020), p. 8

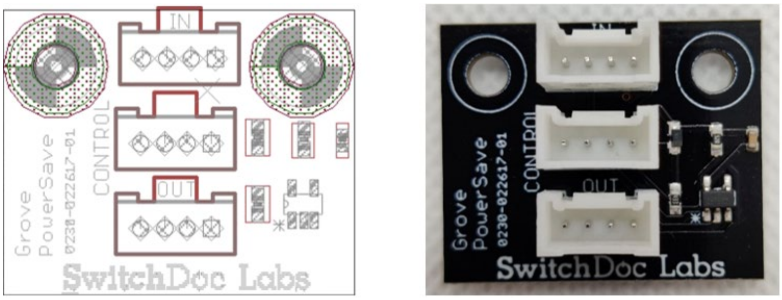

Fig. 7.16 - GrovePowerSave Board Schematic (left)[399], GrovePowerSave Board (right) - (image by author)

f. Multi-Solar Power Connector

The Multi–Solar Power board is a diode-protected connector board that allows up to four solar panels to be connected (such as 330mA or 100mA Solar Panels), with no soldering required. A JST2 Extender Cable is also included, necessary to connect the board to the SunControl. The Solar Panel Connector Board features four diodes that safeguard the solar panels and keep the current flowing to the battery even if one of them malfunctions or is in the shade while the others continue to perform. The diodes fitted are Schottky 40 Volt 3A diodes. Even if the diode is rated at 40V, this board is limited to attaching 6V Solar Cells. The diode was chosen because of its low forward diode drop (Vf = 0.45V) and current rating.

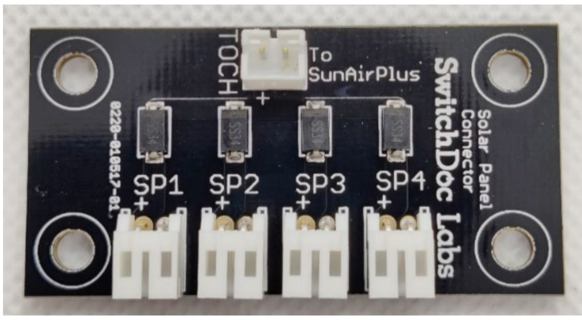

Fig. 7.17 - Multi Solar Panel Connector Board (image by author)

g. 10050mAh 3.7V Li-Ion Battery - ICR18650

The batteries are made from balanced 10050mAh cells connected in parallel and include protection circuitry. Important note: Lithium-ion batteries must be handled

<https://www.switchdoc.com/2017/05/tutorial-using-grovepowersave-usb-powercontrol-to-reduce-solar-power-requirements/>.

[399] SwitchDocLabs, 'GrovePowerSave / USB PowerControl to Reduce Solar Power Requirements'.

with great care and must be charged/discharged according to the instructions in the technical data sheet. They can never be dented, folded, punctured, crushed, or damaged in any way.

The battery is delivered with a 100mm cable that ends with a standard bipolar JST-PH connector. It also includes a protection circuit to prevent overcharging/discharging and is protected against short circuits.[400]

Characteristics:

- 3.7V nominal voltage
- 100mm cable with JST-PH connector
- Delivered with 30% charge for long-term storage
- 4.2V charge interrupt and 2.4V emergency discharge interrupt
- Short circuit protection

Fig. 7.18 - 10500mAh 3.7V Battery (image by author)

h. 330 mA / 6V Solar Panel

A solar cell (often known as a "photovoltaic" cell) represents a system that transforms photons into electricity, containing both solar and non-solar light sources (such as photons from incandescent lights). The device must primarily

[400] WenFei Liang, 'ICR18650 10050mAh 3.7V Li-Ion Battery Technical Specification' (Shanzhen: Pkcell, 2020), p. 9 <http://www.pkcell.net>.

perform two purposes: Photogeneration of charge carriers in a light-absorbing medium, followed by separation to a conductive connection for energy transfer.

Solar cells have traditionally been employed in remote power systems such as orbiting satellites, but also in consumer electronics such as remote radio-telephones, portable calculators, and water pumps where grid electricity is unobtainable.[401]

Characteristics:

- Size: 136x110x3mm
- Max. voltage: 6V
- Max. power: 2W
- Current: 330mA

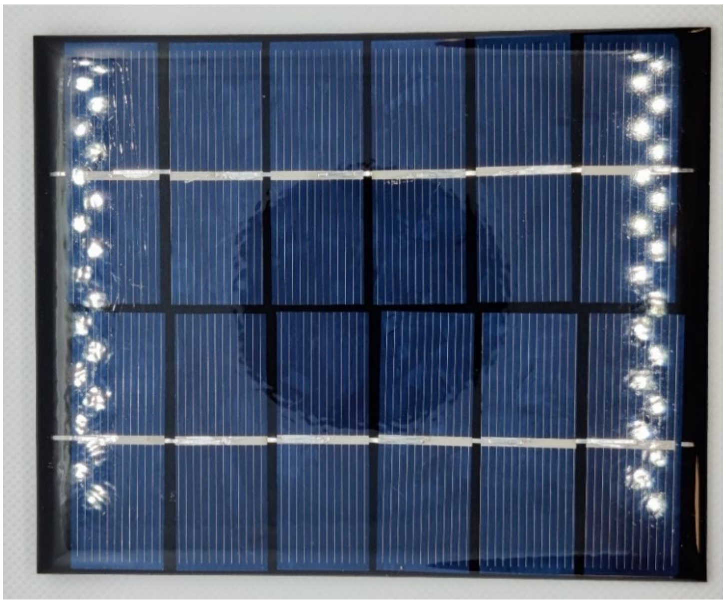

Fig. 7.19 - Solar Cell (image by author)

i. RS485 to USB Converter

PC users can use an RS485 converter in order to connect their RS-485 equipment to systems that contain a USB interface, without being necessary to open the case (for motherboard access) or switch off the PC to install a hub. The converter provides the user with an additional high-speed RS-485 port right away.

[401] 'Solar Cell' <https://www.sciencedaily.com/terms/solar_cell.htm> [accessed 24 May 2021].

Furthermore, the power comes from the USB connection, eliminating the need for power adapters. As a result, the converter is excellent for PLCs and printers, point-of-sale systems, and other industrial control devices.[402]

The Converter will be used to connect the pyranometer sensor for solar irradiance.

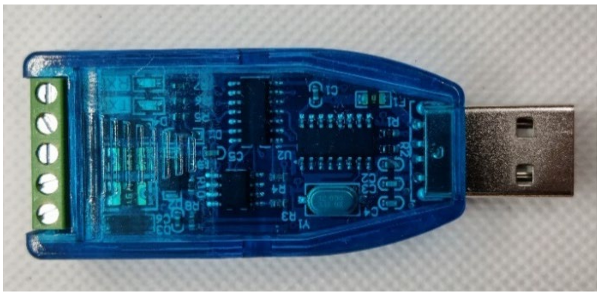

Fig. 7.20 - RS485 to USB Converter (image by author)

j. PYR20 – Pyranometer Sensor for Solar Radiation

The PYR20 pyranometer, also known as a solar radiation sensor, detects both direct and diffuse global irradiance. An Eppley Precision Spectral Pyranometer is used to calibrate each sensor, which ensures high accuracy and consistency. The sensor can be used in scientific research, solar power, greenhouses, and weather stations, among other things.[403]

- Measurement ranges up to 2000W/m^2, Spectral range 400-1100nm
- Output interface with RS485
- Temperature compensated
- Level indicator and spring-loaded installation
- IP66 certified waterproof for outdoor usage
- Reverse power protection and built-in TVS/ESD protection

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[402] N. Seidle, 'USB to RS485 Breakout Schematic', 2021, p. 1.

[403] EndeavourTechnology, 'Solar Radiation / Pyranometer Sensor User Manual' (Dalian: INFWIN, 2021), pp. 1–21 <http://www.infwin.com>.

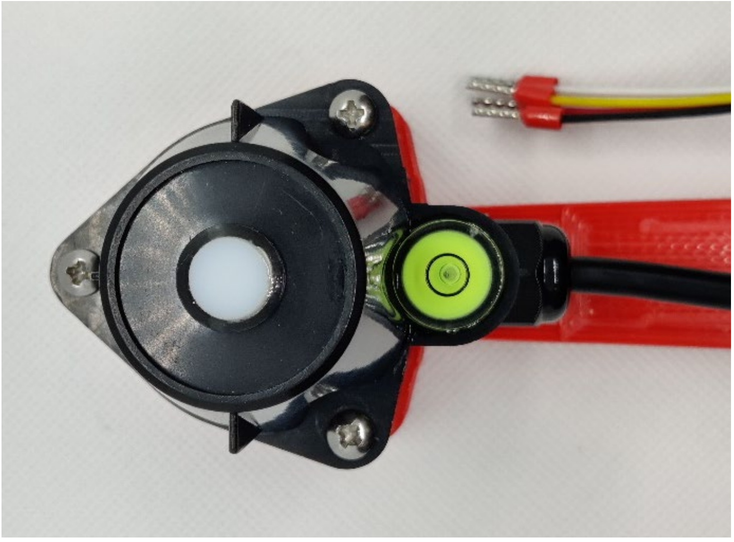

Fig. 7.21 - PYR20 – Pyranometer (image by author)

k. GPS Module: Gy-GPS6MV2

The Gy-GPS6MV2 employs the u-blox NEO-6M GPS module with integrated EEPROM (electrically erasable programmable read-only memory) and attachable antenna. This works with a variety of flight controller boards that have a GPS module built in. These small, easy-to-install modules offer excellent GPS performance as well as a wide range of connectivity options, design, and power. Their small form-factor and surface mount technology pads enable completely automated assemblies using usual pick-and-place and reflow-soldering instruments for high-volume production and cost-effectiveness.[404]

Features:

- Model: GY-GPS6MV2
- Power Supply Range: 3 V to 5 V
- EEPROM for preserving configuration data when the device is turned off
- Backup battery
- Default Baud Rate: 9600 bps
- Ceramic antenna, 25 x 25 mm
- LED indicator

[404] U-blox, 'GPS Module - Lea-6 / Neo-6 / Max-6' (Singapore: U-Blox, 2017), 85 <www.u-blox.com>.

- Mounting Hole Diameter: 3 mm
- Module Size: 25 x 35 mm

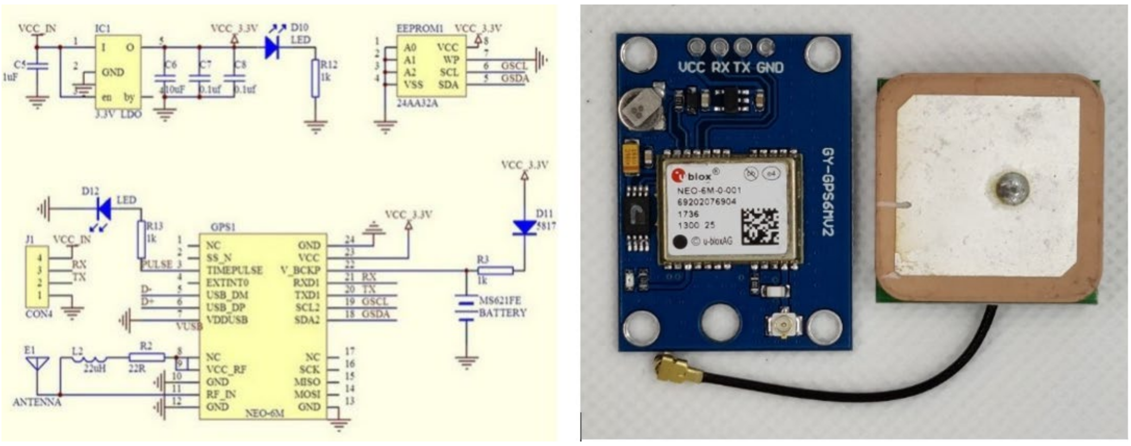

Fig. 7.22 - Breakout Board Schematic (left)[405], U-Blox GPS Module (right) - image by author

I. AM2315 - Digital temperature and humidity sensor

The AM2315 sensor employs both a thermistor temperature sensor and a capacitive humidity sensor. The readings are done by a small microcontroller inside, which has a basic I^2C interface for accessing the finalized and adjusted output data. The sensor is encased in a tough housing with an assembly support, making it better than a standard sensor placed on a PCB.[406]

- 0-100% humidity readings with 2% accuracy
- 0.5 Hz update rate
- Temperature measurements from -20 to 80°C with an average accuracy of 0.1°C
- During conversion, the maximum current used is 10 mA (while requesting data)
- I^2C 7-bit address
- 3.5V to 5.5V power and input/output
- Weight: 82.64g

[405] U-blox, 'GPS Module - Lea-6 / Neo-6 / Max-6'.

[406] Aosong, 'Digital Temperature and Humidity Sensor AM2315' (Guangzhou: Aosong, 2016), p. 18 <www.asong.com>.

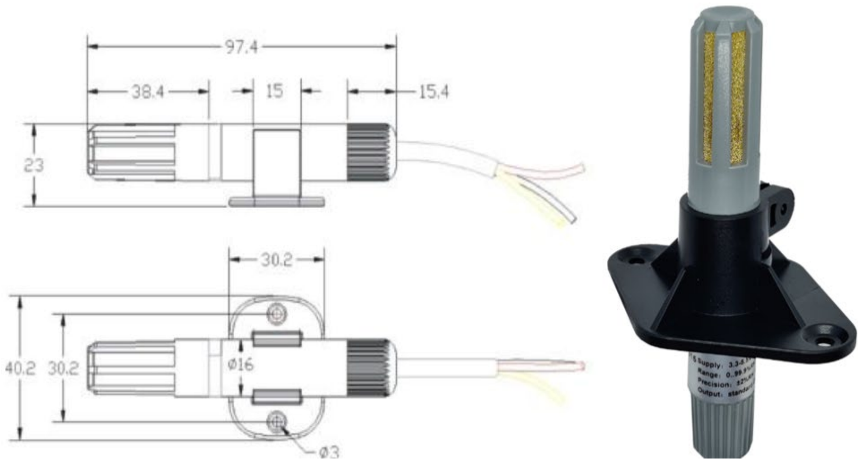

Fig. 7.23 - AM2315 Sensor Dimensions (left)[407], AM2315 Temperature and Humidity Sensor (right) - image by author

m. TSL2591 – Light to Digital Converter

The TSL2591 employs a light-to-digital converter with extremely high sensitivity that converts light intensity into digital signals using an I^{2}C interface. On a single complementary metal oxide semiconductor integrated circuit. One visible and infrared photodiode and one infrared-responding photodiode are combined within the device. The photodiode currents are converted into a digital output that denotes each channel's measured irradiance by two integrated ADCs. This digital output can be fed into a microcontroller, which will calculate the illuminance in lux by applying an empirical formula that approximates the eye's reaction.[408]

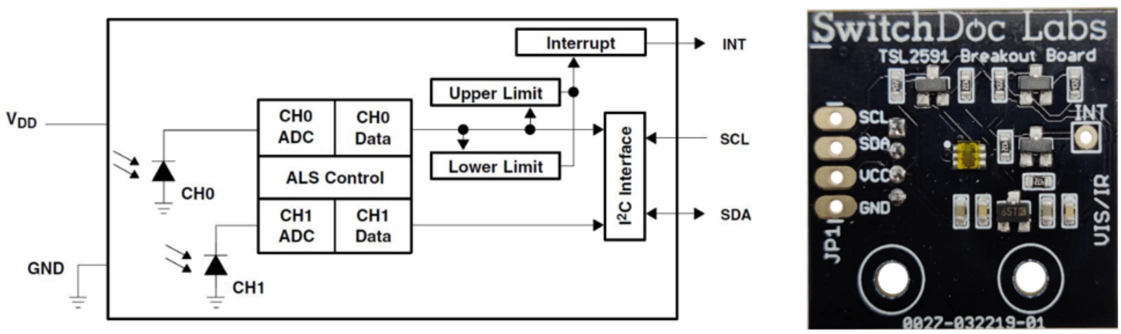

Fig. 7.24 - TSL2591 Block Diagram (left)[409], TSL2591 Breakout Board (right) - image by author

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407 Aosong, 'Digital Temperature and Humidity Sensor AM2315'.

408 AMS, 'Datasheet - TSL2591 - Light-to-Digital Converter' (Premstaetten: AMS, 2018), pp. 1–33 <https://ams.com/tsl25911#tab/documents>.

409 AMS, 'Datasheet - TSL2591 - Light-to-Digital Converter'.

n. B-LUX-V30B – Light to Digital Converter

The B-LUX-V30B is a photodiode and ADC-integrated ambient light sensor with an I2C digital interface. The light intensity is converted into electric current by a photodiode inside the sensor, which is then processed into a digital bitstream by a low-power circuit. The bitstream is digitally processed and saved in the output register, which is then read over the I2C interface.

The optical response design matches the spectral response of the human eye, and the on-chip filter prevents UV and infrared light from entering the photodiode. The second photodiode array is primarily infrared-sensitive and is used to match the light signal emitted by fluorescent and incandescent bulbs. Low current consumption (usually 700 A) and an exceptionally large optical dynamic range (from 0.054 lumens to 200,000 lumens) are two significant aspects of the sensor's analog construction. We don't have to bother with the gain range setting because of the on-chip automated range adjustment technology. The sensor is designed to work with a supply voltage range of 2.7V to 6V and uses 0.7 mA at full load.[410] Characteristics:

- 0 to 200,000 lumens wide detection range, with low light precision - 0.054Lux
- VCC = 2.7V to 6V
- Working current ICC = 0.7mA
- -40C to +85C operating temperature range.

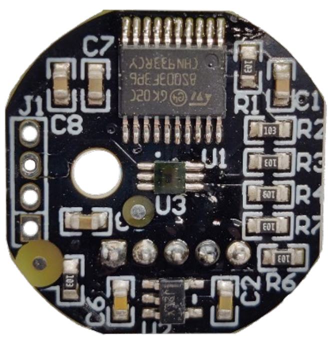


Fig. 7.25 - B-LUX-V30B Breakout Board (image by author)

[410] BCE, 'B-LUX-V30B - Manual' (Guangzhou: BCE, 2018), pp. 68–70.

o. ADS-WS1 Wind/Rain Sensor Assembly

A wind vane and an anemometer for determining wind direction and speed, as well as a rain gauge, are included in this kit. The rain gauge comes in the form of a tipping-bucket. A digital counter input can be used to record each 0.2794mm of rainwater that enables one brief contact closure. Two middle conductors of a connecting RJ11-terminated cable are linked to the gauge's switch.

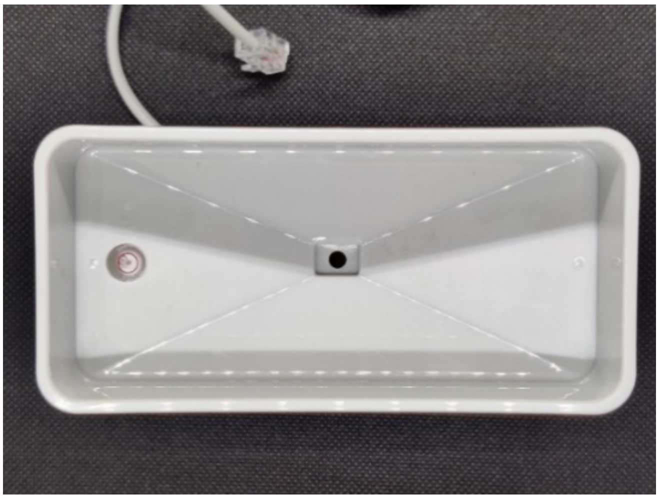


Fig. 7.26 - ADS Rain Gauge (image by author)

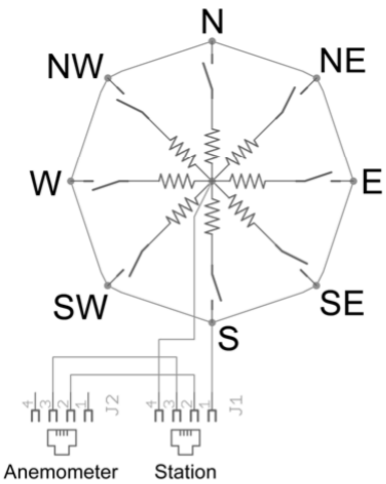
The cup-type anemometer detects wind speeds via closing a contact when a magnet passes through a switch. The switch closes once every second when the wind speed hits 2.4 km/h. The anemometer's switch is attached to the wind vane's RJ11 cable's inner two conductors (pins 2 and 3).

Fig. 7.27 - ADS Anemometer (image by author)

The wind vane seemed to be the most difficult of the sensors to calibrate. It contains eight switches, each of which is connected to a separate resistor. The wind vane magnet is capable of closing two switches simultaneously, indicating up to 16 distinct positions.

As illustrated below, a peripheral resistor may be used to create a voltage divider, generating a voltage output that may be monitored using an analog to digital converter.

The table contains resistance values for each of the sixteen available places. The resistance values for the places between those illustrated in the diagram are the result of two neighboring resistors connected in parallel when the vane's magnet activates two switches simultaneously.[411]



Direction (Degrees)	Resistance (Ohms)	Voltage (V=5v, R=10k)
0	33k	3.84v
22.5	6.57k	1.98v
45	8.2k	2.25v
67.5	891	0.41v
90	1k	0.45v
112.5	688	0.32v
135	2.2k	0.90v
157.5	1.41k	0.62v
180	3.9k	1.40v
202.5	3.14k	1.19v
225	16k	3.08v
247.5	14.12k	2.93v
270	120k	4.62v
292.5	42.12k	4.04v
315	64.9k	4.33v
337.5	21.88k	3.43v

Fig. 7.28 - Argent Wind Vane Resistor Arrangement (left)[412], Resistance Values for the 16 Positions (right) – Image by Argent Systems[413]

[411] Argent, 'ADS Weather Station' (Santa Maria: Argent Data Systems, 2018), p. 4 <https://www.argentdata.com/catalog/product_info.php?products_id=145>.

[412] Argent, 'ADS Weather Station'.

[413] Argent, 'ADS Weather Station'.

Fig. 7.29 - ADS Wind Vane (image by author)

p. Raspberry Pi IR-CUT Sky-Camera

The main purpose of the sky camera is to offer a real time view of the surrounding environment. The Raspberry Pi IR-CUT Camera module can be used during the day and night and connects directly to the Raspberry Pi through an FFC Cable.

Specifications: Sensor best resolution: 1080p, Aperture (F): 1.8, Field of View: 175 degrees, Focal Length: 3.6mm.

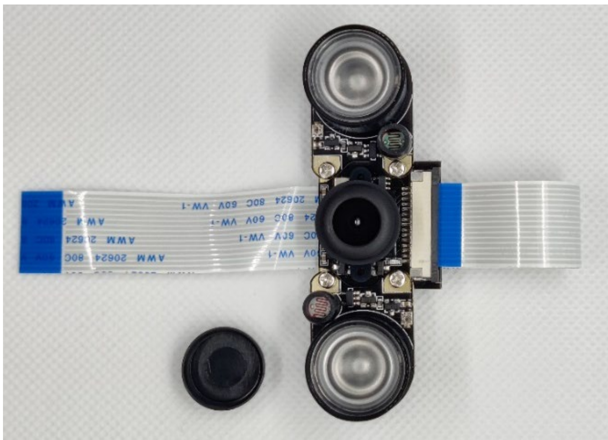


Fig. 7.30 - Raspberry Pi IR-CUT Camera Module (image by author)

q. Mounting and Support

The main Support of the station consists of a heavy-duty aluminum tripod that will be grounded by a weighted mold.

The tripod is meant to hold up to 25 kg and can stretch up to 2.8 meters in height with a 101cm footprint diameter. The tripod also has an air-cushioned feature and a 4-section twist lock.

The housing for all the electronic boards consists of an electrical junction box that is IP65 certified. The measurements of the housing are 290mm*210mm*35mm. The box will be cut and adapted to suit the elements within.

In addition to the main housing, we also have a smaller IP65 junction box that will suit the Illuminance sensors, measuring 63mm*58mm*35mm.

Fig. 7.31 - Main Housing (left), Illuminance Sensor Housing (right)[414]

The Illuminance sensor housings will fit two sapphire crystals that allow a broad wavelength of light to pass through and get as much as an accurate reading as possible.

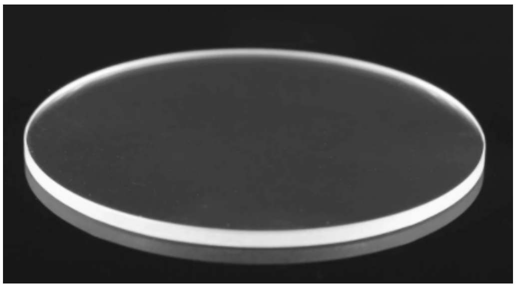


Fig. 7.32 - Sapphire Crystal[415]

All cables and connections leaving the housings will be protected by waterproofing cable glands of varying diameters.

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[414] Image Source: www.aliexpress.com/item/4000774620905.html?spm=a2g0s.9042311.0.0.71ad4c4d4tNJIb

[415] Image Source:

www.aliexpress.com/item/32976100003.html?spm=a2g0s.9042311.0.0.1d644c4dqGTdTD

Fig. 7.33 - Waterproofing Cable Glands

In the case of the rain gauge and temperature sensor, we have a mounting brace that will secure the sensor tightly to the main support.

Fig. 7.34 - Rain Gauge Brace (image by author)

The temperature sensor also comes equipped with a Stevenson screen that needs a 3D printed part to be properly mounted.

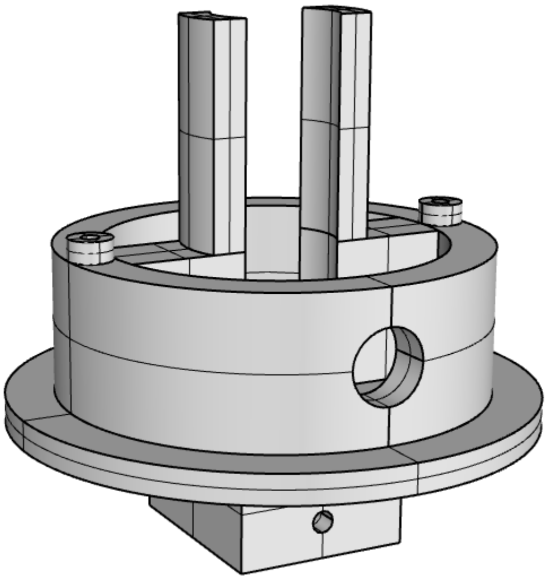

Fig. 7.35 - Temperature Sensor Support 3D Model (image by author)

The radiation sensor did not have proprietary mounting support so we decided to 3d print it to fit the exact parameters.

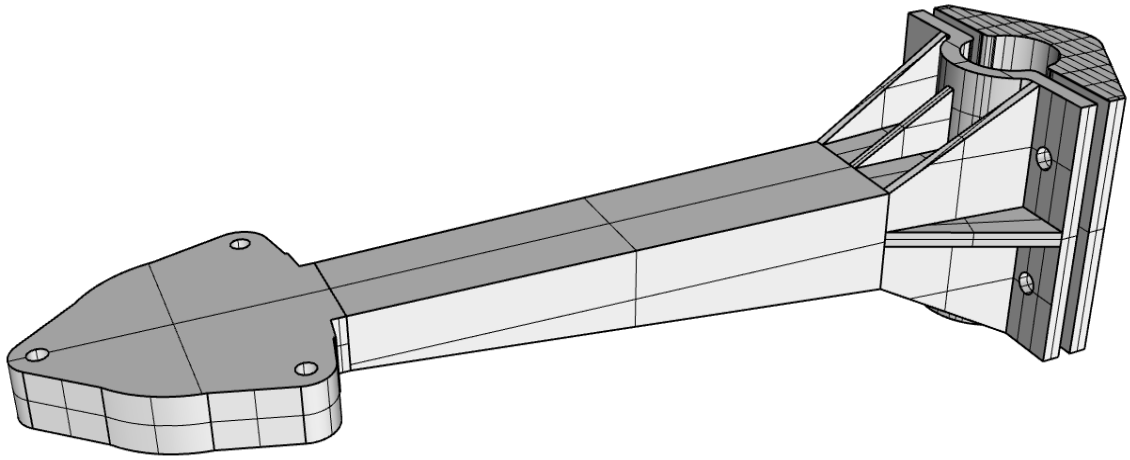

Fig. 7.36 - PYR20 Support 3D Model (image by author)

The last support that we needed was for the four solar panels. These supports are represented by four interlocking frames that allow the solar panels to be rotated on the Z-Axis for better orientation.

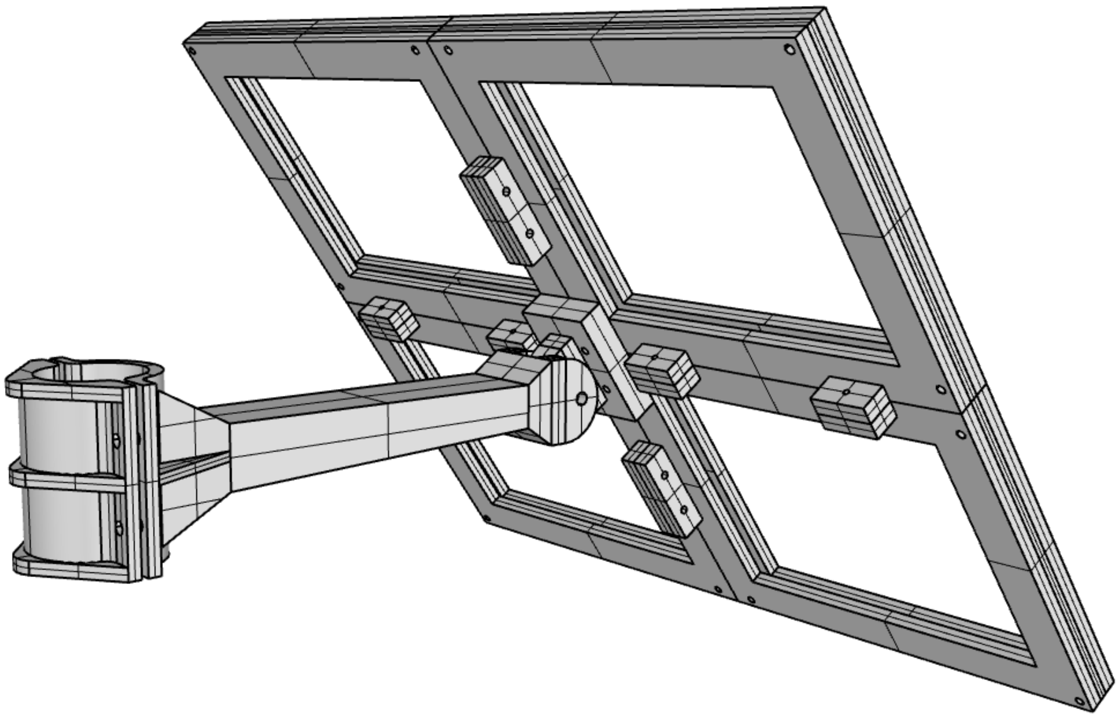

Fig. 7.37 - Solar Panel Frame and Support 3D Model (image by author)

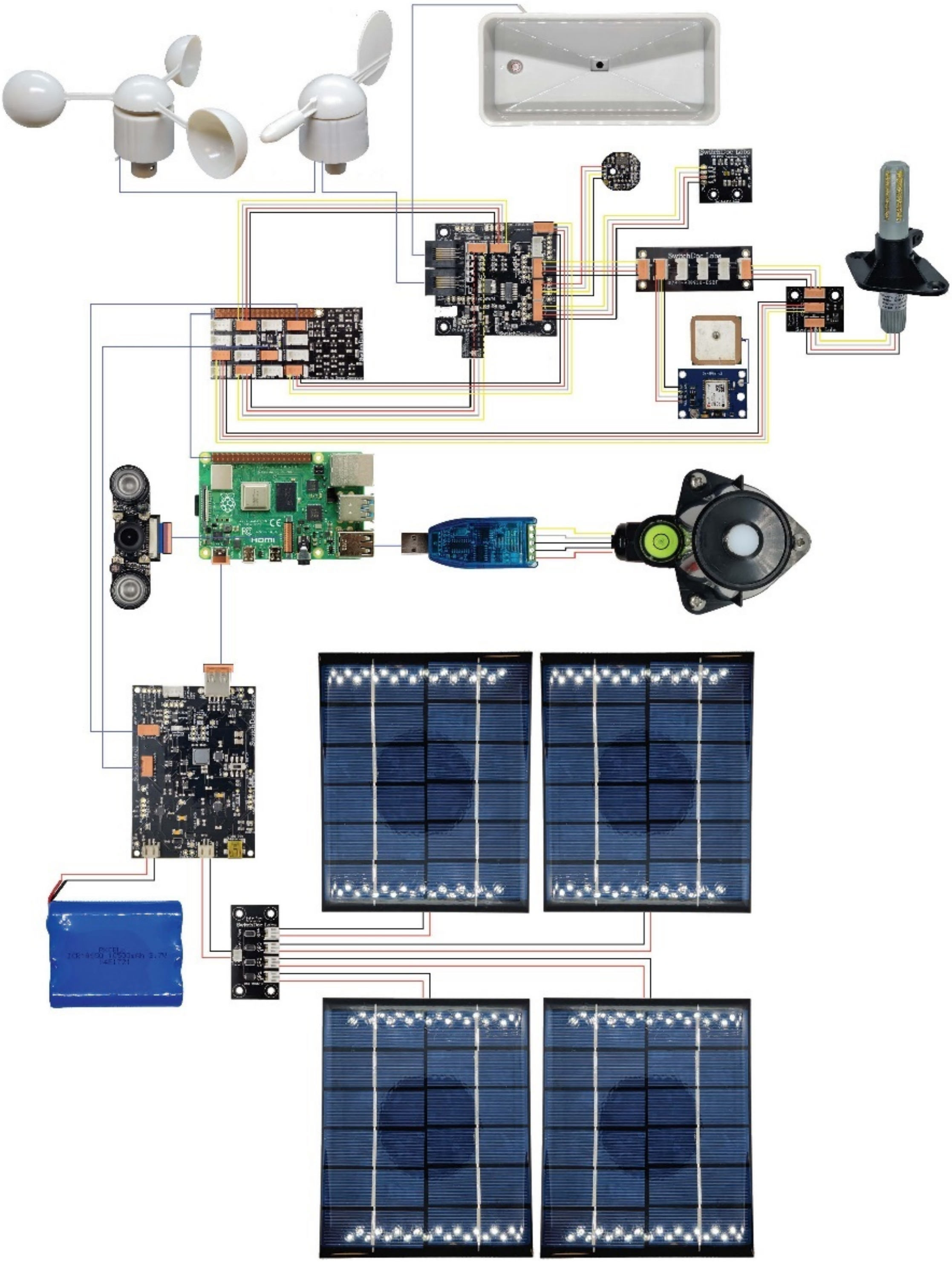

Fig. 7.38 - EDIS - Project Layout and Connections (image by author)

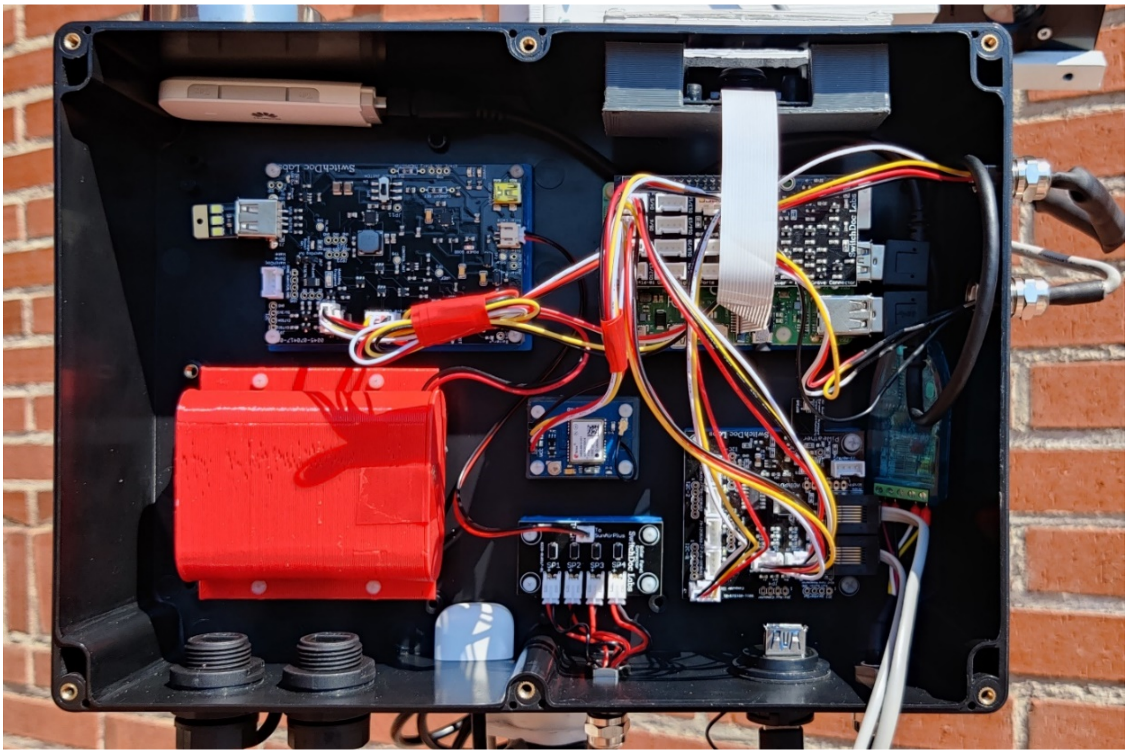

Fig. 7.39 - EDIS Inner Case Layout (image by author)

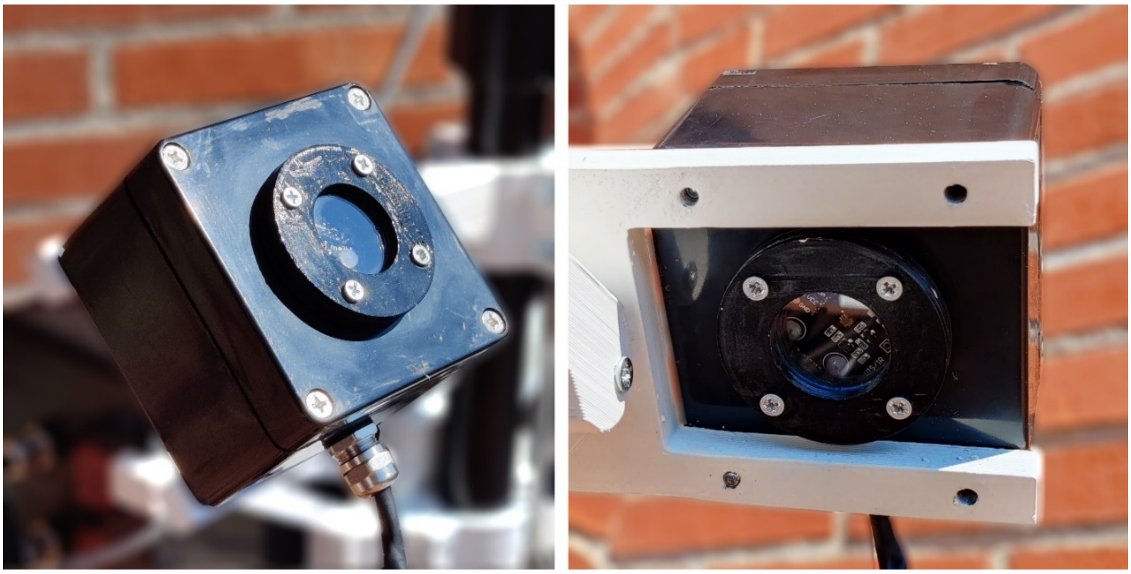

Fig. 7.40 – EDIS Illuminance Sensor Layout (front side sensor for Global Illumination and backside for Diffuse Illuminance) - image by author

7.3.2. The functionalities and specifications of the EDIS

The main purpose of the device is to record environmental data in real time and compile it into an *.epw file format while being also accessible through the internet.

In order to achieve this, we have developed a program for the Raspberry Pi that would read all the sensor data and organize it within an *.epw template. The file itself is structured in two parts: the header, which contains informational data regarding specific site characteristics (location, time-zone, etc.), and the collected data part that contains all the hourly recorded values throughout the span of a year. The data that is missing will be filled with a value equal to the maximum cap of the field.

The program we have developed is functioning based on five codes. The first allows us to edit the setup of the libraries and packages needed to run the program, the second enables us to edit the header of the *.epw file, the third initiates the data collection, the fourth part allows us to compute the collected data within the units that we need or to calibrate the sensors with a certain factor and the fifth converts the collected data into the designated file.

All the codes were developed in collaboration with one of the co-supervisors of the thesis, Gabriel Ciubotaru, and can be attained by accessing the following link: https://github.com/k2ux/EDIS.

a. The "# Setup" code

The "setup" file allows us to edit the header of the *.epw file. The main elements we have to set are:

- correct headers (location, GPS data, etc.)
- \`sample_time\`
- \`PYR20.port\` to correct USB port (use \`ls /dev/ttyUSB*\` to find the correct port)
- correct scale for sensor data

b. The "# Config.json" code

This part of the program defines the header and the defining fields for the collected data. Here we can set the details of the location as well as set correction scales to the sensor outputs. Each sensor can be found by its set name within the *.epw file.

c. The "# Collect Data" code

This part of the python code is used to run the function of collecting all sensor data in order to be assigned within the *.epw file.

d. The "# Convert data" code

To convert the data to `EPW` format, we need to run the following line within the Raspberry Pi console:

7.3.3. The Program Graphical User Interface

A graphical user interface, abbreviated as GUI, is a type of user interface that enables users to interact with computers and other electronic devices through visual indication representations. The GUI for the EDIS is a simple window with buttons that will automatically run the function codes when needed.

Fig. 7.41 - Graphical User Interface (image by author)

The software program interface allows us to start and stop the data recording, show the Config code to be able to edit the computed data, export the latest recordings, and also show the data logs in case of errors.

7.3.4. Prototype data Test

Since the main use of the EDIS is to generate data that should be analyzed within Ladybug, we have done some testing and comparison with the already available data from Barcelona. To do this we made an analysis chart for all the available data on the span of one day and put them side by side.

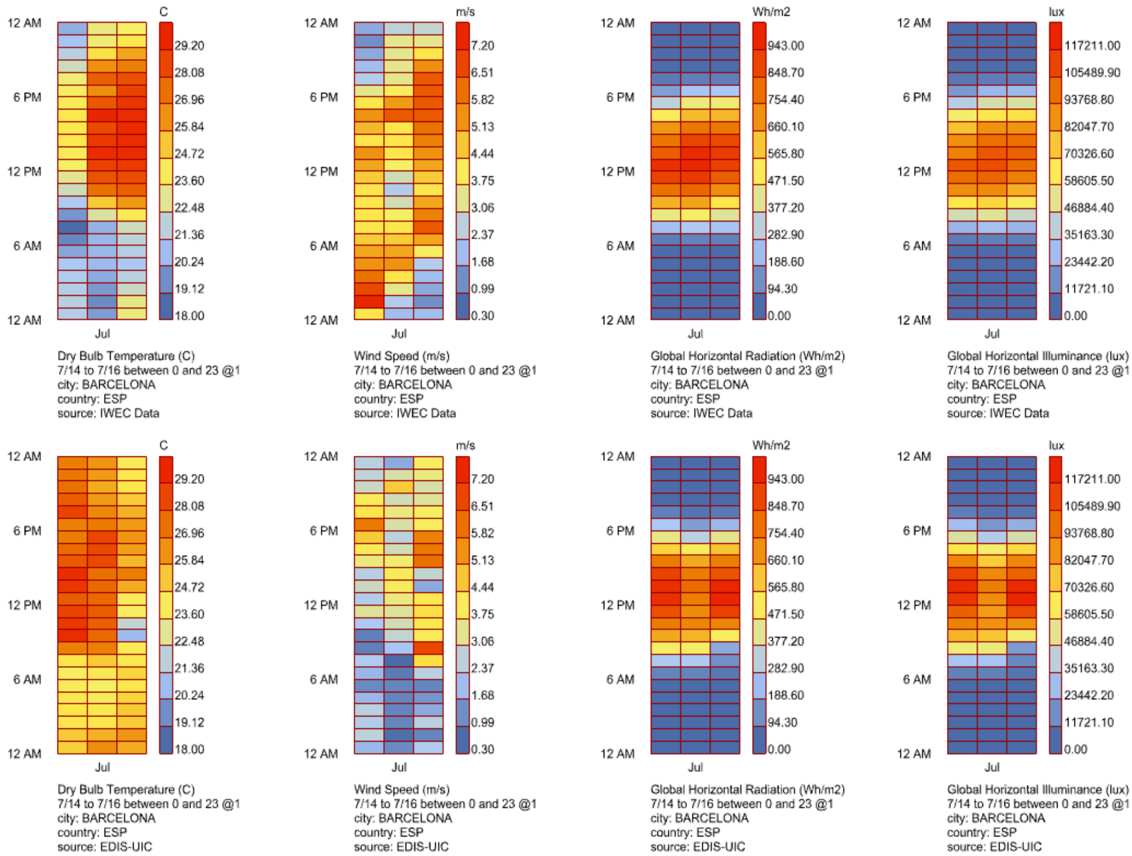

Fig. 7.42 - Test Data Comparison in Ladybug (image by author)

Thus, we can see that the file works correctly, having the existing data in the first row and the collected test data in the second one. For a more visual experience, we will use the Global Horizontal Radiation data and map it on the university building. To achieve this, we have imported the Google Earth photogrammetric model of the building site as a mesh.

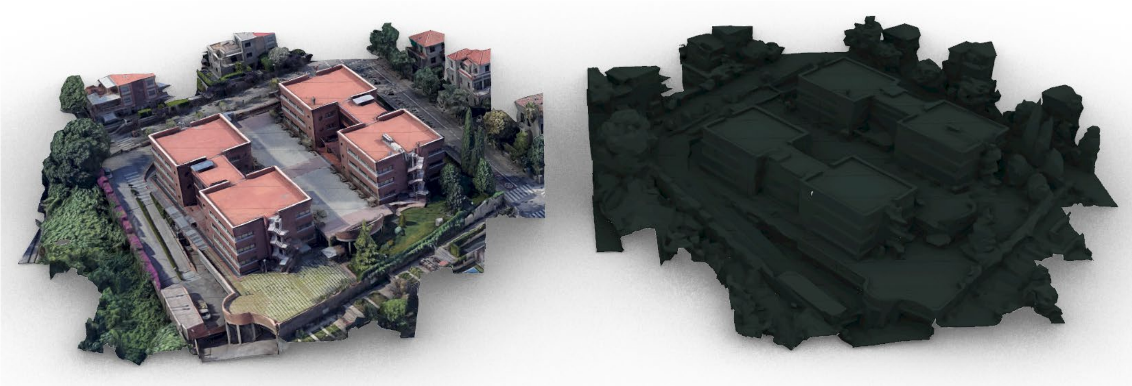

Fig. 7.43 - UIC Campus imported from Google Earth to Rhino (image by author)

On the left side, we can see the site model with the satellite images mapped on it, while on the right we have a bare mesh representation.

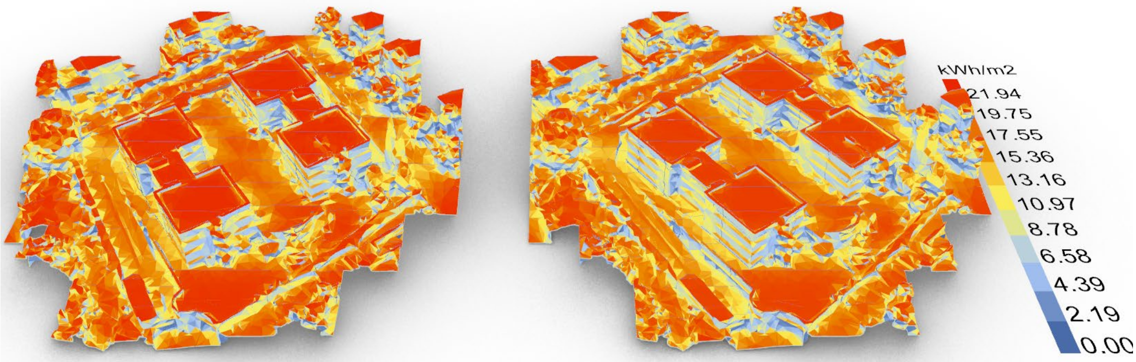

Fig. 7.44 - Radiation Analysis comparison on the UIC Campus (image by author)

Thus, through the comparative analysis we can observe that for the three-day span of data that we have used, the site was exposed to slightly more radiation based on the old *.epw (left, collected at the El Prat airport) than on the one generated by the EDIS (right, collected on-site).

Now all that is left to do is to set the EDIS outside and let it run for as much as possible.

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ABEM

Adaptive Building Efficiency Methodology

8. Adaptive Building Efficiency Methodology (ABEM)

Through all the means and information on hand, this chapter is envisioning its use through an adaptive building efficiency methodology.

The idea focuses on the development of a framework that would guide architects and designers towards achieving highly-efficient adaptivity within novel construction. This would imply the development of adaptive systems that are procedurally based on the interpretation of the data collected by the EDIS, (which is destined to be widely available to anyone who wishes to use it), the efficiency standards (based on the site's location), and by the conceptualization of adaptive behaviors (based on the study of the nearby natural environment).

In the end, we believe that collective contribution and open-source collaborations will take a concept beyond its limits and will be to everyone's good use.

The algorithm parameters that compose the facades enable a method for developing responsive solutions and scenarios based on conclusions that transform static modeling into interactive. These results allow the designer to compute and optimize the appropriate design parameters by providing the input algorithm flexibility. As a result of the logic evaluation, a dynamic series of design instruction processes emerges.[416]

[416] Alireza Jahanara and Negar Kalantar, 'KINETIC SHADING SYSTEMS: A Parametric Approach to Optimizing Daylighting Performance', ed. by Karen Kensek, Douglas Noble, and Matt Elder, *Facade Tectonics - SKINS on Campus: Bridging Industry and Academia in Pursuit of Better Buildings and Urban Habitat*, 1 (2018), 461–73.

8.1. Methodology description

The ABEM consists of a succession of interrelated logic-based translations of a larger idea to investigate adaptability in the contemporary architectural era. This can be seen as a fusion of ideas and transfer of intelligence within an intermixture of technology-based systems that in turn offers an accentuated degree of complexity, both in the finished product and in its development.

The increasing complexity of ideas and information develops through time, extending the mind's perception bubble to create more concise adaptive systems. To simplify this process, a workflow is envisioned in order to translate and manage all the information acquired within the previous studies.

The first step is related to the actual site on which our edifice will be generated, or in other words, “location, location, location” (Harold Samuel). The site analysis should be mandatory since it will influence the characteristics and efficiency strategies of the building.

The second step consists in the development of the initial massing of the building, alongside its functions. This can be done by taking into account the destination of the building alongside its specific architectural characteristics. This step highly implies conceptualization based on existing natural adapted and adaptive systems within the surrounding environment. These conceptualizations are intended to establish an early-stage relationship between the future indoor and outdoor environments, whilst capitalizing on adaptivity traits uncovered within the natural surrounding area (see Fig. 8.2).

Thirdly, the massing itself should be optimized to capitalize on the energy efficiency aspects. The optimization will be based on procedural modeling including the computational evaluation. Through this procedure, we will obtain the main informational reference that will be used to generate the envelope and morphology.

The final step is to manage the reference based on the recursive development of design surfaces, each of which will hold all the information regarding the environment and specifications of the efficiency strategies. These elements will be labeled and categorized as Informational Reference Surfaces (IRS).

The IRS themselves are envisioned as having certain characteristics or hierarchical positions within the project that would define the generated envelope. In this sense, the usage of inflexible rectilinear coordinate systems of grids and elevations cannot be used to graphically define our complex systems, since they lack the informational characteristics obtained from the previous steps.

Thus, the IRS will be the main control reference, being the base geometry from which the envelope will be unveiled, representing either the glazing, cladding, or structural areas.

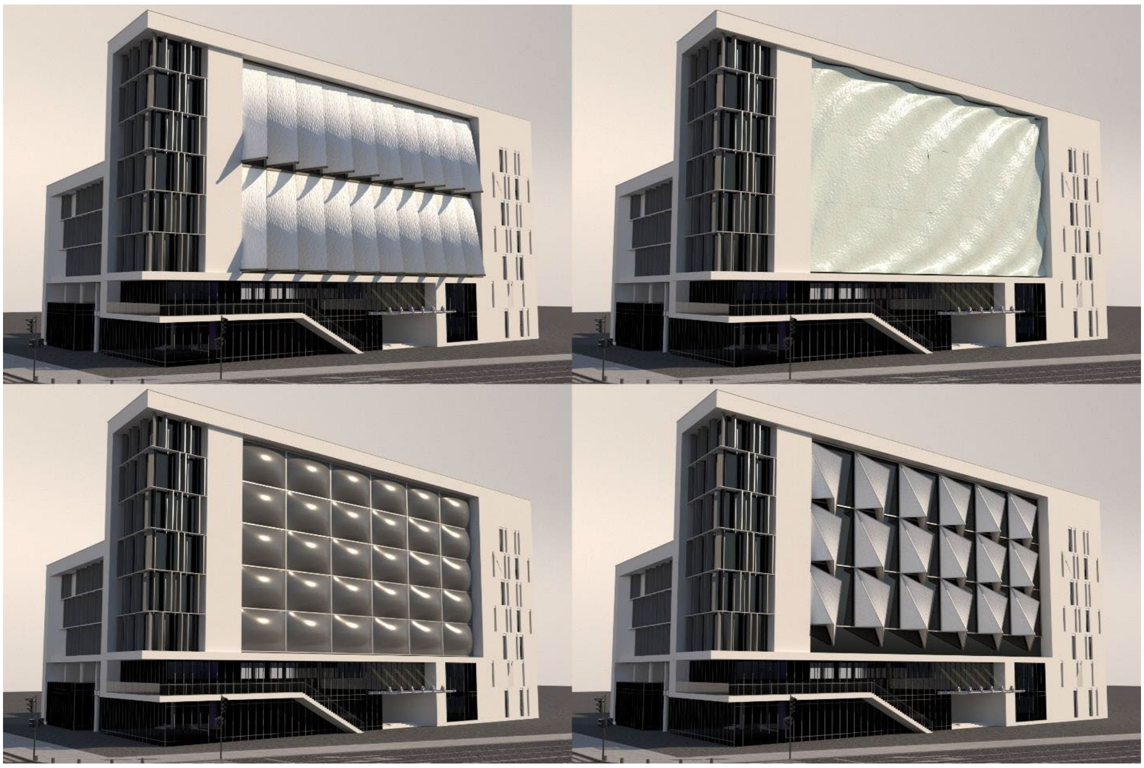

Fig. 8.1 – Envelope Variation based on IRS

Depending on the type of morphology we have, we have to address the edges or the border between two or more types of IRS. In most cases within architecture, one would argue that these are vexing issues in architectural detailing, instead of ideas that just need further thought and debate about how they will function as a system.

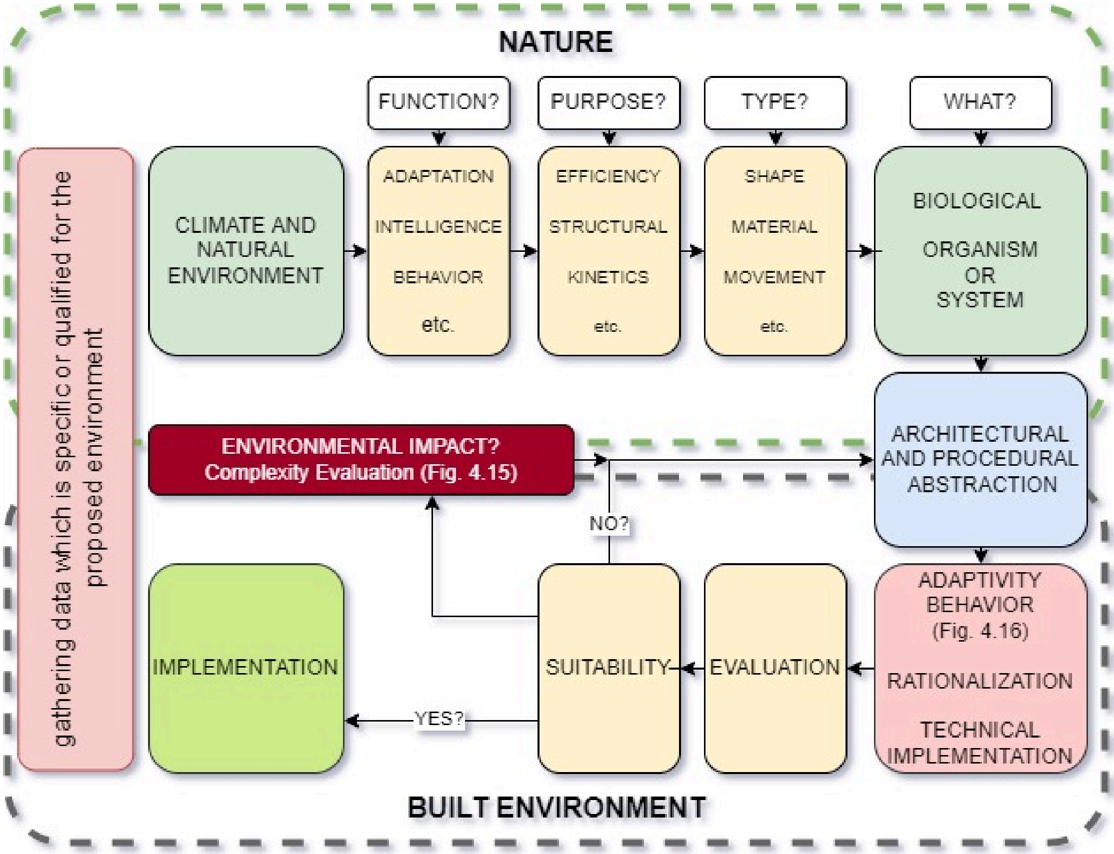

Fig. 8.2 - Biolearning Process and Conceptualization (image by author)

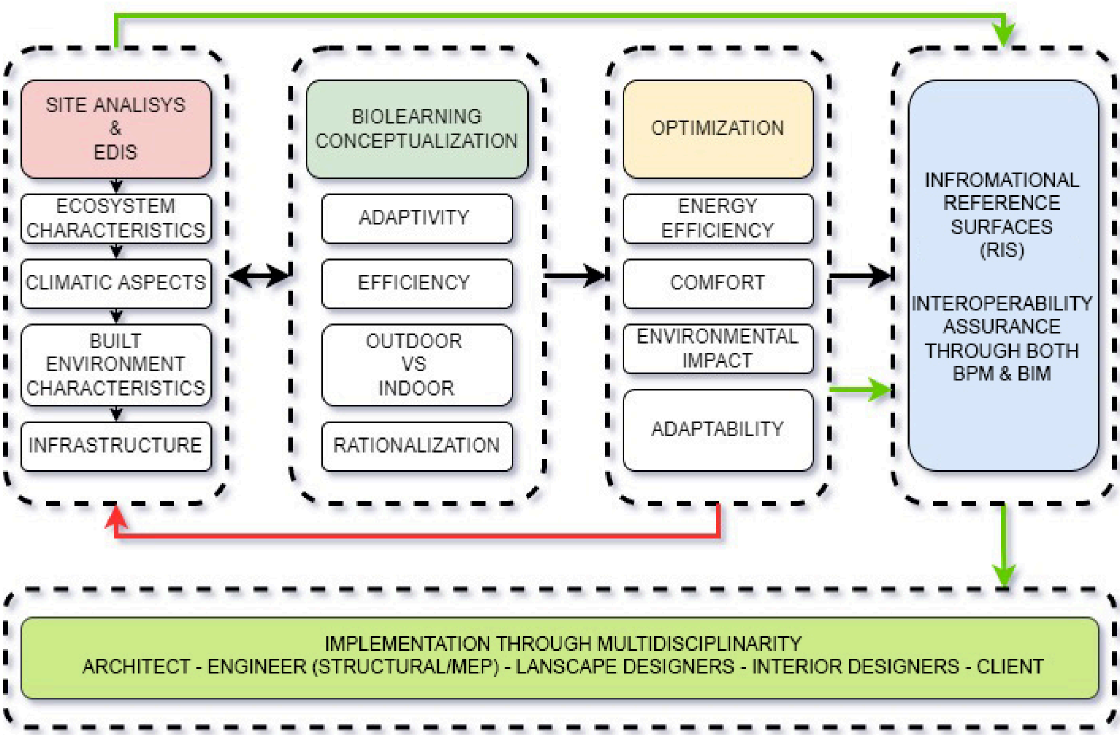

Fig. 8.3 - ABEM framework (image by author)

Within this section of the thesis the ABEM is addressed by showcasing some of the student's designs, elaborated within the Master of Biodigital Architecture studios: "Architectural Biolearning" and "Adapted and Adaptive"; conducted by the author of the thesis. All the projects are detailed as the students did within their submissions.

8.2. Architectural Biolearning Studio

The Architectural Biolearning studio accounts for the conceptualization of the development's adaptivity behavior. Thus, this studio focuses on the investigation, theory, and design methods for integrating natural intelligence in advanced architecture through different morphologies and technological applications.

The program is structured on the span of one intensive week in which the students have to complete four design exercises to develop their methodologies for implementing natural intelligence.

The first exercise is a practical one, constructed on the idea of hybridization. The participants have to gather two or more natural elements and combine them to form a holistic pavilion concept that would offer a type of performance.

The second step is to study how nature solves connections and develop a digital model of a connector. The functionality of the resulting concept can be interpreted from three perspectives: connection to the self, to another similar unit, or to something else entirely.

The upcoming exercise implies the development of a digital model of a performative panel, by focusing their studies on skins, boundaries, or natural surfaces.

As a final step, the students have to create a "biolearnt" digital pavilion, by combining the methodologies of all previous exercises.

In the following, we will showcase some of the student results alongside their comprehension regarding biolearning. All the projects are detailed as the students did within their submissions.

a. Hybridization Project 1: Root Pavilion

Result by Natalia Andrea Alonzo Ramirez

This experiment is based on the hybridization of grape branches and mushrooms.

Fig. 8.4 - Elements used to design the Hybridized Pavilion (mushrooms and grape branches)[417]

In this sense, the concept of this pavilion is about a central structure formed by the branches of grapes, which are emerging from the ground, rising in order to form arches. The mushrooms are emerging from the tip of the branches as large parasols, which also extend to the ground to supplement the structure.

The intelligence factors taken into consideration were the mushroom gills and textures that offer good sound insulation, as well as its porosity that has good insulating capabilities in terms of heat dissipation.

Fig. 8.5 - Pavilion elevations[418]

The branches allow for the connection of all the services to the mushroom panels, which scatter both the light and the sound towards the different spaces that are created under their shadow.

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[417] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

[418] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

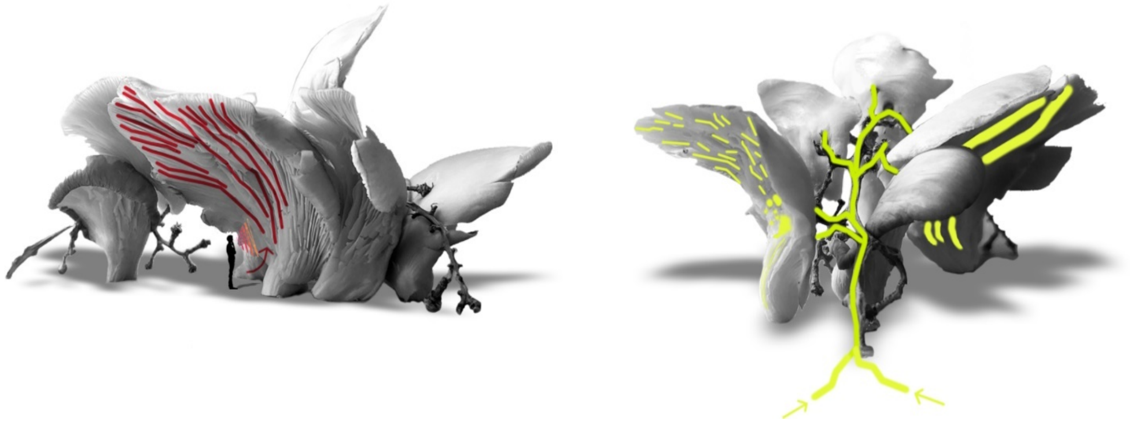

Fig. 8.6 - Pavilion Performances[419]

[419] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

b. Hybridization Project 2: Bottle Tree Pavilion

Result by Surekha Dasari

This project is created by the use of two elements of the same plant specimen, which is a bottle tree. The boat-shaped seed pods of the tree are full of many seeds that are coated with hairy strands, forming a dense layer of fuzz.

Fig. 8.7 - Pavilion elements[420]

The attachment between the seeds is done by natural contact forces, turning the layer into a dense matt of spines. Hence the matte behaves as a continuous surface that serves as a canopy for the pavilion.

Fig. 8.8 - Pavilion Perspectives[421]

The purpose of the stem/stalk of the pod is to hold its major organs, being achieved by a star-shaped geometry that forms its base and a slender, elongated geometry that represents the main connection between the base and the main

[420] Image by Surekha Dasari, post processed by the Author

[421] Image by Surekha Dasari, post processed by the Author

plant. The inverse reciprocation of this concept is used in the pavilion as the supporting structure. Two extra support modules are arranged between the supports to form a continuity and generate leisure spaces.

Fig. 8.9 - Pavilion base and elevation[422]

[422] Image by Surekha Dasari, post processed by the Author

c. Hybridization Project 3: SunShower Pavilion

Result by Julieta Grimberg Golijov

The Sun Shower Pavilion was born from the idea of combining two elements found in nature independently and without any relationship between them. One of the parts is the leaf of the "Ficus Lyrata" plant with a similar hue to the sun and a pattern that follows the Voronoi diagram. On the other hand, we have a seed that in itself is structural and provides a roof and a floor that protects its breeding pump from the rain.

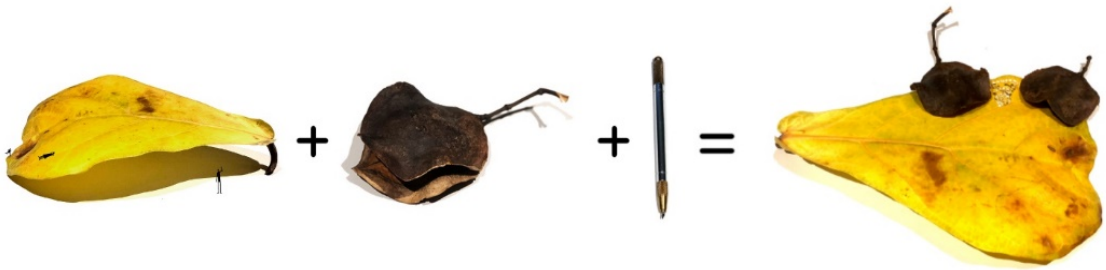

Fig. 8.10 - Pavilion elements[423]

By joining these elements by using the seedpod as a "stapler" and causing perforations in the surface of the leaf that remains between them (following the pattern that forms it) we can achieve a canopy that shifts the sunlight. We can add as many seeds as the leaf can contain in its perimeter.

Fig. 8.11 - Pavilion Details[424]

[423] Image by Julieta Grimberg Golijov, post processed by the Author

[424] Image by Julieta Grimberg Golijov, post processed by the Author

As a result, we have a big open pavilion that contains vast areas employed in different experiences such as playgrounds, concerts, or resting areas.

Fig. 8.12 - Pavilion Perspective[425]

[425] Image by Julieta Grimberg Golijov, post processed by the Author

d. Connector Project 1: "Stamen"

result by Natalia Andrea Alonzo Ramirez

This connector is designed based on the morphology and operation logic of the orchid's stamen, this being the male reproductive organ of the flower.

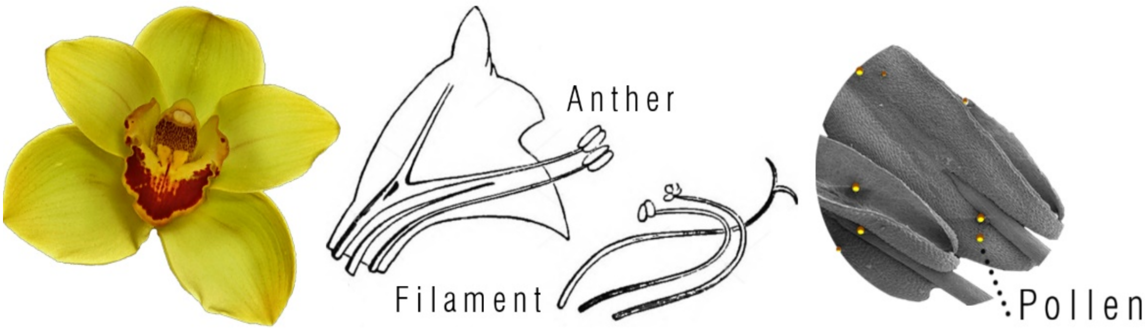

Fig. 8.13 - Stamen details[426]

The stamen is composed of two elements that are the anther and the filament. These function as one producer and pollen storage bag and the other as a structure that supports the anther and facilitates other organisms to gain access to the pollen.

Fig. 8.14 - Connector details[427]

The elements that were further studied for the connection properties were the reproductive organ, translated as a self-replicating connector, and the conductive elements of the filament, allowing for the flow of fluids inside, from one unit to

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[426] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

[427] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

another. The connections are designed to have both a male and female property, allowing for sequence assemblies

Fig. 8.15 - Series connection[428]

[428] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

e. Connector Project 2: “Sapica”

Result by Al Jaafari Abd al Qader

The purpose of this design is to deliver an innovative re-design of the typical building foundation footings. The current foundations and footings require massive excavation works and usually are cast in place concrete works that need to dry until it is functional.

Thus the objective was to provide a prefabricated foundation system that can be pushed into place with minimal to no excavation requirements while maintaining a maximum grip on the surrounding soils.

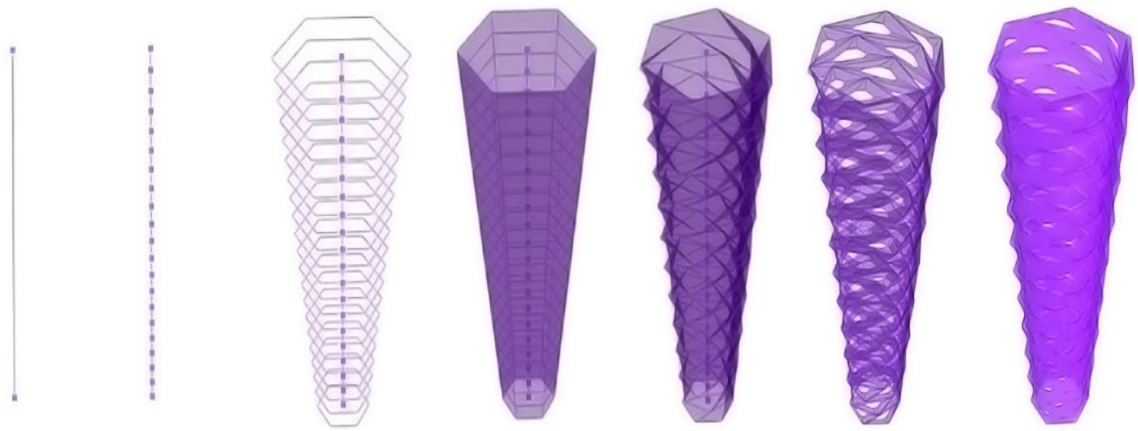

Fig. 8.16 - Model design steps[429]

The idea of the design was inspired by the roots of teeth and the mechanism of how they are fixed into the jawbones. Where they have a conical porous lattice. The general design of the units is conical in shape to allow for better penetration of the soil while the porous skeleton is meant to allow for the soil to envelop the units while not disrupting the surrounding soil or the immediate water table.

Further to that, the units are meant to be rough on the surface with extrusions to assist with the unit's fixation into the soil.

[429] Image by Al Jaafari Abd al Qader, post processed by the Author

A prototype was created and tested with promising results as the unit consumed minimal material, had successfully been drilled into the soil and presented a moderate resistance to being pulled out regardless of its smaller scale and material. Further development and tuning to the texture, pores, material selection, fabrication, and cone angle are required to fine-tune the design.

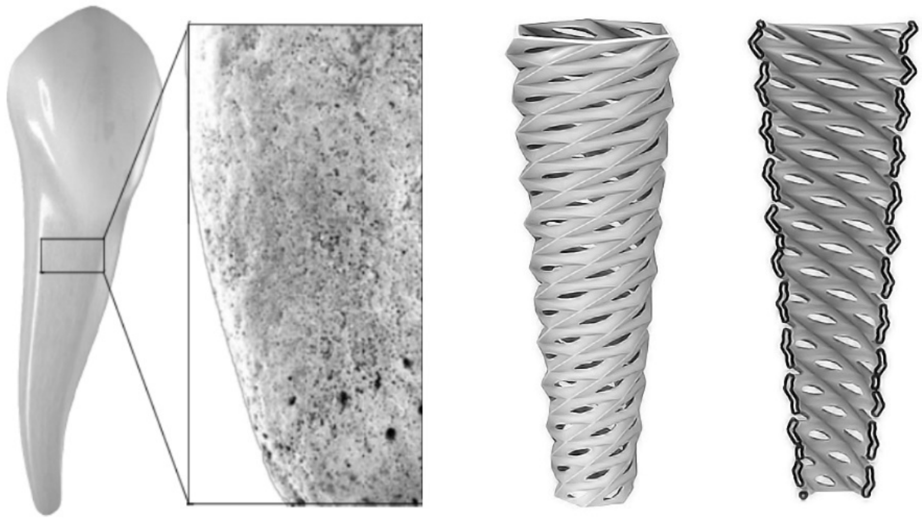

Fig. 8.17 - Study and Connector detail[430]

[430] Image by Al Jaafari Abd al Qader, post processed by the Author

f. Panel Project 1: “Climastone”

Result by Natalia Andrea Alonzo Ramirez

This panel is designed based on the logic of water transport in plants like orchids or Amazon water Lily and perspiration in mammals, this is to achieve a panel that allows the temperature decrease and bioclimatic improvement of different spaces, naturally.

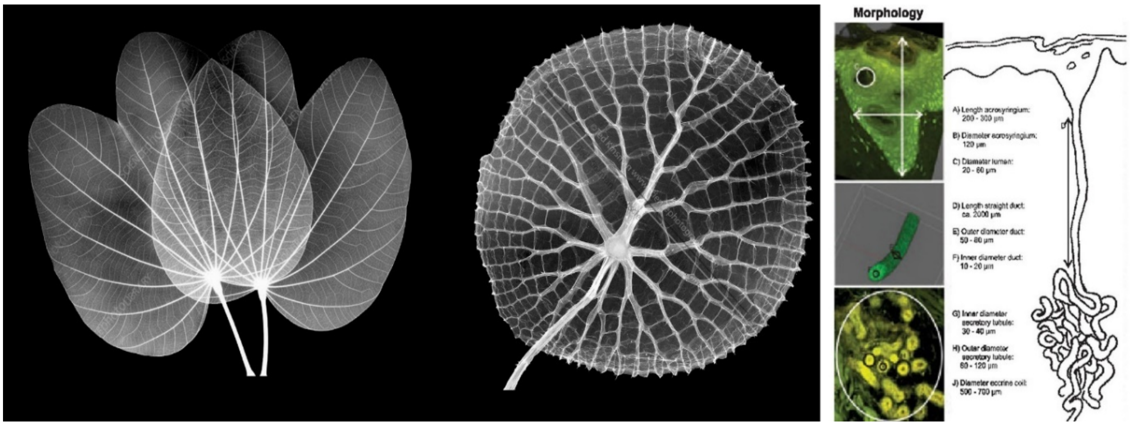

Fig. 8.18 - Study Diagram[431]

The shape of the panel has a rotation on its central axis that allows the presence of plants in its lateral parts. The top of the panel holds the property to collect eventual rainwater, as well as to intricately connect to other panels in a series.

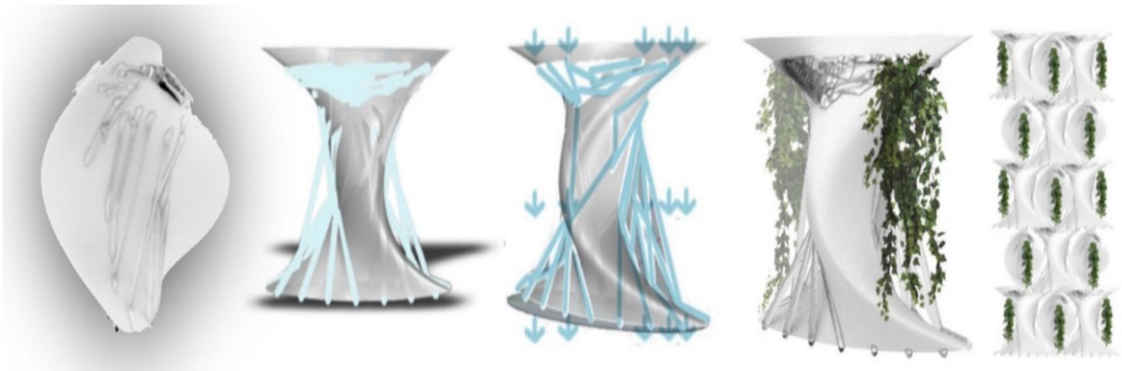

Fig. 8.19 - Elevations and Specifications[432]

[431] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

[432] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

The plants will be sustained and hydrated from a pipe system inherent to the panel that runs from top to bottom, reaching all panels. If the climate is dry, water can be run within the panel from the local system, constantly cooling down the surrounding area.

The panel is envisioned for both indoor and outdoor use and it is meant to be self-sustainable from a structural point of view.

Fig. 8.20 - Climastone Panel Closeup[433]

[433] Image by Natalia Andrea Alonzo Ramirez, post processed by the Author

g. Panel Project 2: "Mazing Panel"

Result by Javier Gonzalez Castillo

From the combination of physical features of a surface and simple controls of growth rates over time, biological systems can develop complex structures. External factors such as light, heat, gravity, humidity cannot be excluded from the natural growth process.

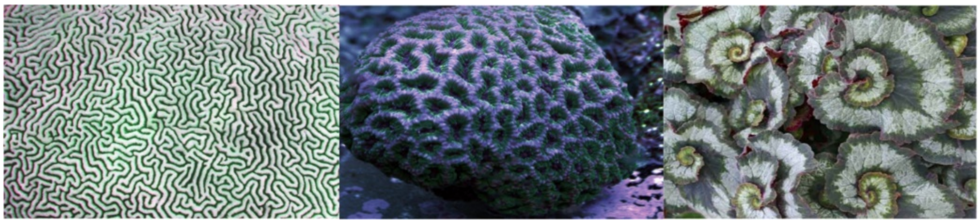

Fig. 8.21 - Brain Coral, Mushroom Leather Coral, Rex Begonia "escargot" [434]

The panel was created through the concept of differential growth. This is a cell characteristic of the organs they build, as well as of the entire being. The differential growth regulation resides in three organizational levels. Each one resides in the level below the one in which it is articulated. Therefore, the behavior is governed by the cellulose microfibrils in the walls and patterns of intracellular microtubules, by the pattern of cell growth, and by the relative rates of organ growth.

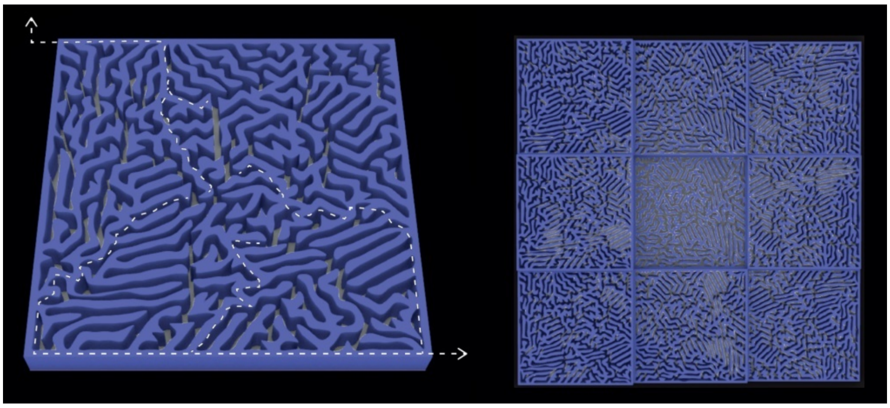

Fig. 8.22 - Panel Unit and Series[435]

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[434] Image by Author

[435] Image by Javier Gonzalez Castillo, post processed by the Author

The performative aspects of the panel were revolving around acoustics and sound absorption. In this sense the panel texture variates based on how much sound needs to be conducted. In terms of materiality, clay and silk fibers were considered, in order to either absorb or reverberate the sound.

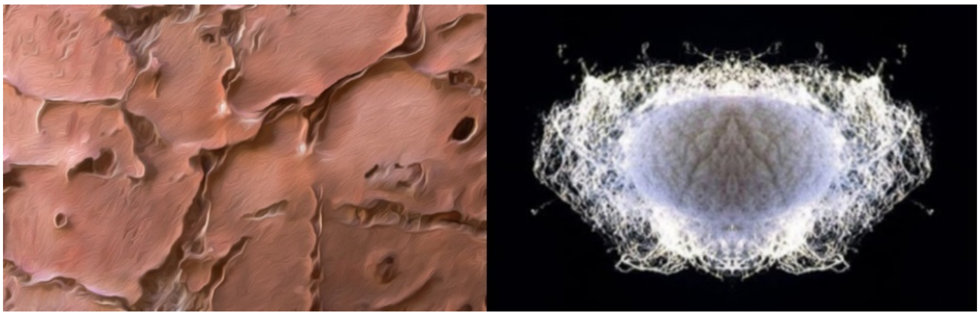

Fig. 8.23 - Clay and Silk[436]

[436] Image by Author

h. Pavilion Project 1: "Iridescent Pavilion"

Result by: Al Chami Khadija, Dasari Surekha Srinivas, Tarek Elgazzar Nadine

As inspiration for the development of the pavilion, the students looked at the white royal butterfly egg and hummingbird feathers.

Fig. 8.24 - Butterfly Egg (left), Hummingbird Feather (right)[437]

The eggs are laid on the backside of a grown leaf by the female. Each egg measures around 0.7mm in diameter and is covered in a reticulated pattern of ridges and pits.

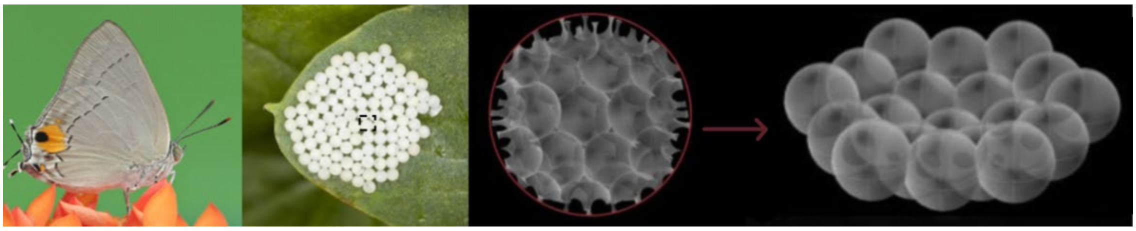

Fig. 8.25 - The white royal butterfly, its eggs on a leaf and a model of the egg structure[438]

The plumage of the hummingbird is functionally identical to those of other birds, but they generate unique iridescent colors. The feather's shaft is made up of alternatingly thread-like barbules and hooks that expand at appropriate angles to cling together and preserve structural integrity while being sufficiently flexible to

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[437] Image source: https://wewanttolearn.wordpress.com/ and https://www.audubon.org/

[438] Image source: https://wewanttolearn.wordpress.com/

bend or disengage without breaking. Feathers are stacked one over another, revealing just the iridescent tips and include keratin proteins, which give flexibility, integrity and act as a natural insulator. Birds' bodies and appendages are covered in contour feathers. Differences in the angles of these feathers lead to variations in the colors visible from various positions.

Iridescence is affected by the object's position, the observer's position, and the light rays impacting the object. The Pavilion takes advantage of the color palette, which was inspired by the iridescence of the feathers. Color is both an aesthetic device and a powerful tool of communication. By emitting colors in reaction to dynamic atmospheric changes, it serves as a signal for current and upcoming occurrences.

Vibrant colors are a means of expressing energy and passion, as well as increasing the users' sensory and spatial experiences - both close up and far away. The pavilion maximizes and enhances sunlight reflectance while reducing the number of artificial light sources.

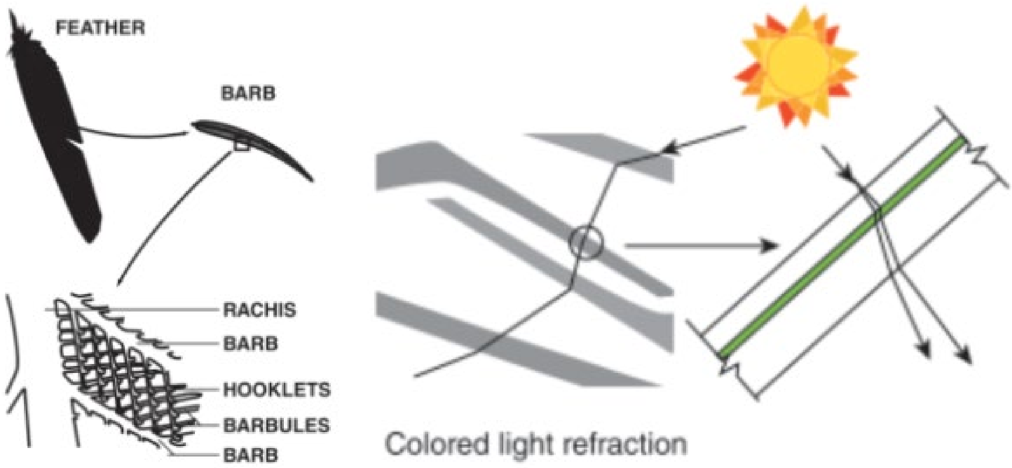

Fig. 8.26 - Feather elements and light refraction principle within the pavilion[439]

The Pavilion's joinery system is inspired by the hooksets and barbules in a Hummingbird's feather, as well as the use of light refraction concepts amplified by water. Each panel is curved inward to mimic the butterfly's egg geometry, while

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[439] Mazzoleni and Price, *Architecture Follows Nature: Biomimetic Principles for Innovative Design*.

also using the property of concave mirrors to allow light to be refracted in different directions.

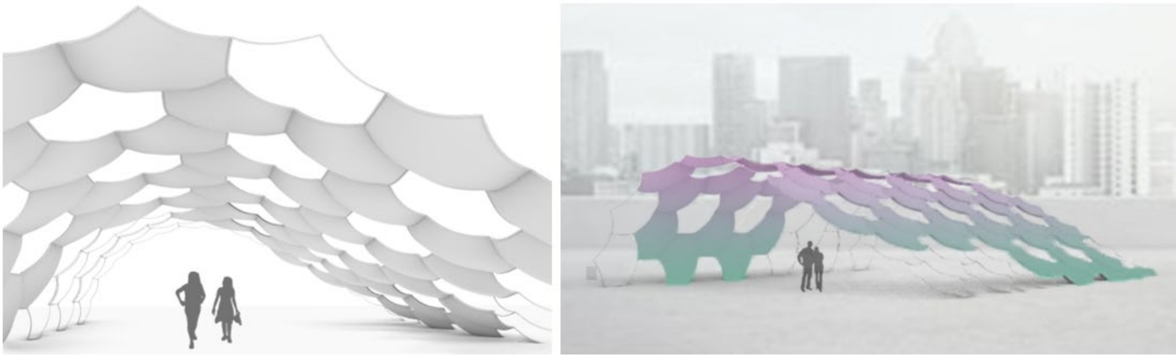

Fig. 8.27 – Pavilion Initial approach[440]

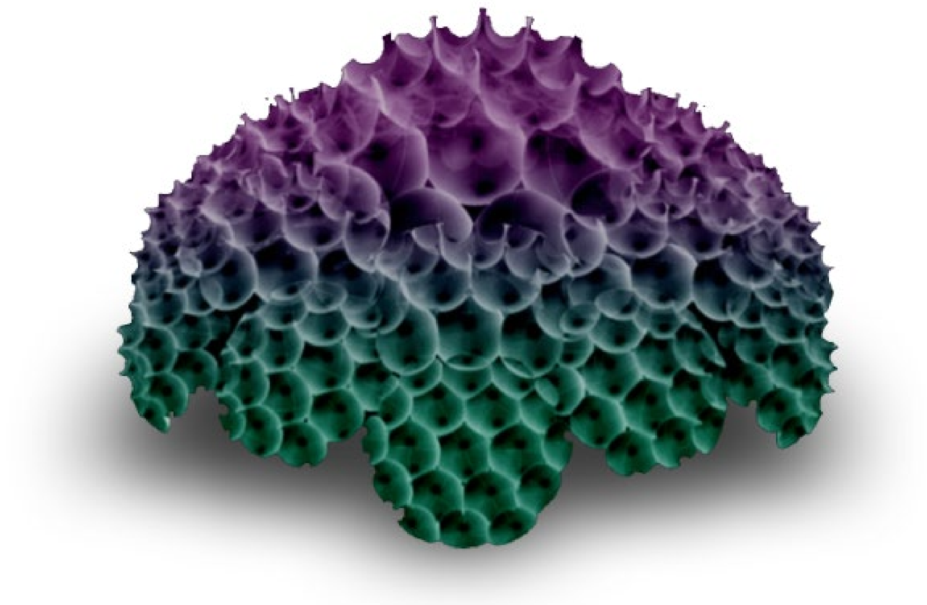

Fig. 8.28 - Final Variation of the pavilion[441]

[440] Image by Image by Javier Gonzalez Castillo, post processed by the Author

[441] Image by Javier Gonzalez Castillo, post processed by the Author

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i. Pavilion Project 2: "MNMS Pavilion"

Result by: Alonso Ramírez Natalia, Tipnis Mruga, Maksoud M. Mohamad

The students used two concepts for the creation of this pavilion: jellyfish locomotion and soundwave behavior.

The jellyfish's movement is based on the contraction and relaxation of its body generating a force of impulse in the desired direction, this contraction and relaxation generates in the water forms of a vortex and therefore waves.

Fig. 8.29 - Jellyfish locomotion and movement fields[442]

The initial pavilion shape was inspired by these motions and the structure was envisioned to expand or contract depending on the movement of people who enter it. The surface can also deform creating spaces with a roof.

Fig. 8.30 - Pavilion development[443]

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442 Image source: https://www.youtube.com/watch?v=5nzep7JRJfs&ab_channel=NicholasBattista

443 Image by Alonso Ramírez Natalia, Tipnis Mruga, Maksoud M. Mohamad, processed by the Author

The second implementation was focusing on the interactions of the people and the pavilion, by taking into consideration the soundwaves, which are defined as longitudinal mechanical waves, caused by the movement of some portion of an elastic medium (solid, liquid, or gaseous) concerning its equilibrium position. Due to the elastic properties of the medium, this disturbance can move from one place to another.

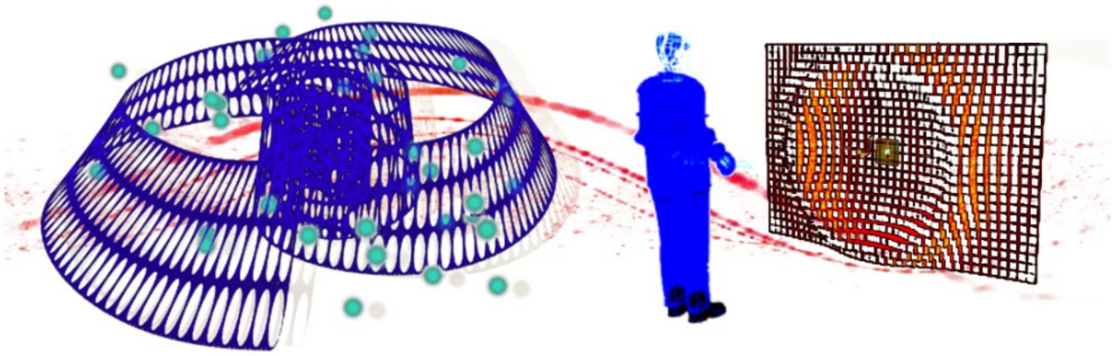

Fig. 8.31 - Pavilion final iteration and Interaction example[444]

Finally, our main point here is to focus on how we can reflect learning from nature to our project so we can generate and create a system that can change the behavior of itself as if it is a living creature, not a solid geometry. So whenever there are different sound waves, it is going to act in regards to it.

Fig. 8.32 - Interior ambiance[445]

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[444] Image by Alonso Ramírez Natalia, Tipnis Mruga, Maksoud M. Mohamad, processed by the Author

[445] Image by Alonso Ramírez Natalia, Tipnis Mruga, Maksoud M. Mohamad, processed by the Author

If we can imagine having this pavilion in a forest, and how it is going to change the actual form and act depending on different sound waves that are going to get from nature such as wind, animals, etc.

8.2.2. Observations

The studied exercises point out the viability of natural intelligence within the conceptualization of architectural design regarding certain needs, such as thermal, acoustics, connections between elements, conductivity, light management, etc.

These concepts can be analyzed from two perspectives: how hypothetical or realistic they might be, and based on the viability of conceptualization.

Nr.	Concept Name	Hypothetical / Veritable	Viability of Conceptualization
		-5 = Most Hypothetical 5 = Most Veritable	-5 = Less Viable 5 = Most Viable
1	Root Pavilion	3	5
2	Hybridized Pavilion	-5	-2
3	SunShower Pavilion	1	-2
4	Stamen	4	3
5	Sapica	5	3
6	Climastone	4	2
7	Mazing Panel	5	5
8	Iridescent Pavilion	2	0
9	MNMS Pavilion	-1	-3

Table 8.1 - Conceptualization Comparison

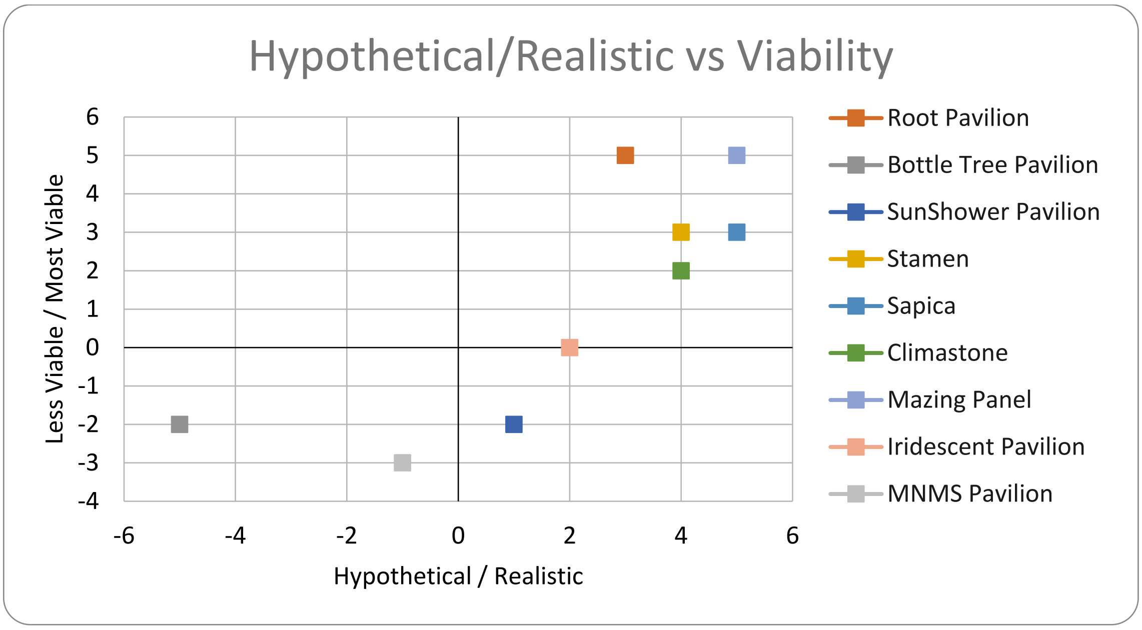

Fig. 8.33 - Conceptualization Comparison Visualization (image by author)

These perspectives are valuable in order to understand the ease of implementation as well as the research depth and concept approach. As observed, most projects show a higher tendency towards viability and realism.

To justify the assigned evaluation it is necessary to review each project individually. The chosen topics (hybridization, connection, performative panel, and pavilion) are meant to simulate different needs within an architectural development.

The hybridization approach is purposed to help students experiment using inspirations from different mediums and successfully combine them into a holistic solution. The connection approach is for them to focus on a clear function by studying it in nature. Performative panels became common in architecture, being part of either the building's envelope or as functional tools for the interior environment, thus the students had to capitalize on pure performance from an architectural perspective. Finally, the last pavilion exercises are meant to combine all experiences from the previous into a holistic design.

Root Pavilion

The "Root Pavilion" hybridization was envisioned as a public space for performers. The approach towards achieving high acoustics using the morphology of a mushroom's gill, as well as its convex overall shape, and combining them with certain material types that would absorb or reverberate sounds presents high viability of correct implementation.

In this regard, the conceptualization is rather realistic in terms of developmental properties.

Bottle Tree Pavilion

The "Bottle Tree Pavilion" concept was envisioned as a shade generator with seating areas. The approach is rather hypothetically focusing on the materiality of two elements of the same species. In one case the concept could have viability regarding the seed's ability to stick to its neighbor (or something else), but the scale at which it is envisioned would impede the implementation.

Thus, the conceptualization is less viable for the proposed theme as a pavilion.

SunShower Pavilion

The “SunShower Pavilion” has a good ambiental approach. Focusing on material hue and pattern whilst envisioning a space using the individual morphologies of each element posits a realistic achievement. On the other hand, the viability at a large-scale leaves open questions regarding structural materiality.

Stamen

The “Stamen” connector posits a very interesting approach since the studied elements do not present a connection property. But, the rationalization of the morphology and integrating it as a modular connector offers a viable approach. This enables a variety of combinations to achieve different functionalities holistically.

Sapica

The “Sapica” connection solution is offered by the study of tooth roots, especially at a macro level where functional perforations can be observed. This approach is meant to be envisioned both at a large scale. The translation of the concept morphology into a type of less invasive drill while accounting for the connection can be easily implemented and tested.

Climastone

The “Climastone” panel was envisioned as having cooling properties based on the lily pad veins, and the perspiration function within mammals. These natural traits represent a good approach regarding the main intention of the student since vascularity and transpiration have been developed by living beings over a huge period of time.

The conceptualization also focuses on an interesting morphology that maximizes the exposed surface for more contact and interaction between the built and natural environments. Thus, this approach presents highly veritable in terms of functionality, while the viability is slightly reduced due to its complexity.

Mazing Panel

The “Mazing Panel” proves to be a highly efficient approach towards acoustic solutions. The conceptualization proposed by the students revolves around the behavior of differential growth as well as common material properties. Their solution to acoustic optimization is emphasized through a procedural application that influences the depth of the grooves as well as their shape. This enables further testing within the computational domain as well as within actuality.

Thus, in terms of both aspects of viability and veritableness, the conceptualization can be seen as successful.

Iridescent Pavilion

The “Iridescent Pavilion” presents a complex approach from the study of the royal butterfly egg connection performance and the humming bird’s feathers’ refraction and interconnection. Since the connection aspects were addressed just in terms of morphology without a high emphasis on the actual performance the project presents medium conceptualization viability. On the other hand, the visual effect towards which the students aimed by studying the hummingbird feathers brings forth realistic ways of implementation for the desired purpose.

MNMS Pavilion

Within this project, the students’ approach towards conceptualizing a pavilion focuses on the behavior of a jellyfish in terms of movement and the movement’s effect on its immediate surroundings. The behavioral functionalities were intended to be implemented as a reaction-feedback mechanism built-in within the pavilion, but the premise was not fulfilled within full, lacking both in details regarding mechanism and materialism. Thus, the conceptualization is rather hypothetical and with a small chance of viability.

Conclusion

Looking over the graph within Fig. 8.31 we can observe that most of the exercises were resolved with a high tendency of realism and viability.

8.3. Adapted & Adaptive Studio

Through the “Adapted and Adaptive” studio the students followed the process of implementing adaptivity strategies in architecture within the development of energy-efficient buildings through computational environmental analysis.

The students studied the Passive House and Active House principles and tried to apply them within their design by analyzing and evaluating the environment through the Ladybug tools.

The methodology employed is based on what we have synthesized within this chapter of the thesis. Thus, as a start, each group of students had to choose a specific biome, analyze the site’s environment, conceptualize based on biolearning principles and develop a house meant to be adapted (suitable for the environment in which it is been placed, from both the natural aspect, as well as from its occupant) and adaptive (in terms of the environmental shifts)

In the following, we will showcase some of the student results alongside their comprehension regarding adaptivity in architecture. All the projects are detailed as the students did within their submissions.

8.3.1. Project 1: "Sunflower House"

Results by: Julieta Grimberg Golijov and Rizkallah Ghazaly

The "Sunflower House" is a house inspired by nature and with a low environmental impact. Taking the sunflower as a bio-reference, we are inspired by its patterns and behavior to define the morphology and functionality of the house. The project location was set in Barcelona, Spain.

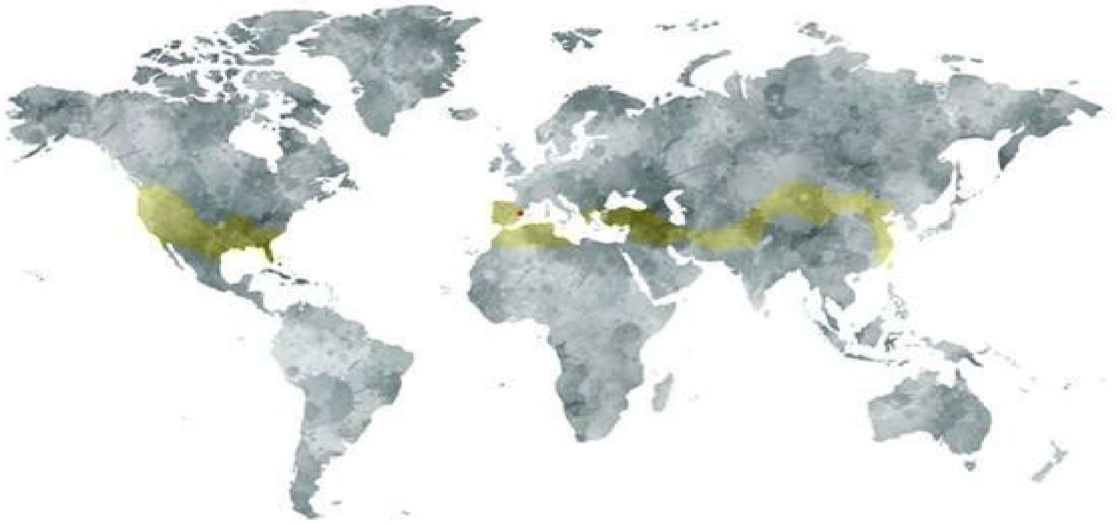

Fig. 8.34 - Biome: Warm / Climate: Mediterranean / Environment: Chaparral[446]

In the sunflower, we can see how the Fibonacci series is not only manifested in the position of the seeds but also in that they increase in size as they move away from the center of the flower. We take this concept of growth in three dimensions to define the morphology of the house.

The movement of the flower throughout the day inspired us to generate the position of the different floors of the building (rotating from its center), together with the search for the best orientation for each function in the house.

On the ground floor, we can find the common area of the house (kitchen, dining room, and living room). The night area (bedrooms) is distributed on the middle floor and, on the top floor, we find an elevated pavilion that houses a south-facing

[446] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

study that is protected from the sun with a canopy inspired, once again, by the seeds of the sunflower.

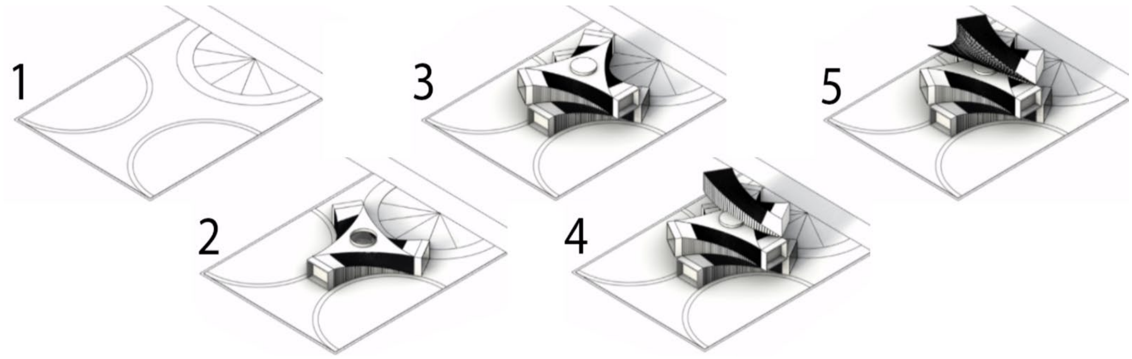

Fig. 8.35 - Sunflower House Morphology[447]

All the floors are linked by a vertical core with a spiral staircase that rotates around it, generating a feeling of great spaciousness in all the floors. At the last level, this nucleus is transformed into furniture outside, generating a rest space that flows with the design of the entire house.

Each level starts from a facade as a practically opaque vertical plane that, with the movement of the house itself, is transformed into a warped surface that goes from being vertical to being horizontal. The pattern of this surface is a grid that generates a filtered and controlled light inside. This frame will serve as a structure to support one of the kinetic facades also inspired by the sunflower.

After an exhaustive analysis of the sun-path and the incident radiation in each of the planes, we define the kinetic facades that will be part of the entire system. On the facades of the ground floor and first floor facing South, we have a system of vertical and flexible elements that follow the movement of the sun to protect the interior from a high incidence and, at the same time, guarantee direct views to the outside free of obstacles.

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[447] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

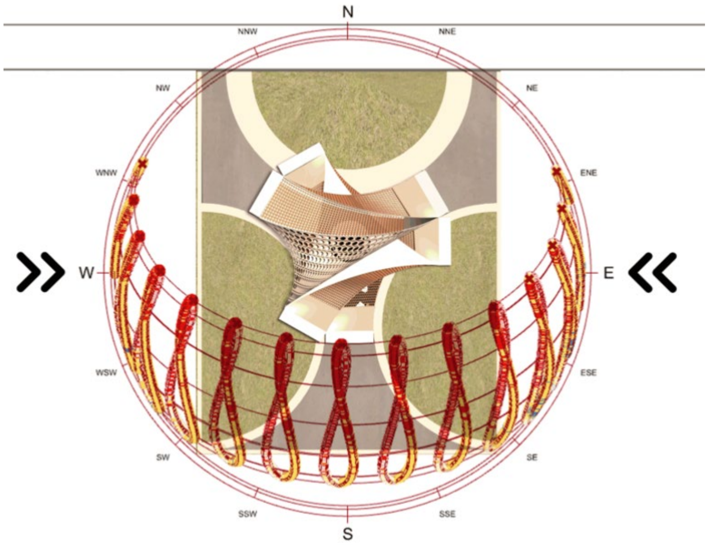

Fig. 8.36 - Sunflower House Orientation and Sun-path[448]

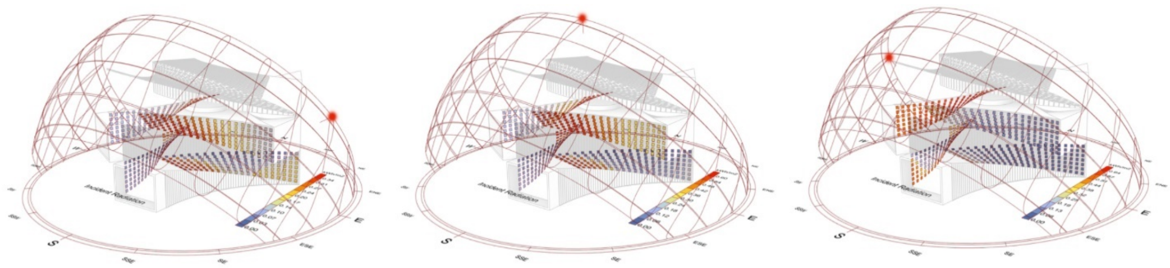

Fig. 8.37 - Radiation analysis at glaze level. Comparison depending on the time of day[449]

On the East and West facades of the matching floors, the incidence is more intense, so the protection has to be more powerful. Inspired by the path of the sunflower that follows the sun all the way from dawn to dusk, we designed a system of small solar panels that follow the morphology of the flower's seeds and their behavior.

The panels are in constant motion, always positioning themselves at 90º from the sun's rays. In this way, they not only protect the interior of the house from direct radiation, but they are also absorbing all the solar energy to obtain it from renewable sources for the house.

[448] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

[449] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

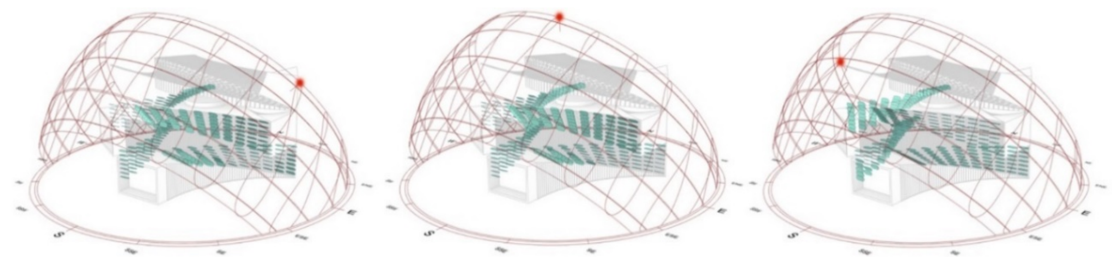

Fig. 8.38 - Kinetic facade louvers position based on the sun position and radiation level[450]

The very movement of the kinetic facades is also supported by the energy obtained from the sun stored in batteries without the need to use additional electricity.

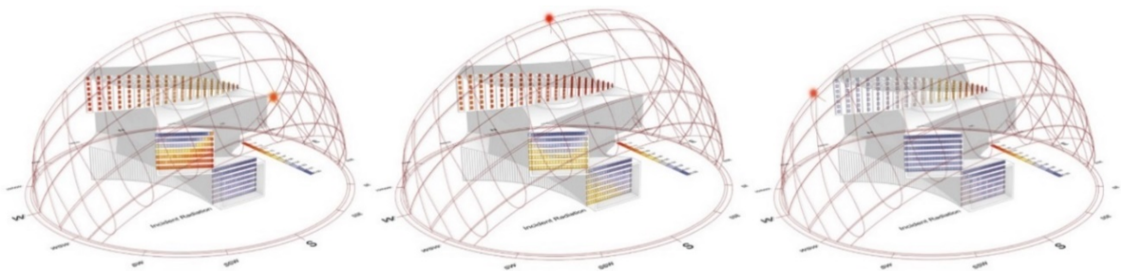

Fig. 8.39 - Radiation level on side facade glazing[451]

The “side” areas of the facade contain a central pivoting system kinetic facade that adjusts itself depending on the interior temperature demands or based on the sun position.

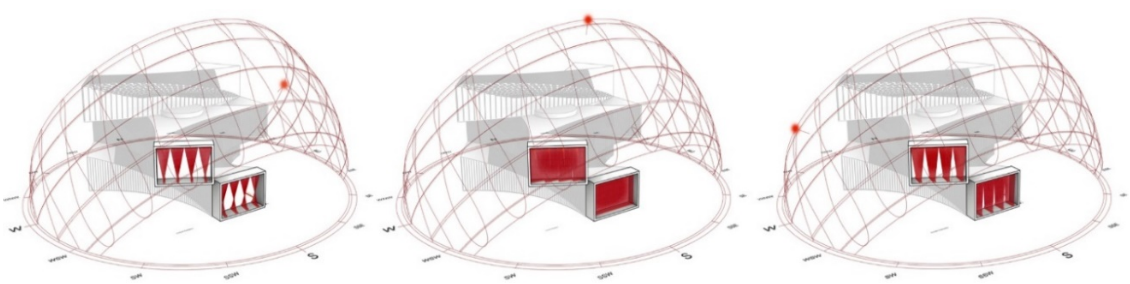

Fig. 8.40 - Side facade Louvers[452]

In addition to these measures, the Sunflower House is a building completely designed under Passive House standards. Among the design decisions taken,

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[450] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

[451] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

[452] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

are the following: continuous thermal insulation throughout the exterior of the volume of the house (including the foundations), high-performance windows, hermeticity checked with a blower door test, design free of thermal bridges, aerothermal power to feed the hot water system and the air conditioning, heat recovery connected to a Canadian well to decrease the need for energy consumption and economic lighting.

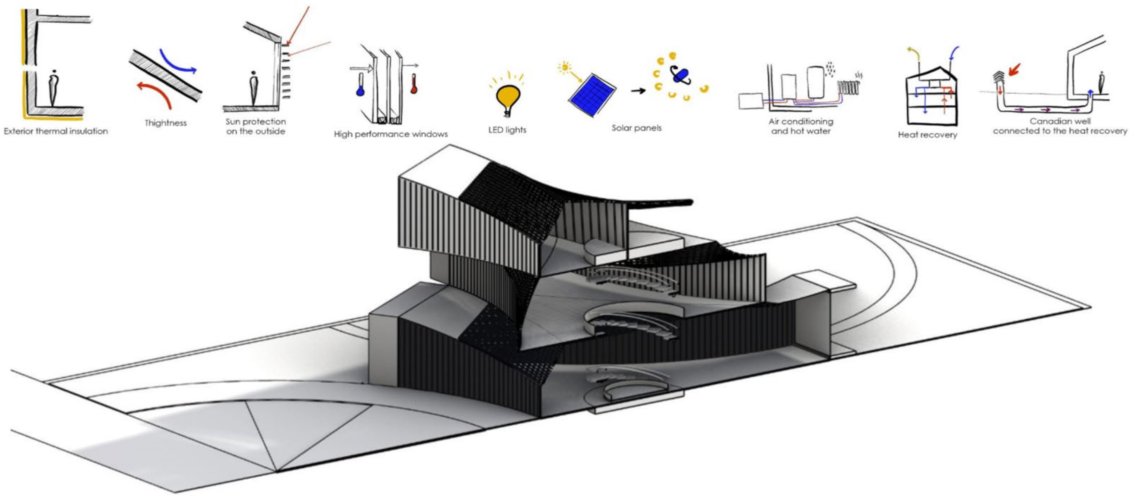

Fig. 8.41 - Section and Passive Strategies Used[453]

With all the active and passive measures taken in this sunflower-inspired home, we achieve a zero-consumption construction.

Fig. 8.42 - Aerial Perspective[454]

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[453] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

[454] Image by Julieta Grimberg Golijov and Rizkallah Ghazaly

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8.3.2. Project 2: "[LAPIS]"

Results by: Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

The objective of this design is to produce a fully digitally generated design inspired by the local biome of the project location while pertaining to the biome's specific environmental conditions and needs.

The Taiga biome is notorious for its cold temperatures, relatively high humidity, medium seasonal winds, and very rich fauna and flora that adapted to those conditions.

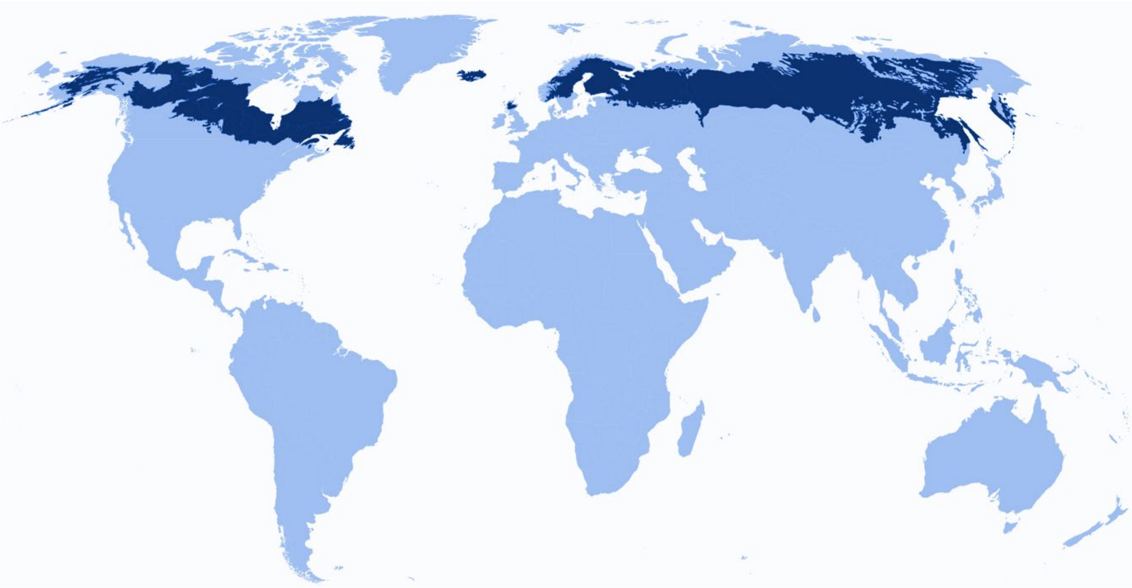

Fig. 8.43 - Selected Biome: Taiga[455]

For the project, we selected a plot in Tampere, Finland where the fauna and flora have flourished within the Taiga biome. We also noticed that apart from the evergreen forest that filled the land, Tampere had a very rocky land buildup.

The design of the form was based on the surrounding rock formations, smooth and solid molded by the environmental conditions to perfection.

[455] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

Fig. 8.44 - Site Location - Tampere, Finland[456]

That perfect mold was adapted and simplified then digitally augmented to adapt to the yearly heat radiance of the area to maintain high heat retention while minimally affecting the surrounding local biome as our study showed a 34.8% decrease to the radiance exposure of the immediate area with only 5% intrusive shadow to the surrounding forest, thus achieving a decent change to the localized climate of the livable space with minimal intrusion into the natural habitat of the surrounding.

Based on these characteristics, the initial morphology was envisioned as an element that would fit within its surroundings, and the ones that came to mind were the rock formations.

Fig. 8.45 - Concept Premise[457]

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[456] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[457] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

Thus having an initial idea of how we want our structure to look we went on and started to analyze the site for its specific environmental characteristics, such as dry bulb temperature, relative humidity, wind speed, and outdoor comfort levels.

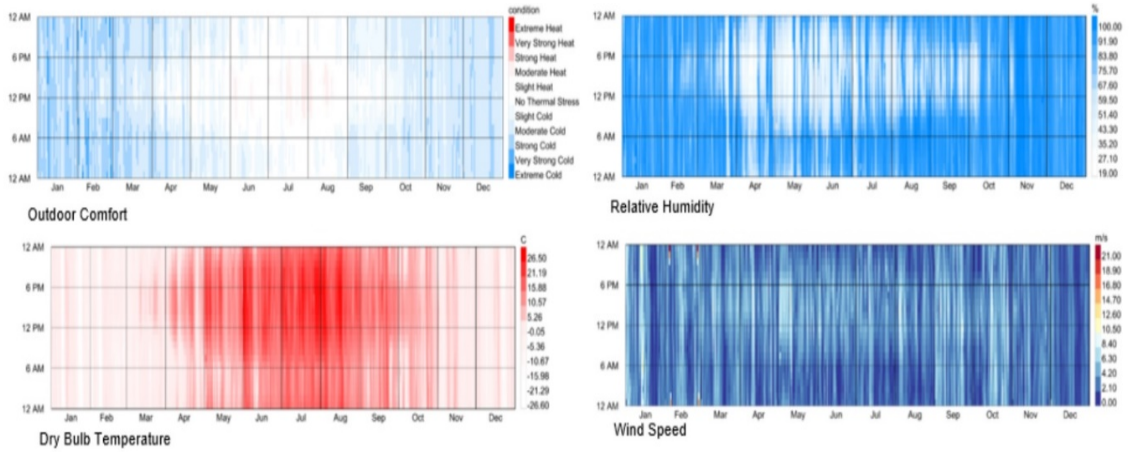

Fig. 8.46 - Site annual analysis for outdoor comfort, relative humidity, dry bulb temperature, and wind speed[458]

Once seeing the annual data we also studied the levels of radiation and the direct sun hours on the site to determine where to position the edifice.

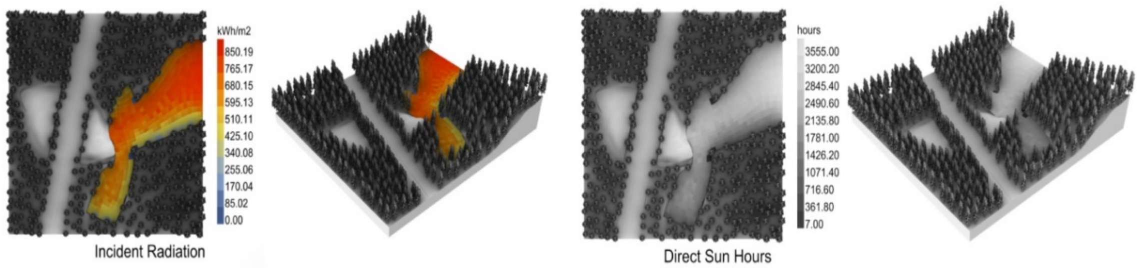

Fig. 8.47 - Site Radiation and Sunlight Hours analysis[459]

The initial massing was based on a prism that had different control points set on a span of seven levels. To create an initial morphology we decided to run Galapagos to determine the actual shape based on the levels of radiation caught on the referenced massing.

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[458] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[459] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

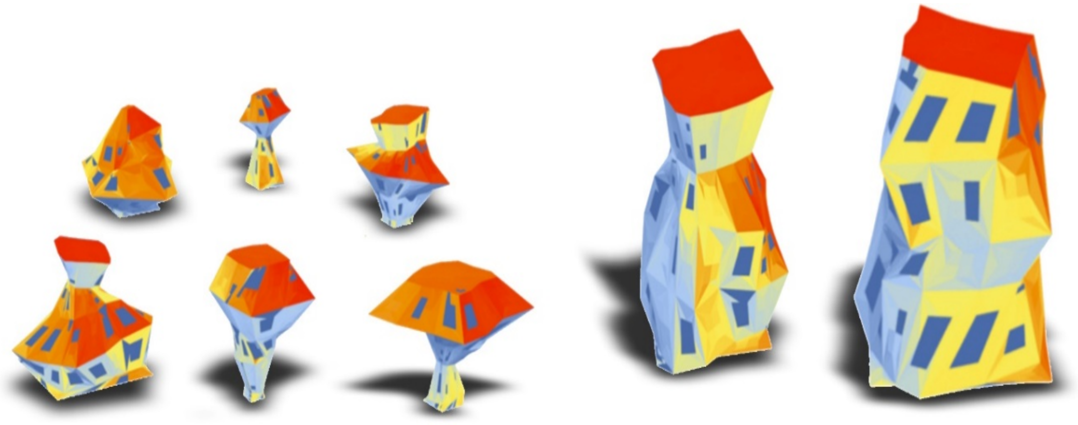

Fig. 8.48 - Morphology Iterations. Excluded (left), viable (right)[460]

Since the climate we chose implies extremely low temperatures, we decided to employ a double facade for the building, in which the exterior layer will home two types of skins, one kinetic and one static.

The exterior skin of the building was further studied to determine the areas of the skin that are highly exposed to the elements (heat, sun, humidity, wind). The areas of low exposure to heat were noticed to be highly exposed to wind and thus we opted to develop a static skin in those locations. This static skin was inspired by beaver dams' design and functionality as the beavers utilize a weaved network of wooden branches and sticks that is buffered by air pockets.

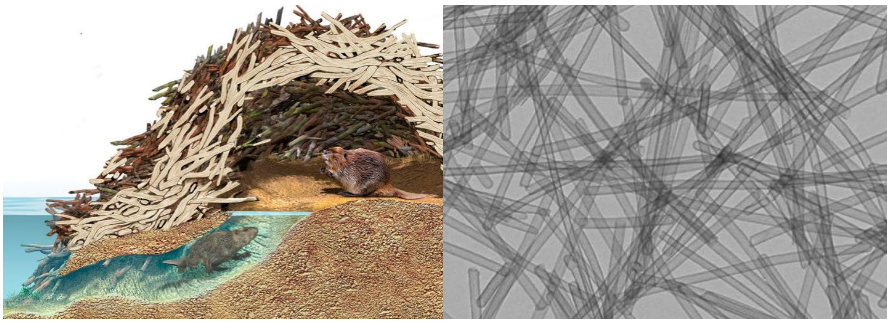

Fig. 8.49 - Static facade concept[461]

The static facade was dispersed depending on the irradiance levels to cover the areas most avoided by the sun, to compensate for heat loss.

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[460] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[461] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

The areas with higher values are left open to allow the sun to heat the interior.

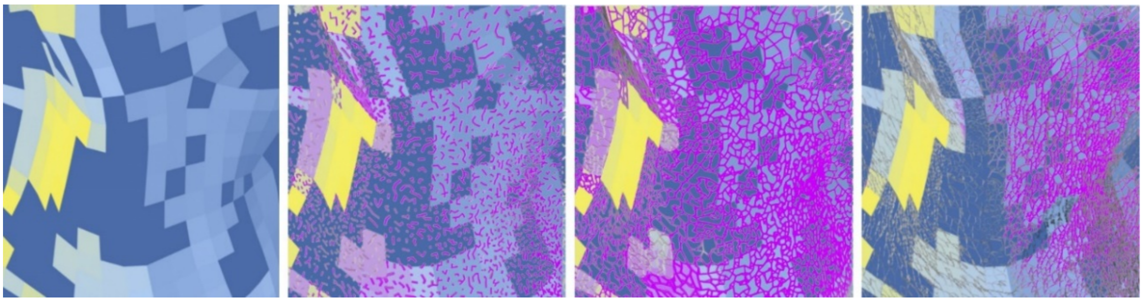

Fig. 8.50 - Static facade distribution[462]

This led to the development of a matching woven system of wooden elements sourced from the surrounding materials to minimize material sourcing pipelines, the pockets of air inspired the use of ETFE Transparent panels interweaving the wooden elements to maintain a closed system that still allows light into the space.

Further to that, we noticed that the local trees cultivated a tendency to grow moss, which is beneficial for our purposes as the moss will act as an environmental filter for the space filtering the air humidity and any minor pollutants present.

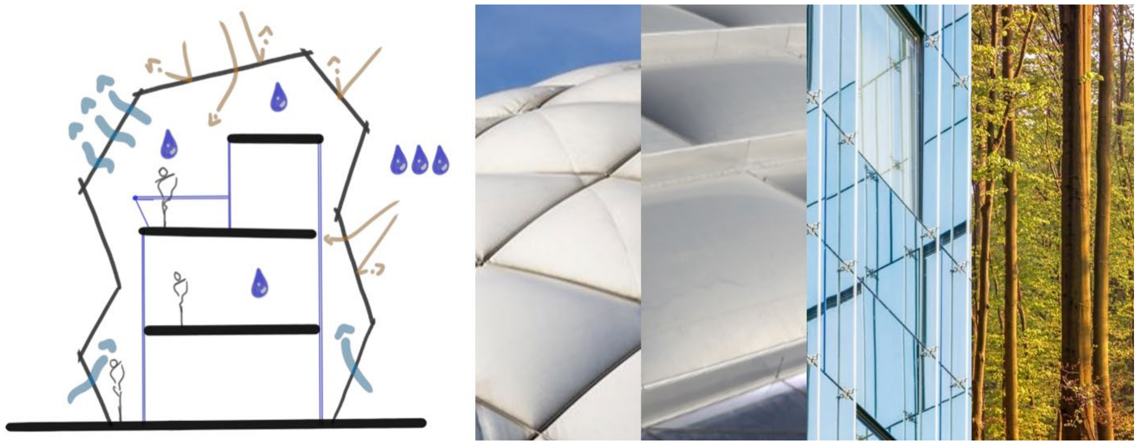

Fig. 8.51 - Skin functionalities and technologies[463]

On one hand, the objective of the adaptive "exo" skin was to provide a controllable method of exchanging air into the intermediate insulating air layer (between the

[462] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[463] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

"exo" and the "endo" skin systems) while providing a more advanced sunlight control and snow resistance.

The design was inspired by the conical shape of the pine pods and was intended to be built out of modular opaque ETFE, those pyramid units are designed in relevance to the yearly sun angles and are capable of moving in two axes.

The top portion of the conical pyramid is to expand in the XY plane of the surface to control the sunlight intake at any moment of the day due to the change in the area of the opaque surface.

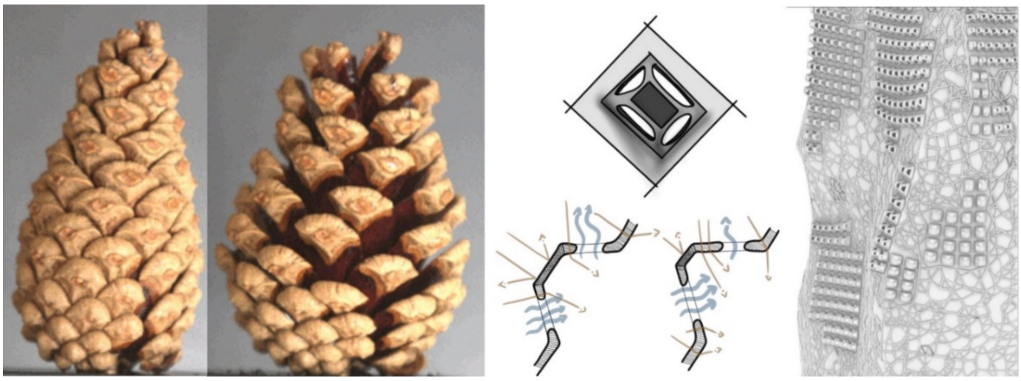

Fig. 8.52 - Kinetic Facade Concept[464]

On the other hand, the porous sides of the pyramid units are made of a more translucent ETFE unit to allow indirect and refracted light into the internal space while the pores open and close to allow the mediation of humidity and temperature of the internal space.

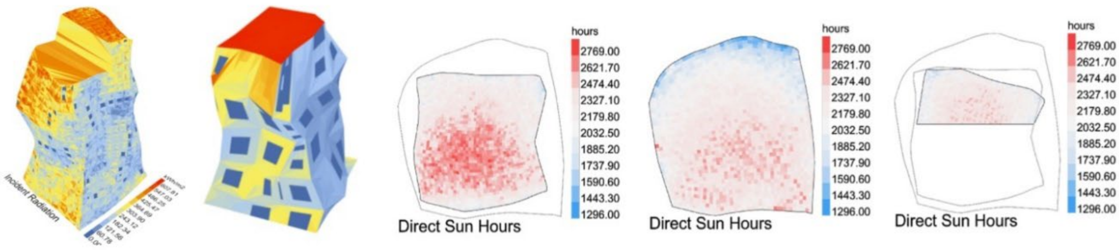

Fig. 8.53 - Radiance analysis for the interior and exterior layers (left) and sunlight hours for each level of the building[465]

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[464] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[465] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

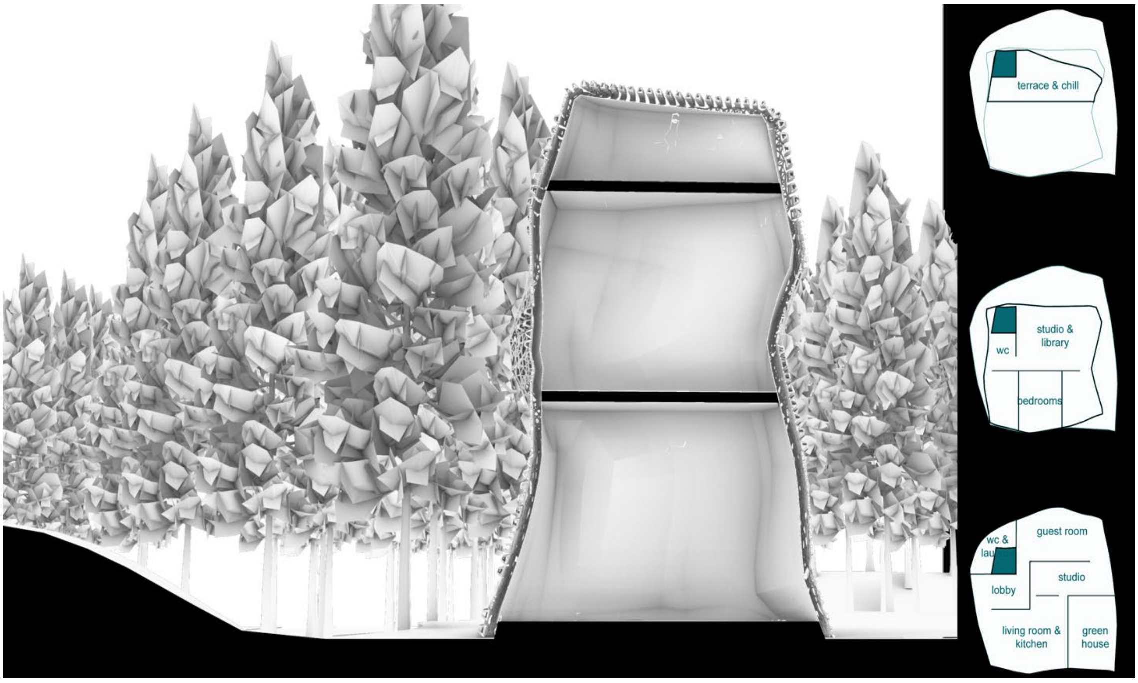

Fig. 8.54 - Section and possible plan layouts[466]

Fig. 8.55 - Perspective[467]

[466] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

[467] Image by Abd Al Qader Al Jaafari and Javier Gonzalez Castillo

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8.3.3. Project 3: “Shady”: Communal Social House in Rio De Janeiro, Brazil

Results by: Yara Mohammed Ewida and Victoria Olivia Roznowski

We chose our site within the tropical rain forests of Rio de Janeiro, and we envisioned a communal social house layout, by taking into consideration the environment, where people could participate in creating a sustainable community.

Fig. 8.56 - Amazon Biome[468]

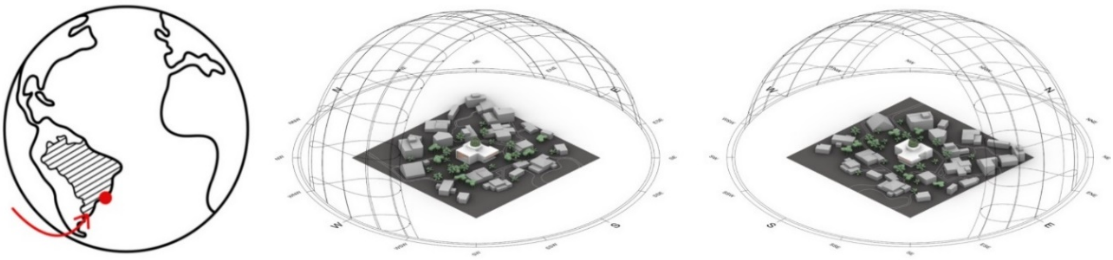

Fig. 8.57 - Site location and sun path[469]

We wanted to build the edifice in harmony with nature, be inspired by it, and help save it. Thus, the design of the house was inspired by biological systems existing in the surrounding environment and respecting the climatic conditions for this area.

[468] Image Source: https://www.clipartkey.com/view/wwiwbJ_tropical-rain-forest-screen-tropical-rainforest-locations/

[469] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

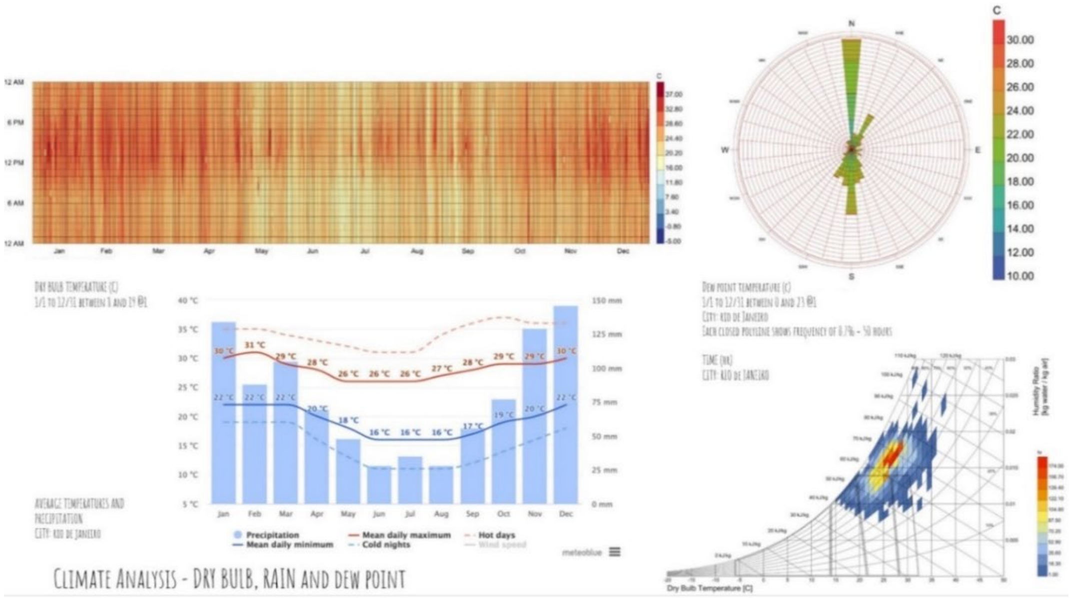

Fig. 8.58 - Climate analysis for dry bulb temperature, rain, and dew point[470]

While studying the climate conditions, three main aspects were taken into consideration: sun, wind, and rain. Since Rio de Janeiro is located in the tropical zone, it has heavy rains for ⅔ of the year, high humidity up to 85%, high temperature up to 30°C, and just a gentle breeze with wind speeds up to 5 km/h. Therefore, the house's interior and envelope were designed to well circulate the air inside the house, isolate it from the high temperatures and humidity outside, and collect its own water.

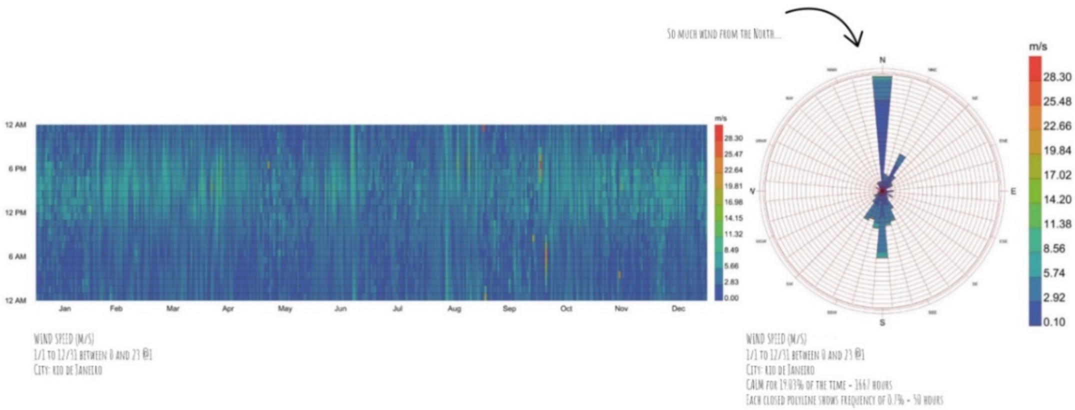

Fig. 8.59 - Climate analysis for wind speed and direction[471]

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[470] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

[471] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

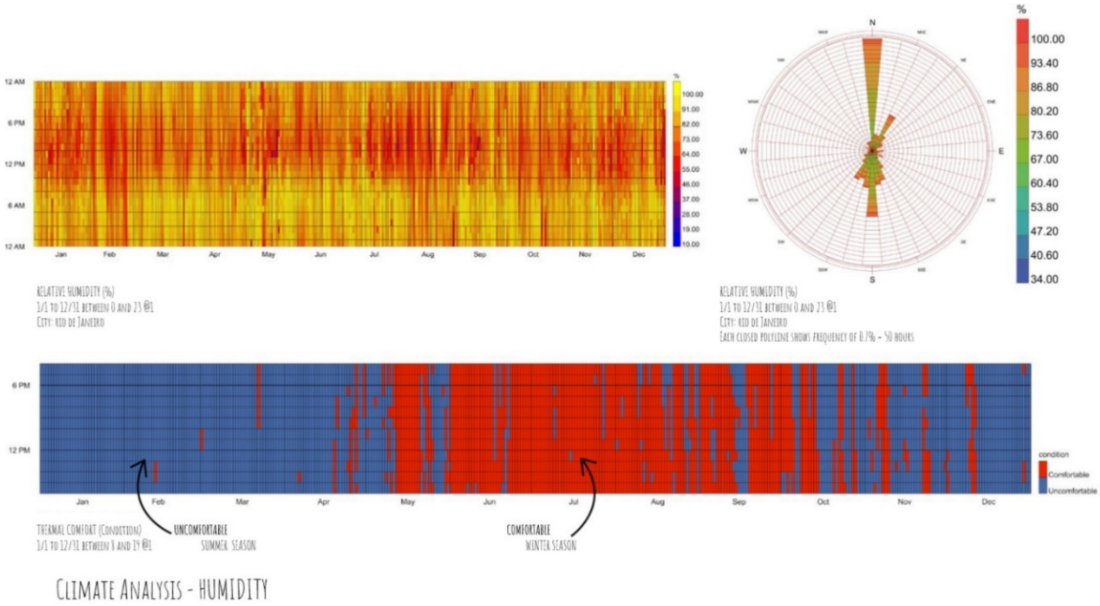

Fig. 8.60 - Climate analysis for humidity[472]

The house is built using adobe blocks made of a mixture of sand and mud and later covered with a layer of mud plaster. This material creates a time lag in heat transfer from the exterior to the interior which makes the interior cool in the morning and warm at night. In addition, the white color of the walls reflects the sun rays which help in heat reduction.

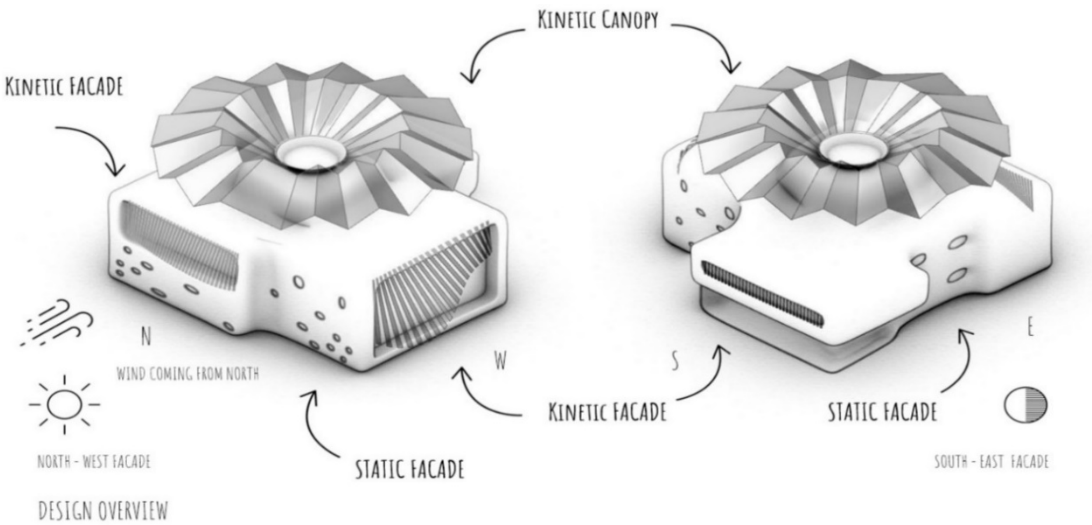

Fig. 8.61 - Design overview[473]

[472] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

[473] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

The openings of the house were positioned to enhance the cross ventilation of the building. Bigger windows are placed toward the northwest direction facing the cool winds and creating a positive pressure over the northwest facade.

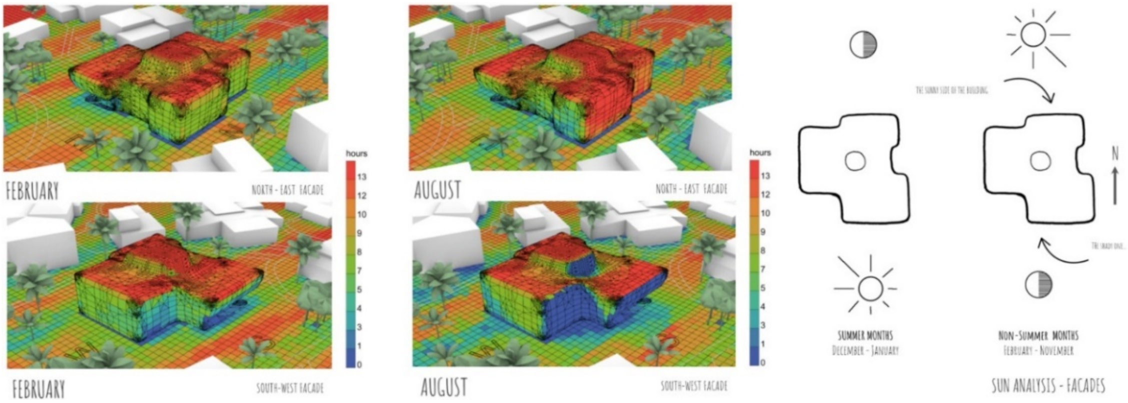

Fig. 8.62 - Morphology analysis and orientation[474]

While the smaller windows are located towards the southeast direction where it has a negative pressure creating a suction effect that enhances the cross ventilation in the building.

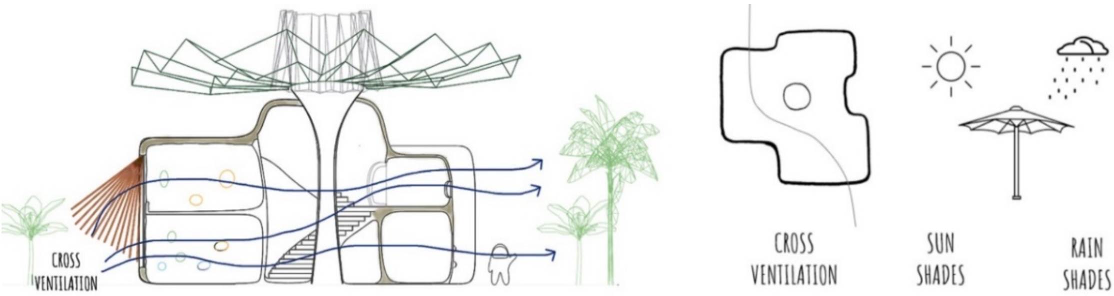

Fig. 8.63 - Cross ventilation concept[475]

Since Brazil is in the southern hemisphere the sun is facing the northern facade in summer and the southern facade in winter all day. We designed a kinetic facade inspired by the "Mimosa Pudica", a sensitive plant whose movement against touching. The facade moves according to the sun’s movement and in rain, it can be fully open creating a shaded and rain-protected extension in front of the house.

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[474] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

[475] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

Fig. 8.64 – Biolearning conceptualization for facade elements

On the south and east facade, the small windows were made of thermochromic glass that changes the color according to the temperature. That mechanism is inspired by the behavior of chameleons when it changes their skin color to adapt to the surrounding environment.

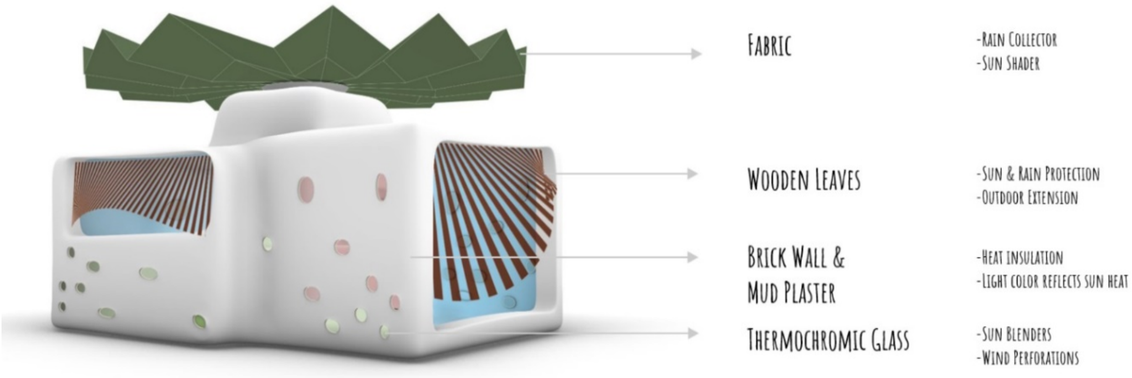

Fig. 8.65 - Kinetic elements design[476]

On the roof, a kinetic canopy was designed for collecting rain and shading from the sun. The mechanism of the canopy is inspired by oxalis plants that open and close in a folding technique. When it's fully open it makes a concave shape with a diameter of 10m, it collects the rain and drains it through a shaft that goes down to a water storage underneath the house where it filters the water and pumps it back for daily usage. When the rain stops it folds closing and allowing the roof garden's plants to take their daily dose of sun.

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[476] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

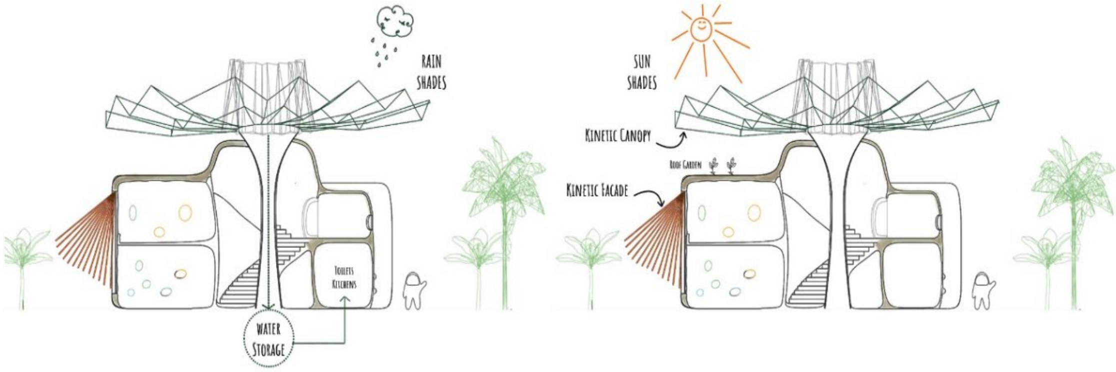


Fig. 8.66 - Building Sections and Functions[477]

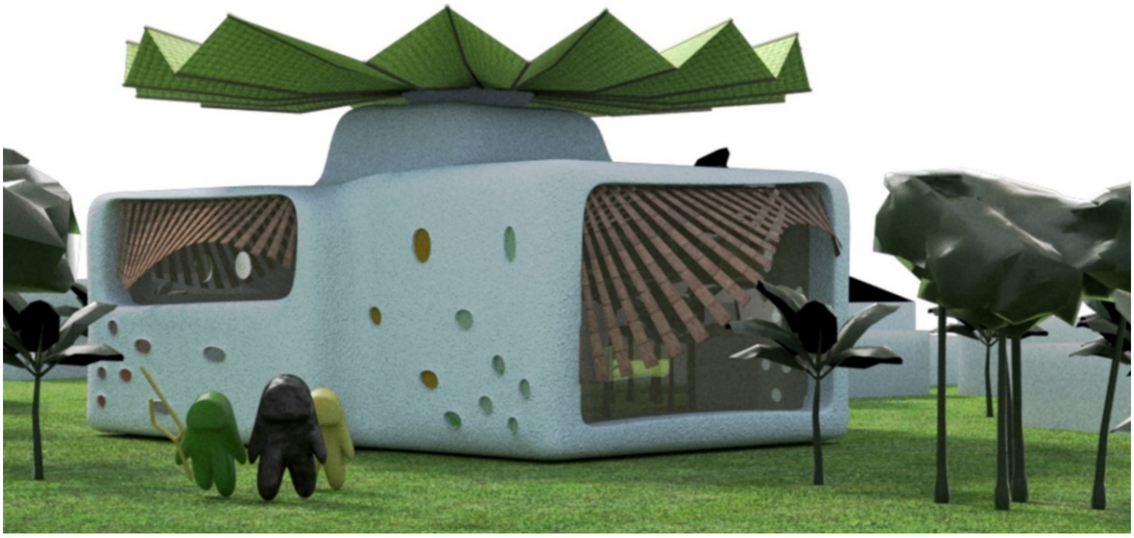


Fig. 8.67 - Building Perspective[478]

[477] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

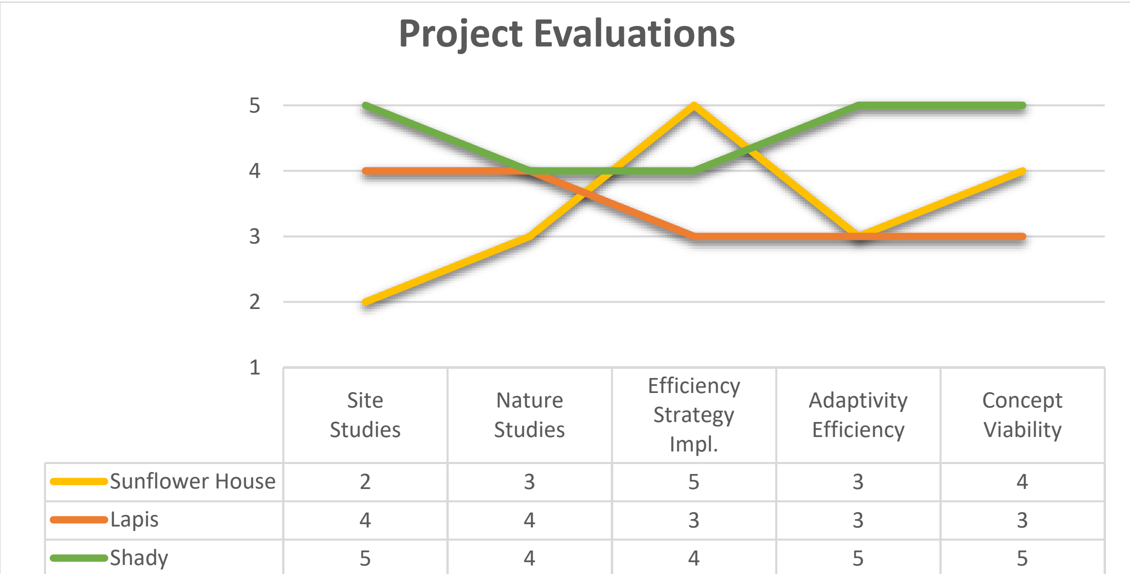
[478] Image by Yara Mohammed Ewida and Victoria Olivia Roznowski

8.3.4. *Observations*

The showcased projects point out the viability of natural intelligence as well as the effectiveness of energy efficiency standards within the conceptualization of architectural adaptive design.

The students focused on and studied the surrounding environment in order to develop certain solutions for most of the architectural requirements (functionalities, thermal, acoustics, connections between elements, conductivity, light management, etc.).

These concepts can be analyzed from the following perspectives: site studies, natural studies, efficiency strategy implementation, adaptivity efficiency, concept viability. The evaluation criteria will be rated from 1 (least) to 5 (most).



	Site Studies	Nature Studies	Efficiency Strategy Impl.	Adaptivity Efficiency	Concept Viability
Sunflower House	2	3	5	3	4
Lapis	4	4	3	3	3
Shady	5	4	4	5	5

Fig. 8.68 – Project Evaluations (image by author)

Sunflower House

The "Sunflower House" project started from the behavior and morphological patterns conceptualization of the sunflower. These aspects were highly emphasized in terms of overall shape, as well as adaptivity functionalities of the proposed house. Thus, the concept influenced the development's orientation on the site and the facade's behavior.

On the other hand, the project lacks a lot in terms of site analysis, only focusing on the sun-path, radiation, and the illumination level, without envisioning more of the surrounding environment. Regarding energy efficiency strategies, all main points of the Passive House were taken into consideration as well as the building-site interaction aspects of the Active House concept. From the perspective of the efficiency of its adaptive systems, the project fairs well with straightforward kinetics on the slathered facades as well as on the straight sides.

The concept viability can be considered high since most technology is easily implementable, posing no high difficulty in terms of construction.

Lapis

The "Lapis" project was envisioned in a cold biome, on an existing site. The student's approach towards site analysis was highly appreciated since they included shadow, illumination as well as radiation studies, all taking into consideration the other elements present in the nearby environment.

From the perspective of nature studies, the students focused on the regional fauna by looking into beaver behavior to determine a concept in terms of energy efficiency. Thus, they have proposed a double facade inspired by beaver dams. In terms of overall morphology, they used the idea of rock formations and devised a procedural algorithm that would output different iterations based on the collected environmental data. The active adaptivity aspects were inspired by the pine cone seed release mechanism, thus proposing a modular kinetic panel that would fit in certain areas of the building.

Regarding energy efficiency strategies, the only focus was related to high insulation and orientation, with little regard to other efficiency or comfort factors. The adaptivity aspect of the concept presents moderate viability in terms of implementation.

Shady

The "Shady" project was proposed as a community house on an existing site in Brazil. Being in the southern hemisphere, it was interesting to observe the difference in data compared to the previous projects.

Site analysis was done thoroughly for different seasons and scenarios, taking into consideration most climatic conditions affecting the area. These conditions were mitigated through the adaptivity systems employed, by studying the nearby fauna and choosing the behavioral aspects of the “Mimosa Pudica” and “Oxalis” plants, in order to conceptualize a shading system for the facades and a rainwater collecting canopy for the top terrace.

In terms of energy efficiency, specific materials and natural ventilation systems were employed to account for passive cooling and humidity. Other aspects of interior comfort were envisioned through thermochromic glass installation for adaptive interior lighting.

In terms of actual implementation, the project presents high viability through straightforward systems and compactness.

Conclusion

Observing the chart presented in Fig. 8.66, we can see that most students reliably used site analysis to a high degree in order to justify their design. The nature studies of the surrounding habitat pushed them to develop specific efficiency designs that were suited for the setting of each project. Also, the freedom of choosing the site, made them also consider the level of comfort fit for their occupants in each setting, emphasizing on adaptivity efficiency.

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Conclusions

9. Conclusions

> *"Adaptation is the evolutionary process whereby a population becomes better suited to its habitat. This process takes place over many generations, and is one of the basic phenomena of biology." On the Origin of Species, Charles Darwin*

9.1. English version

The research focuses on the development of technical and informational implementations for adaptive architectural efficient developments, based on the complete environmental spectrum. Centered on the abundance of information, we can delineate a collection of concepts, systems, and materials that are best suited for the developing site. As an outcome, pluri-performative, conscious, and smart-material design approaches will be suitable. This allows the edifice to change its properties and functions accordingly, depending only on environmental stimulus.

Thus, conceptualizations, procedural processes, technological integrations, domain, and case-specific methodologies are among the key outputs of this work.

Through the conclusions, we will look at the initial inquiries we have initially made.

9.1.1. How could the presence of adaptivity in architecture be characterized and justified?

For any project to be adaptive it must not rely only on responsiveness to the surrounding environment, but to be in constant relation with it. The main concepts of adaptation have to respond to their surroundings through a combination of two kinds of behavior. These are defined by dynamic mechanisms and static efficiency strategies, which are elements that continuously influence each other.

9.1.2. What are the basic tasks of an energy-efficient system's multidisciplinary and integrated procedural design?

The growing interest in low-energy, high-performance edifices has sparked the development of energy-free architectural design approaches. These may be used in a variety of climates and locations around the world. The efficiency strategies and standards movements are great examples of the need to produce procedural-based low-energy design methodologies that are easily adaptable in a global setting.

If architectural design remains oriented on dematerializing the protective skin so deeply invested in a building's energy performance, specific methodologies and solutions will be necessary; especially in a time of limited resources. A dedicated understanding of high performance is one that is equipped with critical thinking and material expertise to aid in decision-making.

The limits of previous workflows are no longer an impediment for the designers of today, as procedural tools deliver a holistic design medium. The possibility for further improvement is unbounded thanks to the design community's collaborative approach. Bringing analysis tools towards the designer's environment is becoming increasingly important to foster an ecologically mindful design approach.

Ladybug's open-source nature centralizes environmental study tools, allowing for the progress of the environmentally responsible design. Through these parametric diagrams, climatic data becomes a concept generation tool, providing designers with real-time feedback on the implications of design changes. Ladybug offers a single interface that comes equipped with accessibility and convenience, supporting ecologically responsible building designs for now and the future.

9.1.3. How can adaptivity be implemented?

The implementation can be achieved by envisioning the edifice using reliable data from the Environmental Data Indexing System (EDIS), subsequently keeping them linked after completion.

Based on this idea, we further encourage the use of the Adaptive Building Efficiency Methodology (ABEM) rather than a “one size fits all” approach. Based on the premise that everybody and every setting is different, future architectures need to be provided with a filter that ensures its user a dedicated type of “adaptivity”. This will enable them to connect with the environment at a detailed level according to each individual’s incentives.

As technology advances, the impact of our actions upon the earth expands. As a result, we must expand our awareness of the architectural complexity, as well as of the complicated relationships between pieces in the systems we construct and in which we are embedded.

Our buildings are still constructed in isolation, despite the fact that we dwell in an era of globalization, which shows a tendency toward cultural and technical confluence. We must cultivate integrated system thinking strategies, which allow us to approach architectural complexity from different viewpoints and across disciplinary boundaries. This could lead to the creation of adaptive building systems that respond to societal transformations alongside shifting environments. These structures should consider the long-term side effects of their operations and engage in environmentally friendly and sustainable procedures.[479]

9.1.4. How can we perceive and influence the built environment based on the EDIS and ABEM approaches?

Since system performance is situation-specific and context-dependent, it is impossible to capture it in general principles or evaluation schemes. Building performance simulation, on the other hand, is seen as an advantageous tool, albeit more advancements are required to completely match the standards.

The integration of inputs from diverse physical domains, as well as the flexibility of characteristics to depict adaptive behavior, are both open to further improvement. Complementary to this, it would be fascinating to look into ways to improve the capabilities of constructing performance simulation tools by using

[479] Diana Quintero de Saul, *AN ARCHITECTURE OF COMPLEXITY*, ed. by Rachel Armstrong and Simone Ferracina, *UnConventional Computing: Design Methods for Adaptive Architecture* (Cambridge: Riverside Architectural Press, 2013) <https://doi.org/10.1017/CBO9781107415324.004>.

recent advances in design methodologies, particularly those established to support the design and development of adaptive systems.

The possibility of improving comfort conditions is at least as important as the energy-saving rationale for adaptive edifices. Despite the fact that the significance of human dynamics in the planning and installation of active building technologies is nowadays generally acknowledged, there still seems to be a knowledge gap in this multidisciplinary research domain.

To take advantage of human and natural intelligence in the regulation of environmentally adaptable edifices, inhabitants should be provided the option of manual override or adjustment. The most common issue of intelligent building envelopes is the inability to override the system's judgments.

9.1.5. What are the fundamental requirements for architectural adaptivity in theoretical, methodological, and technical paradigms?

The projects examined in this study demonstrate that the broad use of environmentally adaptable approaches has the potential to become a significant contributor to meeting our increasingly stringent energy performance standards while avoiding the necessity for comfort tradeoffs.

At the same time, our facts add to promising new directions for future construction projects and research in the aforementioned systems. In particular, there is a scarcity of information in the literature about the monitored operational performance of environmentally adaptable approaches and post-construction evaluations. As a result, the last part of the thesis outlines some of the most significant roadblocks and suggests promising research areas to help harness the latent potential of adaptivity in architecture, through both EDIS and ABEM.

Innovative technologies are frequently used within adaptive designs, resulting in difficult projects with significant risks. Due to the fact that risks are connected with unequal payback times (due to increased capital, upkeep, and mistake costs), project developers prefer to take a cautious approach to adopt this type of new technology. Taking a chance, on the other hand, opens up possibilities, but such lofty goals must be backed up by well-informed design judgments. Environmental adaptive edifices must go from an abstract notion to a viable development option, which necessitates the development of systems capable of accurately predicting effective performance throughout the building design phase.

As a result, there is more openness regarding in what way performance gains during operation may compensate for initial rate arguments. Therefore, it is easier to overcome the wary mentality caused by the "anchoring" tendency toward normative and conventional design solutions. The performance benefits of environmentally adaptable edifices are both cumulative and delayed, which adds to the state of complexity.

Moving forward, the rising complexity of geometric, performative, and code-based needs will continue to drive architecture. Within a relational database context, a methodological approach using biolearning, virtual and augmented design, digital fabrication, and installations gives a baseline for future advancement.

This employs new technologies, materials, and workflows. Recognizing design and construction expertise and the ability to integrate material behavior from physical prototypes into the process, allows it to function as both a physical investigation and a digital process at the very same time.

9.1.6. What are the foreseeable prospects in architectural research, teaching, and practice for energy-efficient design, adaptivity, data indexing, and their trans-disciplinarity?

One of the main future developments would be the improvement and reliability of the Environmental Data Indexing System. In terms of scalable developments, the most obvious steps that are considered feasible is to create a network of EDIS's, especially in large cities, to monitor environmental fluctuations (building rehabilitations, restorations, new constructions, and so on).

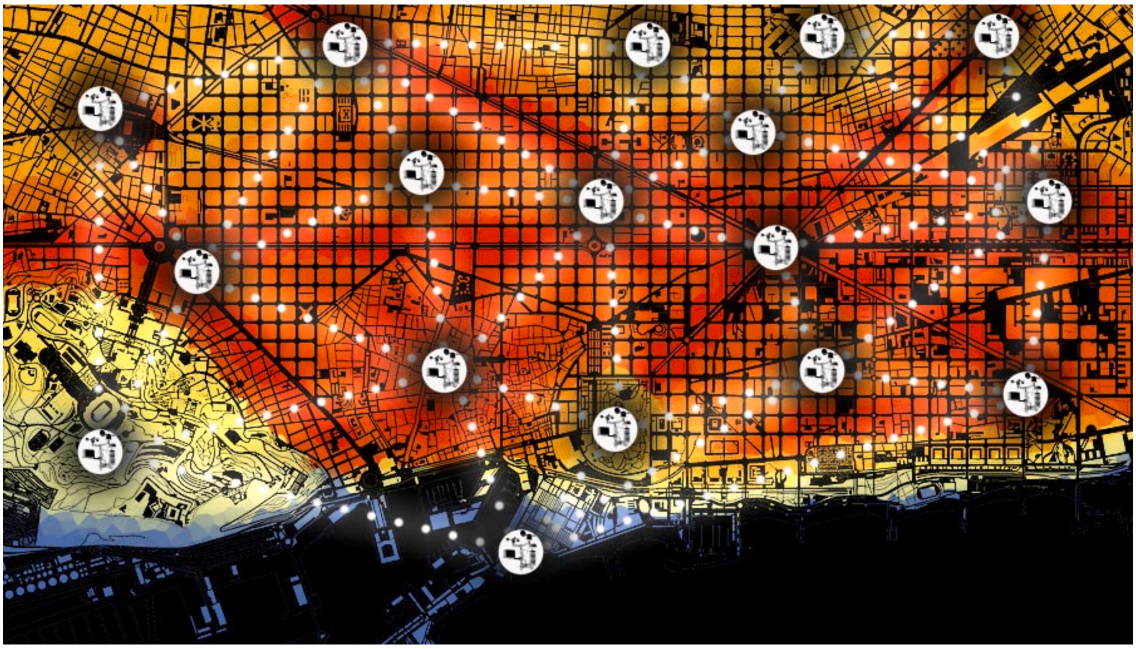

Fig. 9.1 – EDIS network envisioned in Barcelona (image by Author)

This would also help with the general maintenance of the structures since there already are programs that focus on rehabilitation based on certain time spans (usually 10 years). In this sense, a building revision could also include an adjustment regarding facade thermal performances for better interior comfort, green roofs to mitigate hot zones, etc.

In the case of the EDIS itself, a couple of sensor improvements and replacements to generate more accurate data, especially concerning solar radiation, have been planned. Alongside these, there is a strive to develop a platform on which users could have easy access to future databases, allowing them to be more environmentally aware, and design in accordance with up-to-date data.

Thus, we will conclude this thesis with an overview regarding the applicability of energy-efficient procedural designs, achieved through informational prototyping. The main subjects that constitute this concept are seeded in both theoretical (in terms of abstraction and conceptualization of biological systems for adaptivity aptness) and empirical realms (in terms of already proven efficiency strategies and interactive systems). In this sense, the range of applicability should have incipient in pedagogy, andragogy, and practice.

This would ameliorate fearing the novelty status of high-performance systems and computational design through exposure and epitome.

9.2. Versión en español

La investigación se centra en el desarrollo de implementaciones técnicas e informativas para desarrollos arquitectónicos adaptativos eficientes, basados en el espectro ambiental completo. Centrados en la abundancia de información, podemos definir una serie de conceptos, sistemas y materiales que se adapten mejor al lugar. Como resultado, serán adecuados los enfoques de diseño de materiales inteligentes, conscientes y pluri-performativos. Esto permite que el edificio cambie sus propiedades y funciones en consecuencia, dependiendo únicamente del estímulo ambiental.

Por lo tanto, las conceptualizaciones, los procesos procedimentales, las integraciones tecnológicas, las metodologías específicas de dominio y caso se encuentran entre los resultados clave de este trabajo.

A través de las conclusiones, veremos las indagaciones iniciales que hemos realizado inicialmente.

9.2.1. ¿Cómo podría caracterizarse y justificarse la presencia de la adaptabilidad en la arquitectura?

Para que cualquier proyecto sea adaptativo, no debe depender solo de la capacidad de respuesta al entorno que lo rodea, sino de estar en constante relación con él. Los principales conceptos de adaptación tienen que responder a su entorno a través de una combinación de dos tipos de comportamiento. Estos están definidos por mecanismos dinámicos y estrategias estáticas de eficiencia, que son elementos que se influyen continuamente entre sí.

9.2.2. ¿Cuáles son las tareas básicas del diseño procedimental multidisciplinar e integrado de un sistema energéticamente eficiente?

El creciente interés en edificios de bajo consumo energético y alto rendimiento ha provocado el desarrollo de enfoques de diseño arquitectónico sin energía. Estos se pueden usar en una variedad de climas y ubicaciones en todo el mundo. Las estrategias de eficiencia y los movimientos de estándares son excelentes ejemplos de la necesidad de producir metodologías de diseño de bajo consumo de energía basadas en procedimientos que sean fácilmente adaptables en un entorno global.

Si el diseño arquitectónico sigue orientado a desmaterializar la piel protectora tan invertida en el rendimiento energético de un edificio, serán necesarias metodologías y soluciones específicas; especialmente en una época de recursos limitados. Una comprensión realmente dedicada del alto rendimiento es aquella que está equipada con pensamiento crítico y experiencia material para ayudar en la toma de decisiones.

Los límites de los flujos de trabajo anteriores ya no son un impedimento para los diseñadores de hoy, ya que las herramientas de procedimiento ofrecen un medio de diseño holístico. La posibilidad de mejoras adicionales es ilimitada gracias al enfoque colaborativo de la comunidad de diseño. Acercar las herramientas de análisis al entorno del diseñador es cada vez más importante para fomentar un enfoque de diseño ecológicamente consciente.

La naturaleza de código abierto de Ladybug centraliza las herramientas de estudio ambiental, lo que permite el progreso del diseño ambientalmente responsable. A través de estos diagramas paramétricos, los datos climáticos se convierten en una herramienta de generación de conceptos, brindando a los diseñadores retroalimentación en tiempo real sobre las implicaciones de los cambios de diseño. Ladybug ofrece una interfaz única que viene equipada con accesibilidad y comodidad, y admite diseños de edificios ecológicamente responsables para el presente y el futuro.

9.2.3. ¿Cómo se puede implementar la adaptabilidad?

La implementación se puede lograr visualizando el edificio utilizando datos confiables del Sistema de Indexación de Datos Ambientales (EDIS), y posteriormente manteniéndolos vinculados después de la finalización.

Con base en esta idea, alentamos aún más el uso de la Metodología de eficiencia de construcción adaptativa (ABEM) en lugar de un enfoque de "talla única". Basado en la premisa de que todos y cada entorno es diferente, las arquitecturas futuras deben contar con un filtro que garantice a su usuario un tipo específico de "adaptabilidad". Esto les permitirá conectarse con el entorno a un nivel detallado de acuerdo con los incentivos de cada individuo.

A medida que avanza la tecnología, se expande el impacto de nuestras acciones sobre la tierra. Como resultado, debemos ampliar nuestra conciencia de la complejidad arquitectónica, así como de las complicadas relaciones entre piezas en los sistemas que construimos y en los que estamos inmersos.

Nuestros edificios aún se construyen de forma aislada, a pesar de que vivimos en una era de globalización, que muestra una tendencia hacia la confluencia cultural y técnica. Debemos cultivar estrategias de pensamiento de sistema integrado, que nos permitan abordar la complejidad arquitectónica desde diferentes puntos de vista y más allá de los límites disciplinarios. Esto podría conducir a la creación de sistemas de construcción adaptables que respondan a las transformaciones sociales junto con entornos cambiantes. Estas estructuras deben considerar los efectos secundarios a largo plazo de sus operaciones y participar en procedimientos sostenibles y respetuosos con el medio ambiente.

9.2.4. ¿Cómo podemos percibir e influir en el entorno construido a partir de los enfoques EDIS y ABEM?

Debido al hecho de que el desempeño del sistema es específico de la situación y dependiente del contexto, es imposible capturarlo en principios generales o esquemas de evaluación. La simulación del rendimiento de los edificios, por otro lado, se considera una herramienta ventajosa, aunque se requieren más avances para cumplir completamente con los estándares. La integración de entradas de diversos dominios físicos, así como la flexibilidad de las características para representar el comportamiento adaptativo, están abiertas a mejoras adicionales. Complementariamente a esto, sería fascinante buscar formas de mejorar las capacidades de construcción de herramientas de simulación de rendimiento mediante el uso de avances recientes en metodologías de diseño, particularmente aquellas establecidas para respaldar el diseño y desarrollo de sistemas adaptables.

La posibilidad de mejorar las condiciones de confort es al menos tan importante como la justificación del ahorro de energía para los edificios adaptables. A pesar del hecho de que la importancia de la dinámica humana en la planificación e instalación de tecnologías activas de construcción hoy en día es generalmente reconocida, todavía parece haber una brecha de conocimiento en este campo de investigación multidisciplinario.

Para aprovechar la inteligencia humana y natural en la regulación de edificios ambientalmente adaptables, los habitantes deben tener la opción de anulación o ajuste manual. El problema más común de las envolventes de edificios inteligentes es la incapacidad de anular los juicios del sistema.

9.2.5. ¿Cuáles son los requisitos fundamentales para la adaptabilidad arquitectónica en los paradigmas teóricos, metodológicos y técnicos?

Los proyectos examinados en este estudio demuestran que el amplio uso de enfoques ambientalmente adaptables tiene el potencial de convertirse en un contribuyente significativo para cumplir con nuestros estándares de desempeño energético cada vez más estrictos, al mismo tiempo que evita la necesidad de sacrificar la comodidad. Al mismo tiempo, nuestros hechos se suman a nuevas direcciones prometedoras para futuros proyectos de construcción e investigación en los sistemas antes mencionados. En particular, hay escasez de información en la literatura sobre el desempeño operativo monitoreado de enfoques ambientalmente adaptables y evaluaciones posteriores a la construcción. Como resultado, la última parte de la tesis describe algunos de los obstáculos más importantes y sugiere áreas de investigación prometedoras para ayudar a aprovechar el potencial latente de la adaptabilidad en la arquitectura, tanto a través de EDIS como de ABEM.

Las tecnologías innovadoras se utilizan con frecuencia dentro de los diseños adaptativos, lo que da como resultado proyectos difíciles con riesgos significativos. Debido al hecho de que los riesgos están relacionados con tiempos de recuperación desiguales (debido al aumento de los costos de capital, mantenimiento y errores), los desarrolladores de proyectos prefieren adoptar un enfoque cauteloso para adoptar este tipo de nueva tecnología. Correr el riesgo, por otro lado, abre posibilidades, pero estos objetivos elevados deben estar respaldados por juicios de diseño bien informados. Los edificios adaptables al medio ambiente deben pasar de una noción abstracta a una opción de desarrollo viable, lo que requiere el desarrollo de sistemas capaces de predecir con precisión el desempeño efectivo a lo largo de la fase de diseño del edificio.

Como resultado, hay más apertura con respecto a la forma en que las ganancias de rendimiento durante la operación pueden compensar los argumentos de la tasa inicial. Por lo tanto, es más fácil superar la mentalidad cautelosa provocada por la tendencia de "anclaje" hacia soluciones de diseño normativas y convencionales. Los beneficios de desempeño de los edificios ambientalmente adaptables son acumulativos y retrasados, lo que se suma al estado de complejidad.

En el futuro, la creciente complejidad de las necesidades geométricas, performativas y basadas en código seguirá impulsando la arquitectura. Dentro de un contexto de base de datos relacional, un enfoque metodológico que utiliza “biolearning”, diseño virtual y aumentado, fabricación digital e instalaciones brinda una base para el avance futuro. Esto emplea nuevas tecnologías, materiales y flujos de trabajo. Reconocer la experiencia en diseño y construcción y la capacidad de integrar el comportamiento del material de los prototipos físicos en el proceso le permite funcionar como una investigación física y un proceso digital al mismo tiempo.

9.2.6. ¿Cuáles son las perspectivas previsibles en la investigación, la enseñanza y la práctica arquitectónicas para el diseño, la adaptabilidad, la indexación de datos y su transdisciplinariedad energéticamente eficientes?

Uno de los principales desarrollos futuros sería la mejora y confiabilidad del Sistema de Indización de Datos Ambientales. En cuanto a los desarrollos escalables, los pasos más obvios que se consideran factibles es crear una red de EDIS, especialmente en las grandes ciudades, para monitorear las fluctuaciones ambientales (rehabilitaciones de edificios, restauraciones, nuevas construcciones, etc.).

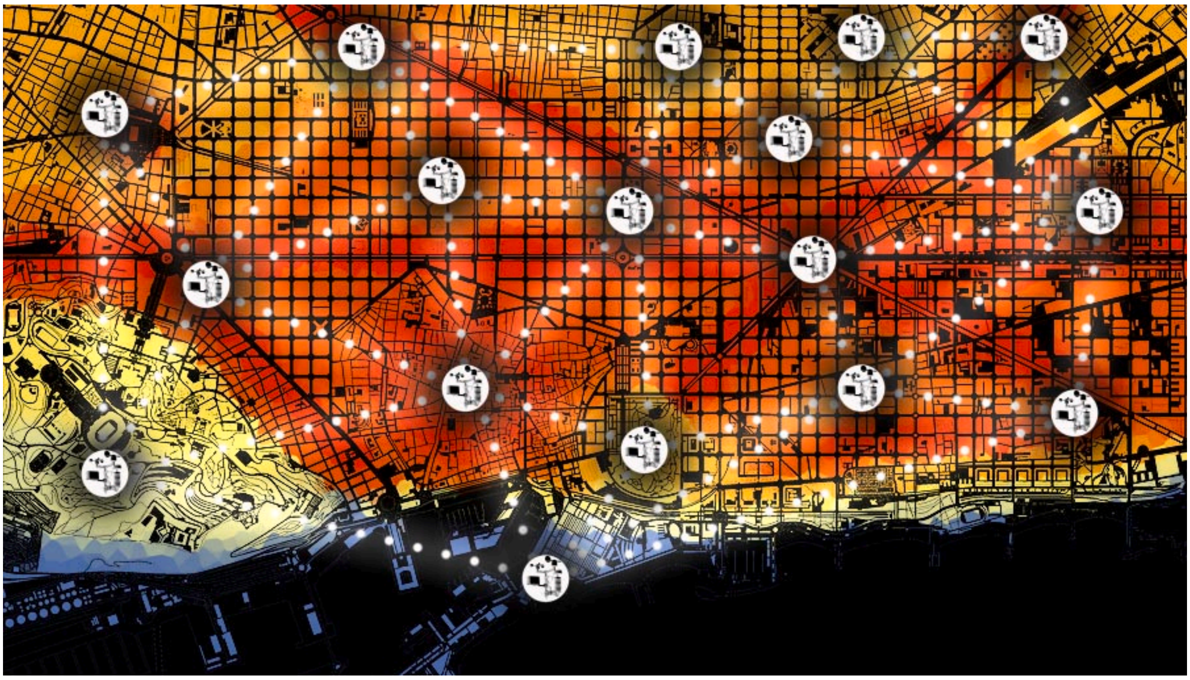

Fig. 9.2 - Red EDIS prevista en Barcelona (Imagen del autor)

Esto también ayudaría con el mantenimiento general de las estructuras dado que ya existen programas que se enfocan en la rehabilitación en base a ciertos lapsos de tiempo (generalmente 10 años). En este sentido, la revisión de un edificio también podría incluir un ajuste en las prestaciones térmicas de las fachadas para un mejor confort interior, cubiertas verdes para mitigar las zonas calientes, etc.

En el caso del propio EDIS, se han planificado un par de mejoras y sustituciones de sensores para generar datos más precisos, especialmente en relación con la radiación solar. Junto a esto, existe un esfuerzo por desarrollar una plataforma en la que los usuarios puedan tener fácil acceso a futuras bases de datos, permitiéndoles ser más conscientes del medio ambiente y diseñar de acuerdo con datos actualizados.

Por lo tanto, concluiremos esta tesis con una descripción general sobre la aplicabilidad de los diseños de procedimientos energéticamente eficientes, logrados a través de la creación de prototipos informacionales. Los temas principales que constituyen este concepto están sembrados tanto en el ámbito teórico (en términos de abstracción y conceptualización de sistemas biológicos para la aptitud de la adaptabilidad) como empírico (en términos de estrategias de eficiencia ya probadas y sistemas interactivos). En este sentido, el rango de aplicabilidad debe tener incipiente en la pedagogía, la andragogía y la práctica.

Esto mejoraría el temor al estado de novedad de los sistemas de alto rendimiento y el diseño computacional a través de la exposición y el epítome.

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Appendices

Appendix A Energy Efficiency Strategies

A.1 Leadership in Energy and Environmental Design

A.1.1 LEED variations and systems applied around the world

Market evaluation and certification programs are crucial for identifying green buildings. These state how environmentally friendly the edifice is and elucidate the principles and techniques used to ensure sustainability. Green building rating systems are tailored to fit the needs of various certifications. Whereas many individuals may concur on the meaning of a "green" building, ratings and certifications help reduce subjectivity. Additionally, green building ratings let the market and others know about the environmental benefits as well as reveal the innovation and expense involved in meeting those requirements.

All energy and resource-saving principles are used when constructing and maintaining a green building. Mechanical, electrical, and material system integration generally increases the overall efficiency in calculating an energy and resource-efficient score for a building, as rating systems generally need third-party verification of numerous parts. As a result, the likelihood of these systems failing to operate as expected is lowered. Similarly, when an edifice is officially evaluated or certified, the likelihood of the project being sold as green when it is not is significantly reduced.

The following are a few examples of other main certification programs used in the United States:

Energy Star: A combined initiative of the United States Department of Energy and the Environmental Protection Agency. The package was developed to lower greenhouse gas emissions besides other contaminants generated by unproductive energy usage, as well as to simplify the user experience towards identifying and buying energy-efficient services (delivering bill savings without losing efficiency, features, or comfort). The framework is intended for already built structures and entails a free Energy Efficiency Rating System. Other elements such as materiality, interior air quality, and recycling are not accounted for.

The method basically contrasts the energy efficiency potential of a specific edifice to one of the regional inventory of comparable edifices. Data inputted into the Energy Star Portfolio Manager application can output energy usage models based on a construction's size, tenancy, environment, and room type. Before the building is awarded a rating between 1 to 100, at least one year of utility data must be supplied. Edifices with a score of 75 or higher are eligible to qualify for and earn the certification label.

The Green Building Initiative (GBI) is a non-profit organization comprised of construction industry leaders dedicated to promoting environmentally progressive building practices that are both convenient and cost - effective for constructors to adopt. The GBI has launched a ranking system called Green Globes, represented by a platform that provides a green building evaluation process and online valuation. It is innovative, customizable, proven and costs little or no money to implement as it's a streamlined online green building program.

Nowadays, LEED is used in over 150 nations and regions around the world and has a membership of 197,000 certified professionals. Additionally, it has 12,870 affiliated administrations from all aspects of the construction industry, aiming to encourage environmentally friendly, profitable, and safe buildings. Alongside LEED, the National Association of Home Builders (a partnership that represents constructors, remodelers, and industry suppliers) has developed NAHBGreen: a voluntary residential green building initiative.

This system includes an online evaluation method, nationwide certification, educational opportunities for industry professionals as well as training for regional verifiers. Builders and homeowners alike can use the online scoring tool for free.

A.1.2 The Green Globes Initiative

The United States has a variety of green building evaluation procedures, with the two most commonly used for commercial buildings being LEED and Green Globes (with their “Go Green” strategy). The LEED Green Building Rating System represents a performance-based rating system for new construction that focuses on buildings with high efficiency and long-term viability. “Go Green” is aimed at possessors of existing buildings who wish to own a more sustainable structure. While Green Globes (in 2019) owns a negligible market share based on certified buildings in the United States, it is expanding rapidly its market share in comparison to LEED certified buildings.

The GBI (Green Building Institute) and the American Institute of Architects engaged in a convergence of will in March 2009, committing to collaborate on the advance of the design and development of sustainable and energy-efficient buildings. Similarly, ASHRAE and the GBI signed a new declaration of intention to collaborate on accelerating the implementation of sustainability standards in the built environment. The initiative of the Green Globes is now on pace to become the United States' premier general standard for marketable green buildings.[480]

A.1.3 Green Delivery Systems vs. Traditional Ones

Global climate change has become painfully obvious over the past few decades and most climate scientists agree that humans are the primary contributors to this effect. People are rarely aware of the environmental effects of preserving interior comfort levels. This might be due to the fact that buildings can be deceivingly complex. They represent the utmost legacy for the future while binding us to the past. However, the position of buildings is evolving as they grow more expensive to construct and sustain, as well as needing continuous alteration to work efficiently throughout their lifespan.

People interpret sustainable or green construction in different ways. In general, it refers to smart construction and design that benefits both the user and the environment. We urgently need to discover means of minimizing energy loads, improving productivity, and using renewable energy sources. Among the main objectives of sustainability in design is to evade resource depletion, while reducing environmental damage instigated by facilities and infrastructure over the course of their lives.

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[480] U.S. Green Building Council, *Green Building Design and Construction*.

Green design initiatives highlight ongoing concerns about inhabitant health, atmosphere, and resource depletion, in addition to the traditional construction design apprehensions of economy, value, and resilience.

The majority of today's conventionally built and constructed buildings have negative environmental and occupant productivity and health consequences. Furthermore, these structures are costly to run and maintain and they contribute to waste generation, emissions, and unnecessary resource use.

The LEED recommendations from the USGBC include both mandatory and suggested practices that aim to minimize the life-cycle environmental impacts of marketable and metropolitan advances, as well as major renovation projects.

Equipping designers with the right resources is a particularly cost-effective approach to high-performance edifices. High-performance construction methods may be used to produce radically improved buildings while reducing the amount of money required to construct them. Following the selection of performance measures, it is important to define performance goals and metrics for each measure.

Codes and specifications are used to describe minimum requirements or baselines. On the contrary, performance reference points can be established to surpass a building type's average performance. Alternatively, performance can be compared to that of the most recent edifice constructed or to that of the best edifice of a specific kind that has been registered.

The use of computer energy modeling can notify the building team of energy-use insinuations within the early stages of the development by providing contextual details like climate data, seasonal shifts, structure morphology, orientation, and daylighting, thus, enhancing integrated design. This allows for rapid investigation of cost-effective design options for the insulation shell and afferent mechanical systems. These explorations are done by estimating the energy consumption of different alternatives when used together.

a Strategies in Green Design

Additionally to incorporating sustainable design principles into novel architecture, representatives for sustainable design often advocate for retrofitting existing structures rather than constructing new ones.

To attain a high-performance edifice, whether retrofitting or constructing from the ground up, an integrated design approach must be used. The architects, civil engineers, landscape architects, and interior designers, can manipulate and guide the ground plane, structure morphology, and planting scheme to increase thermal performance by working together.

For example, an architect, lighting and mechanical engineer may collaborate to design efficient indoor and outdoor light shelves that can serve as an architectural feature while also providing appropriate sunscreens. This would reduce summer cooling loads while allowing daylight to flow within the interior. Most often, the result is more efficient at the same initial expense, followed by a steady stream of continuing operating savings.

An additional characteristic of green development is “Smart Growth. It is associated with the potential to manage struggles, reuse current services, and build walkable urban areas. The proximity of livable areas and offices to public transit is a clear benefit in terms of energy conservation. Similarly, it is more efficient and rational to reuse existing infrastructure rather than building new roads in rural areas far from towns. Smart growth is required to protect green areas, farmlands, as well as to support the growth of already established societies alongside their quality of life.

Though, before dwelling too much into integrated design processes (IDP) and green design, it might be wise to first explain the traditional design process. Conventional design approaches start with the architect and customer deciding on budgets and development concepts, which typically include general massing outlines, standard floor plans, elevations, the overall esthetics, as well as employed materials. Engineers (structural, mechanical, and electrical alike) are therefore tasked with putting the design into action and recommending suitable systems.

This traditional design methodology, despite being vastly oversimplified, is still used by the majority of design consultancy offices, which sadly limits the achievable output to conventional standards. Because of the concurrent contributions of the design team members, the conventional development process has a primarily linear characteristic.

Hence, the scope for optimization is minimal and improvements in the later stages of the development are always difficult. As a result, while this procedure can seem sufficient and necessary, the outcomes frequently reveal an uncanny tale, with raised operational expenses and a subpar interior setting. These aspects may pose a direct effect on an asset's capability to entice quality occupants or obtain long-term rentals, as well as a decrease in the property's value.

b The Integrated Design Process

Since the integrated method necessitates a diverse way of processing and working, designers aiming at integrated processes must learn new skills that were not previously needed as part of their professional practice. In many respects, the IDP methodology varies from the traditional design process.

For example, the owner becomes more engaged in the process and the architect becomes a team leader instead of the lone decision-maker. Supplementary advisors join the team from the start and engage in the development's decision-making progression, rather than after the original project is completed.

IDP entails more time and coordination throughout the initial concept and design stages than traditional approaches. This progresses by crossing disciplinary borders and opposing streamlined planning and design methods. While the term "integrated design" is frequently associated with new developments, it is valid for every step of a building's life cycle.[481]

[481] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*.

Fig. 10.1 - Integrated Design Approach Schematic[482]

The initial time commitment, on the other hand, decreases the time required to generate construction documentation, since the priorities have been extensively discussed and interlaced in the process. Initiatives can be performed more considerately, taking benefit of construction system collaborations and better meeting the needs of their inhabitants or neighborhoods, while also saving money.

The following methods should be carefully considered to confirm the accomplishment of any construction project:

- Creating a vision based on sustainability values to enforce the integrated design method.
- Clearly expressing the development's requirements, aims, design principles as well as priorities.
- Creating a budget that includes green building initiatives, allowing for the inclusion of supplementary options as a contingency.
- Setting performance standards for placement, electricity, water, materials, and indoor environmental value, as well as further sustainable design approaches.

[482] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*.

- Using BIM principles to allow the team to build a virtual model of the development and its numerous features in 3D. This is meant to be exchanged with the whole team.
- Ensuring that workers are properly trained and able of implementing an integrated system initiative during the selection process.

Including a project timetable in the brief, that permits system testing and commissioning.[483]

A.1.4 LEED Technical Requirements and Documentation Process

Completing all of the necessary paperwork can be intimidating for architects, designers, or construction firms who have never worked on a LEED project before. Nevertheless, conferring to the USGBC, the complete LEED documentation and accreditation procedure has been significantly simplified and transferred online to facilitate the procedure. This also reduced the time and expense of obtaining the certification. Development teams now have the possibility of uploading all the documentation electronically.

With LEED-Online, all LEED content, tools, and support are available in one place. However, for the development to be accredited by the USGBC under the LEED scheme, it is required to be registered beforehand.

a Credit Categories

The term “green building” has many connotations. The most commonly accepted form of providing sustainable building certifications today is the USGBC's program LEED.

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[483] Kubba, *LEED v4 Practices, Certification, and Accreditation Handbook: Second Edition*.

A.2 Passive House

A.2.1 The PHPP - Passive House Planning Package

All the development data previously mentioned is meant to be calculated and inserted in a dedicated Microsoft Excel spreadsheet under the form of a dedicated software abbreviated PHPP, standing for Passive House Planning Package. The spreadsheet then processes a technical and physical reproduction of the design.[484]

The calculation of energy demands is conducted following regional climatic data that in turn needs to be validated by the Passive House Institute. Usually, climatic data is provided by the institute or its affiliates, such as Meteonorm, and it is based on surveys taken from meteorological stations over yearly spans. Taking the climate into consideration, the passive house concept may be applied in any geographical setting, depending on the standard of the climatic condition specific to each room, bringing adjacent strategies in terms of either cooling or heating demands.[485]

In 2015 the Passive House Standard redefined itself through three main categories: Classic, Plus, or Premium, which denoted the level of performance of a building following the renewable primary energy demand (RPE) and with the amount of generated renewable energy.[486]

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[484] Feist and others, *Passive House Planning Package - The Energy Balance and Design Tool for Efficient Buildings and Retrofits*.

[485] Piraccini and Fabbri, *Building a Passive House*.

[486] Simon Monk, *Hacking Electronics Learning Electronics with Arduino and Raspberry Pi*, ed. by Michael McCabe and others, Second Edi (New York: McGraw-Hill Education, 2017) <https://www.amazon.com/Hacking-Electronics-Learning-Arduino-Raspberry-ebook-dp-B074HVSBTL/dp/B074HVSBTL/ref=mt_other?_encoding=UTF8&me=&qid=1604489798>.

A.3 Active House

A.3.1 Environmental Loads

a Primary energy (PE)

PE is the cumulative volume of primary energy sourced primarily from the atmosphere, hydrosphere, and geosphere, or a source of energy that hasn't been artificially altered, which includes equally renewable and non-renewable resources. Megajoules (MJ) and net calorific values are used to express primary energy.

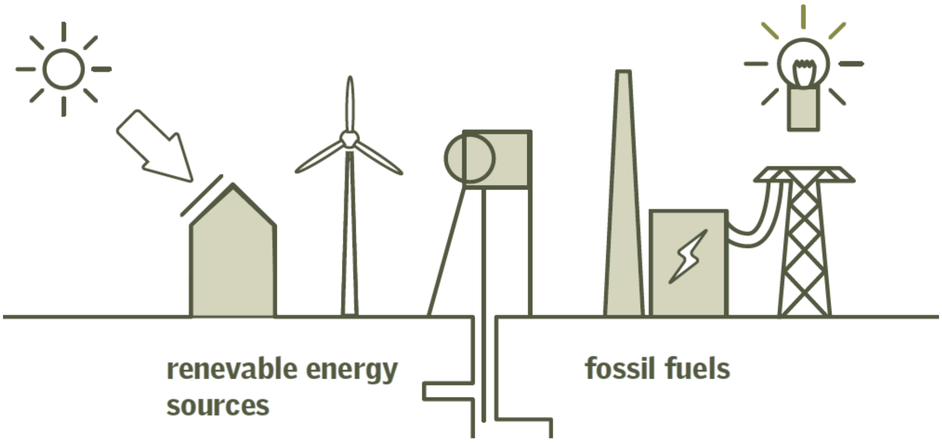

Fig. 10.2 - Difference between renewable energy sources and fossil fuels[487]

Global Warming Potential

Increased infrared radiation reflection from the planet's surface is caused by the concentration of alleged greenhouse gases within the lower atmosphere.

As a result, the earth's surface temperature increases. This phenomenon dubbed the “greenhouse effect” has a detrimental effect on wellbeing, habitats, and society overall. The GWP classifies gases according to their effect on the environment in comparison to carbon dioxide (CO_2).

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[487] Eriksen, Rode, and Gillet, ‘Active House - The Specifications Index’.

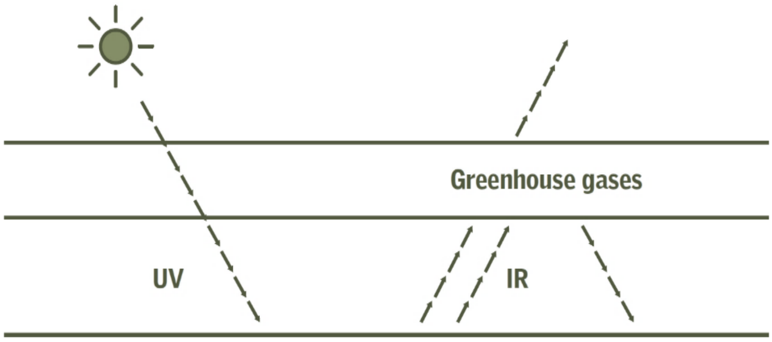

Fig. 10.3 - Greenhouse effect representation[488]

b Ozone Depletion Potential

Ozone (O_3) is a stratospheric trace gas (10 to 50 km high), which assimilates ultraviolet radiation emitted by the sun. However, pollutants cause the stratospheric ozone layer to thin, as some gases, such as halocarbons, act as catalyzers for the decomposition of ozone to oxygen.

Thus, UV-B radiation transmission is increased, which may have detrimental effects on health, land, and aquatic environments. These can include damage at DNA levels, diseases (particularly skin cancer), crop failure, and plankton decline. The ozone depletion potential is a term that encompasses the cumulative effect of numerous ozone diminishing gases.

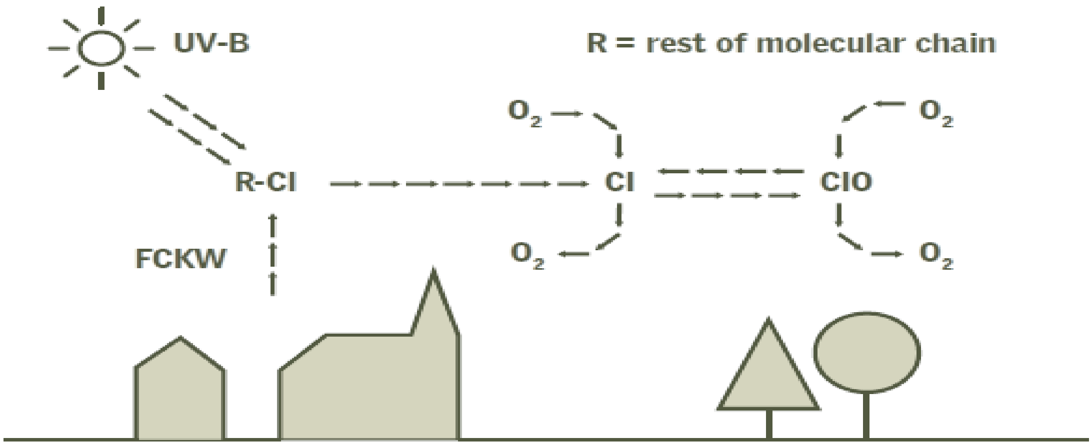

Fig. 10.4 - ODP schematic[489]

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[488] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index'.

[489] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index'.

c Photochemical Ozone Creation Potential

Elevated ozone levels in the troposphere (0-15 km from the earth's surface), labeled as "summer smog," are harmful to people and can also affect plants and materials.

Exposure to solar radiation, nitrogen oxide, and hydrocarbons combine to form ozone at the ground level (tropospheric). This is referred to as photochemical oxidant generation. During partial combustion, nitrogen oxides and hydrocarbons are formed. Both of these are also generated by the use of solvents and petrol. The potential for ozone development is linked to the influence of ethylene (C_2H_4).

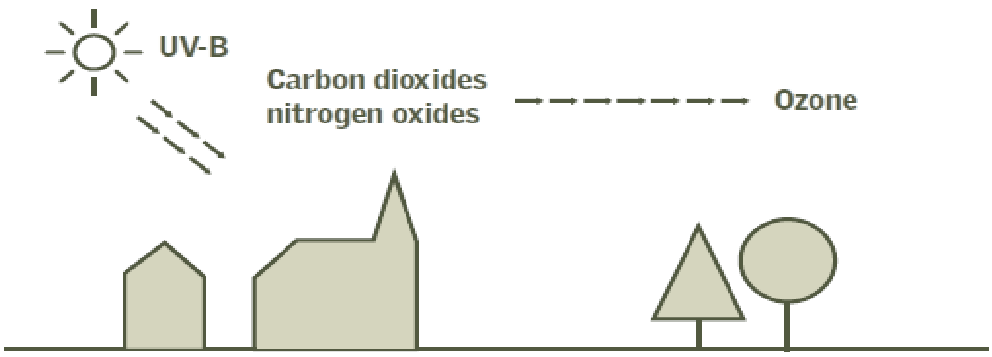

Fig. 10.5 - Photochemical ozone creation potential[490]

d Acidification Potential

Soil and water acidification occurs as a result of toxins in the air being converted to acids. Sulfur dioxide (SO_2), nitrogen oxides (NO_x), and associated acids (H_2SO_4 and HNO_3) are the primary acidifying contaminants. These gases are produced by power plants and industrial facilities during combustion operations, as well as by residential buildings and automobiles.

Acidification has a variety of detrimental effects on surface waters, groundwater, soil, biological organisms, habitats as well as construction materials. This process also influences forest decline and accentuates acid rain. The AP classifies all substances that contribute to acidification relative to SO_2 effects.

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[490] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index'.

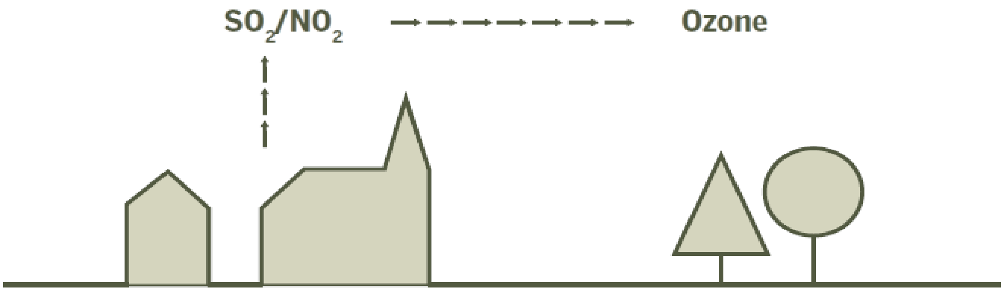

Fig. 10.6 - Acidification potential[491]

e Eutrophication

Eutrophication is a term that refers to extensive fertilization and represents the accumulation and enrichment of nutrients in an ecosystem that can result in a disagreeable change in species composition and increased biomass output. Nitrogen, as well as phosphorus, are the two primary nutrients.

These pollutants can be found in fertilizers, fumes from combustion vehicles, residential wastewater, and industrial effluents.

Excessive fertilization weakens the plants' tissue and reduces their resistance to environmental factors. Raised biomass production in aquatic environments can lead to decreased oxygen levels owing to the extra oxygen consumed throughout the biomass breakdown.

This can be observed in the death of fish and the biological demise of the water. Additionally, a raised nitrate concentration can render ground and surface water unfit for human use, as nitrate reacts to form nitrite, which is harmful to humans.

The eutrophication capacity classifies substances according to their effect on the environment in addition to the impact of phosphate (PO_4).[492]

[491] Eriksen, Rode, and Gillet, 'Active House - The Specifications Index'.

[492] Jeroen Guinée, *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*, ed. by Jeroen Guinée (Springer Netherlands, 2002), VII <https://doi.org/10.1007/0-306-48055-7>.

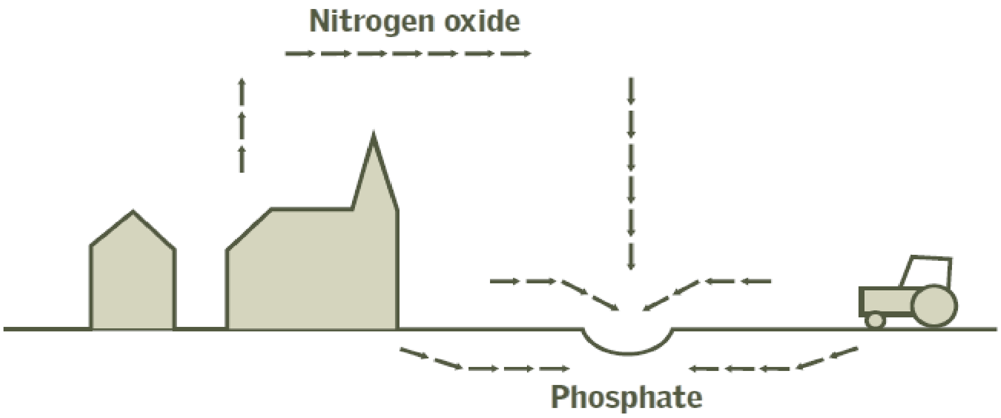

Fig. 10.7 - Eutrophication Effect Schematic[493]

Appendix B Adaptivity in Architecture

B.1 Consciousness in Architecture

Our brains' perceptions of space appear to generate a kind of soft architecture that is not determined by the actual materials and hardness of our environment, but rather by the way an inhabitant approaches this defined space and creates another space in their mind via their perceptions and senses.[494]

How to concisely explain the mental construction of soft architecture and why soft architecture is the architectural result of inner consciousness?

Several theories investigate perception and experience, how we view the environment around us, and the factors that influence our perception. There are two fundamental spatial sensations: surface and edge, which form our basic spatial perception. Additionally, some stimuli provide additional information and enhance the clarity of the image produced in the retina. Additionally, our expectations are selective, so that some aspects of an area will stand out while others will go unnoticed. Both of these variables vary according to our biology.[495]

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[493] Eriksen, Rode, and Gillet, ‘Active House - The Specifications Index’.

[494] Antonio Damasio, *Self Comes to Mind: Constructing the Conscious Brain*, 1st edn (New York: Pantheon, 2010).

[495] James J Gibson, *The Perception of the Visual World* (Westport: Greenwood Press, 1977).

To develop a sense of space, one must be aware of all of this data, and our awareness generates it. According to Damasio (2010), consciousness is composed of two components: the mind and the 'self.' Although the mind is constantly receiving information, we are not passive recipients of it. Our minds contain a sense of self, which conveys a subjective perspective upon the information we interpret. This self is unique to each person because it is reflected on our interior body via our brain map.[496]

The world encompasses the space around us, and we have unconsciously shaped ourselves in response to this space, which in turn is reshaped, after which shapes us again, and so on. This concept reflects the case of collective behaviors and how the presence of another person affects our emotion and perspective, which then reconstructs our space, which in turn affects them, and so on in this loop. Hofstadter also conducted experiments in which he connected a video camera to a screen, aimed it at it, and recorded his hand movements in front of the camera, as well as rotating the camera, to investigate the continuous construction of an infinity vortex, or 'strange loop,' as he termed it.[497]

B.2 Cognition in Architecture

It is imperative to study the experiences of building users (occupants and visitors) while pursuing a human-centered design approach.[498] This entails being acquainted with a variety of design thinking approaches and tools, thus enabling the generation of deep insights into the designs through systematic observation and engagement with key stakeholders. Rapid prototyping is envisioned as well as iteratively evaluating ideas and concepts using a variety of materials and techniques.[499]

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[496] Antonio Damasio, *Self Comes to Mind: Constructing the Conscious Brain*.

[497] Douglas R. Hofstadter, *I Am a Strange Loop*, 1st edn (Philadelphia: Basic Books, 2007).

[498] Christoph Hölscher, 'Cognition in Architecture - Designing Orientation and Navigation for Building Users', *Chair of Cognitive Science - ETH Zurich*, 2021 <https://cog.ethz.ch/teaching/cognition-in-architecture.html> [accessed 19 February 2021].

[499] Thomas Barkowsky and others, 'Spatial Cognition in Architectural Design Anticipating User Behavior, Layout Legibility, and Route Instructions in the Planning Process', *Spatial Cognition in Architectural Design*, 014, 2007.

Appendix C Procedural Architecture

C.1 Ladybug Definitions

C.1.1 Weather Data Visualization and Analysis

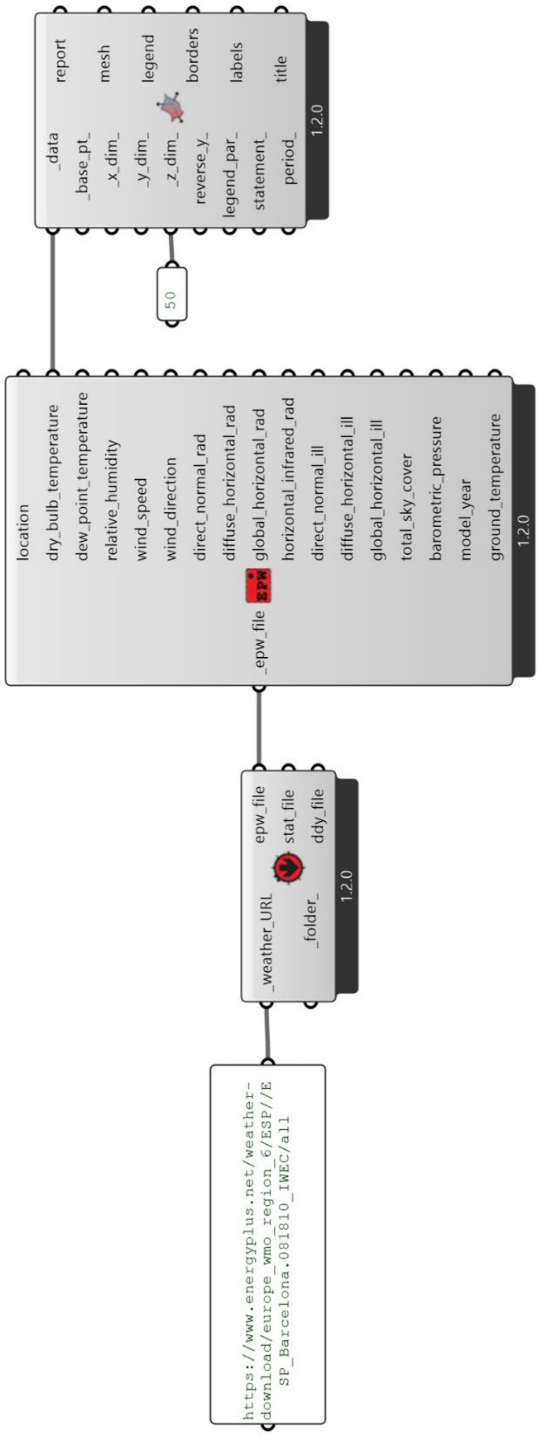

Fig. 10.8 - 3D Chart Script (Image by Author)

C.1.2 Wind Rose

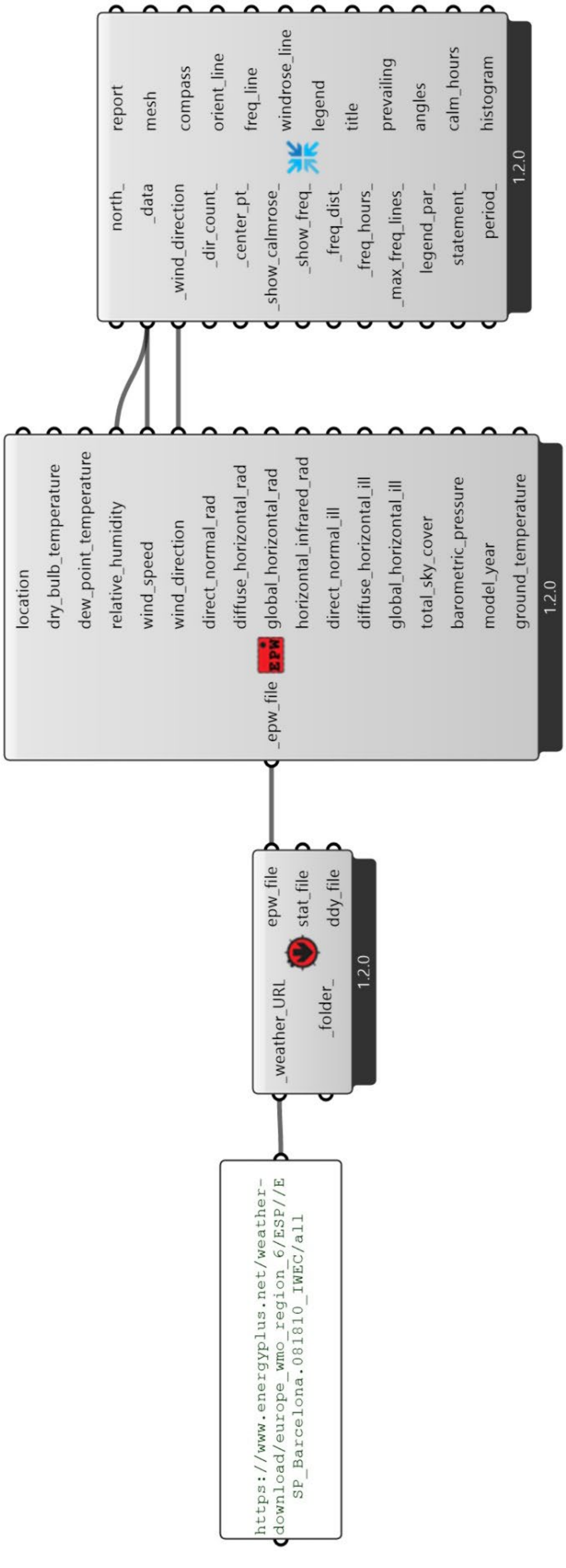

Fig. 10.9 - Windrose grasshopper Script (Image by Author)

C.1.3 Radiation Studies

a SkyDome

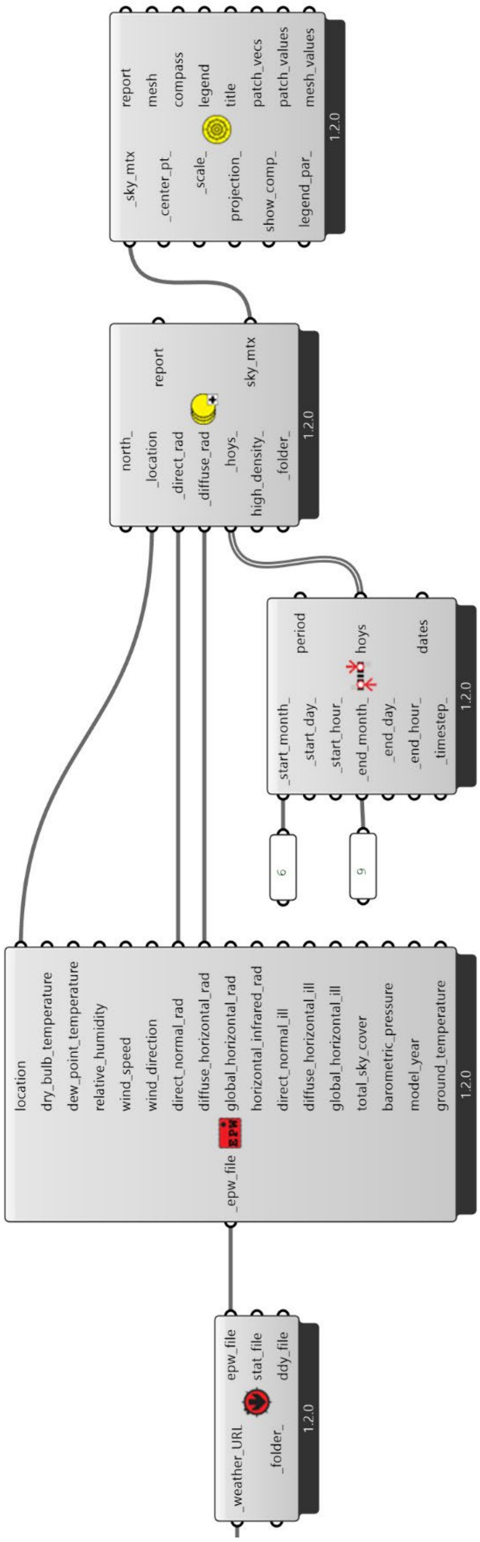

Fig. 10.10 - SkyDome example script (Image by Author)

b Radiation Rose

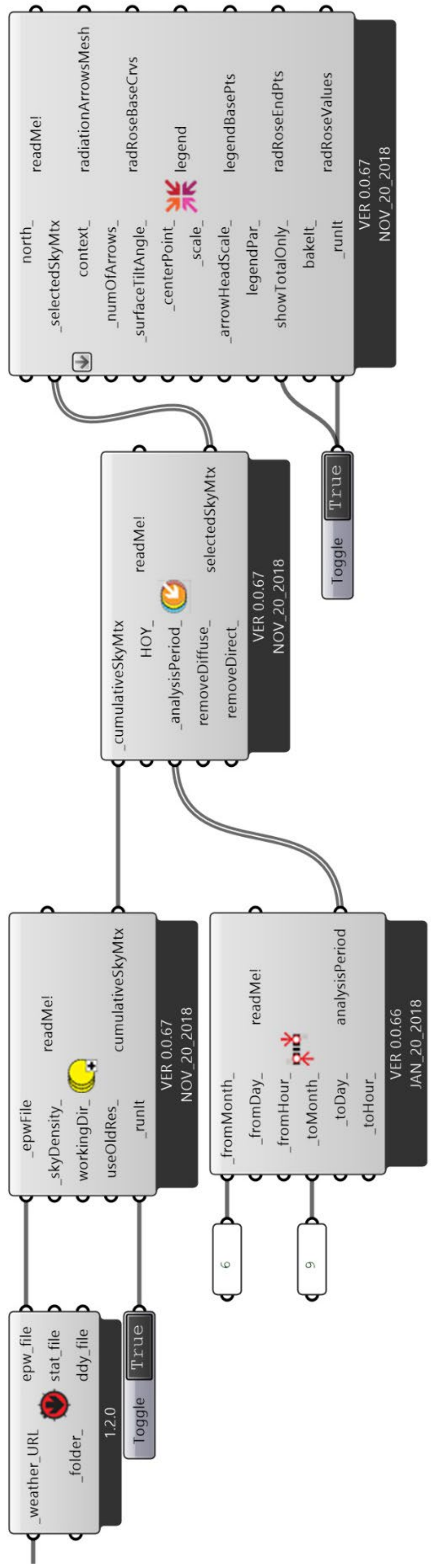

Fig. 10.11 - Radiation Rose example script (Image by Author)

c Incident Radiation

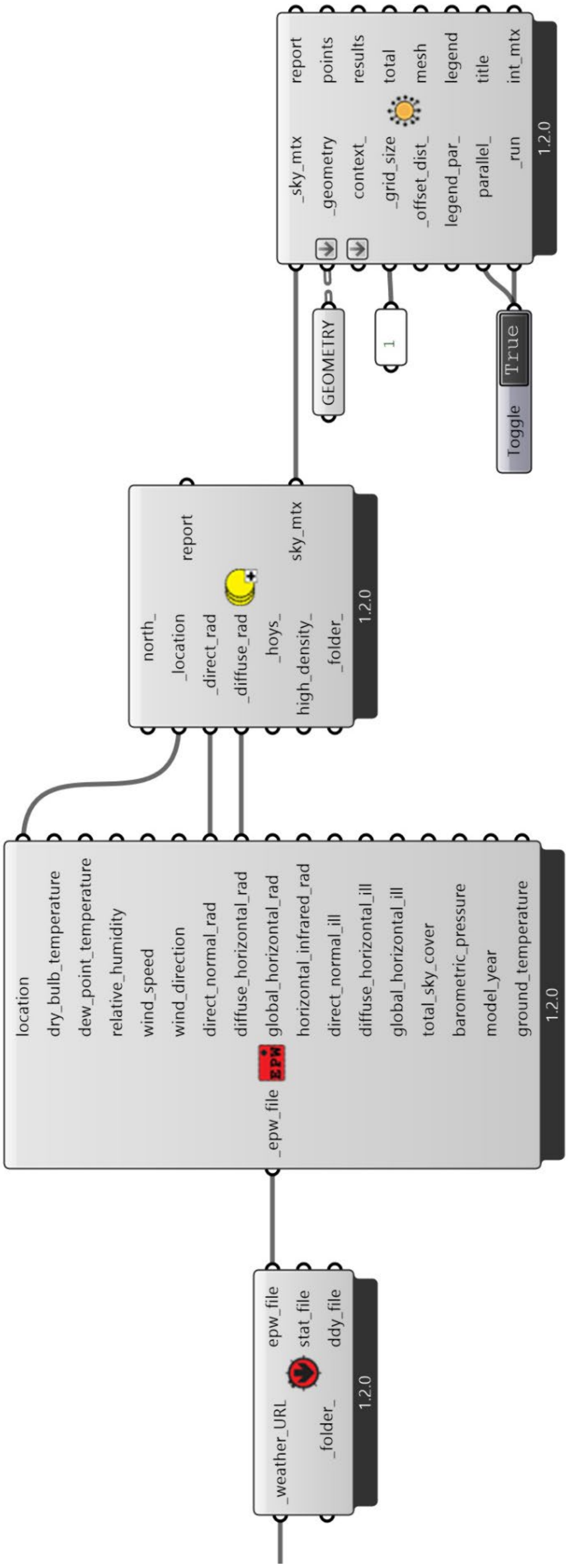

Fig. 10.12 - Incident Radiation analysis example script (Image by Author)

C.1.4 Illumination Studies

a Sun Path

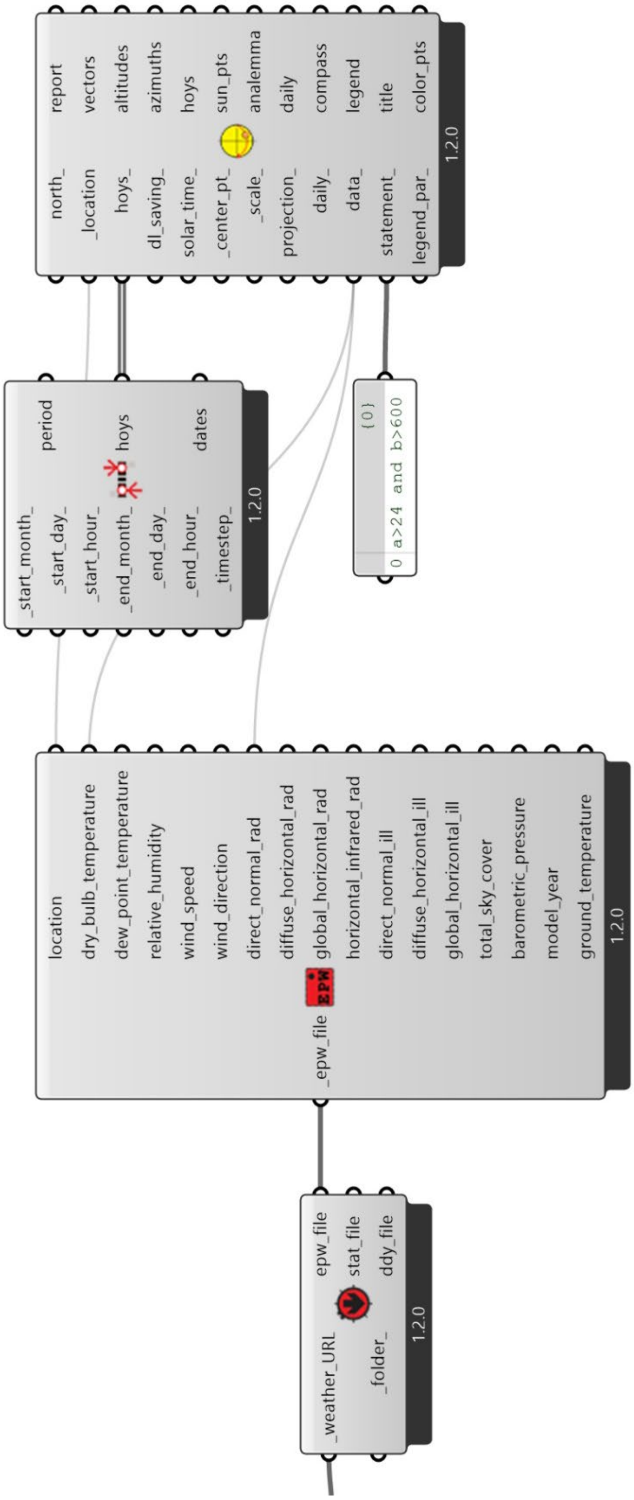

Fig. 10.13 - Sun path example script (Image by Author)

b Direct sunlight hours analysis

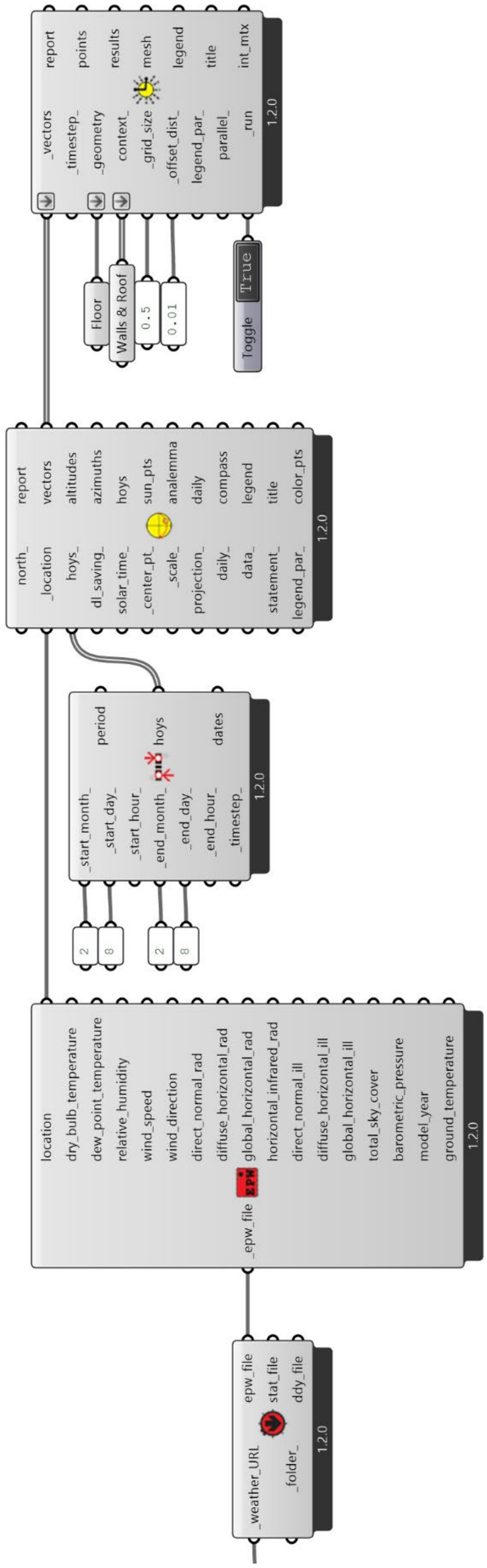

Fig. 10.14 - Direct sunlight hours analysis (Image by Author)

C.1.5 Orientation Studies

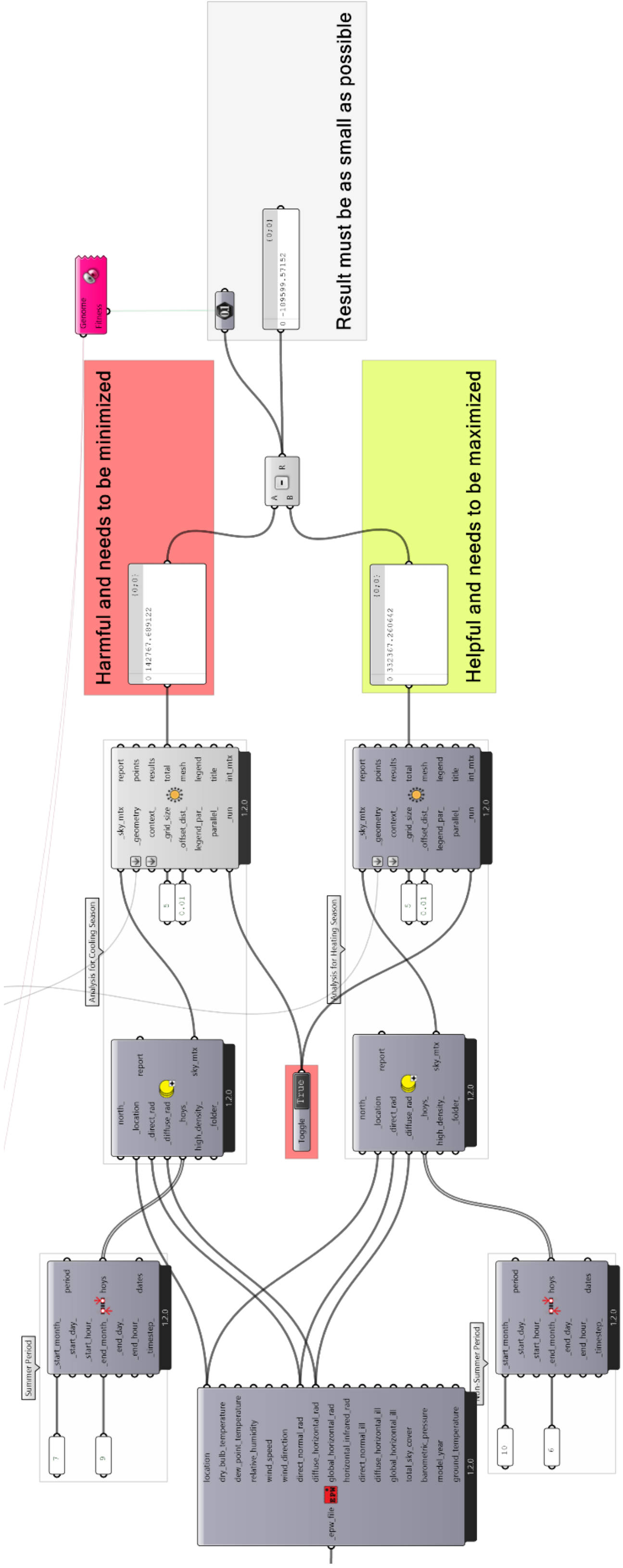

Fig. 10.15 - Orientation Optimization Script (Image by Author)

Appendix D EDIS

The initial EDIS station was thought to be powered by 12V DC, which had to be connected to a DC-DC buck converter that would reduce the 12V input and output it to 9V to safely power the Arduino board. Complementary to the Arduino we added a Terminal Shield for ease of connectivity due to its screw terminals. The next image will depict an overview of each sensor and its reading input.

To aid the testing and verification process, two LEDs were to be included. One would indicate the flow of power to the microcontroller and the other one to show when the data is being communicated.

D.1 Initial Approach Components

The following components were taken into consideration for the development of the Arduino based System

DC-DC Buck Converter: regulates the flow of current from the source to the Arduino at 9V, while keeping it at a constant 12V for the optical rain sensor (Hydreon RG-11) and the Davis Anemometer[500]

Arduino Uno - R3: one of the best boards to get started with electronics and coding since it is the most utilized and well-documented microcontroller of the entire Arduino generation. Its layout contains a USB connection, 6 analog inputs, 14 digital input/output pins, a 16 MHz quartz crystal, a power jack, an ICSP (In-Circuit Serial Programming) header, and a reset switch.[501]

Terminal Shield: converts all of the microcontroller headers into convenient screw connections eliminating the need for soldering. Its center area offers a large space for prototyping, enabling the addition of more parts that would suit the project. All of the auxiliary components for the Terminal Shield are already

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[500] Wikipedia, ‘Buck Converter - Wikipedia’ <https://en.wikipedia.org/wiki/Buck_converter> [accessed 1 April 2020].

[501] Arduino, ‘Arduino Uno Rev3 | Arduino Official Store’ <https://store.arduino.cc/arduino-uno-rev3> [accessed 1 February 2020].

installed as surface-mount elements, and it even provides stackable headers to allow multiple shields to mount on top.[502]

GPS Breakout: a GPS module with 66 channels that can monitor up to 22 satellites. It features an integrated antenna and an outstanding high-sensitivity receiver.

The module has low power consumption and thanks to the onboard voltage level shifter the module is 5v tolerant. It also comes equipped with an integrated coin cell socket (enabling power to the real-time clock to run and allow warm starts), a peripheral antenna connection, and a built-in data logger.[503]

Davis Anemometer: The anemometer will record wind speeds and wind direction.[504]

Hydreon Optical Rain Sensor: Using infrared light beams, the sensor detects water contacting its outer surface. It employs the same sensing concept as rain-sensitive windshield wiper controls in automobiles.[505]

Real-Time Clock Assembled Breakout Board: A real-time clock, abbreviated as RTC, is a device that maintains track of the current year, month, day, and time. Returned Values are the time and date, and can also be used as a Data Logger.[506]

Quad Band GPRS-GSM SIM800L: a quad-band GSM / GPRS module, fitted with a quad-band antenna. By inserting a valid SIM card, it can be used to gain access to the internet in order to send data.

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[502] Freetronics, ‘Terminal Shield for Arduino | Freetronics’ <https://www.freetronics.com.au/products/terminal-shield-for-arduino#.XtU7AzozaUI> [accessed 1 February 2020].

[503] Adafruit Industries, ‘Ultimate GPS Breakout, 66 Channel, 10 Hz Updates, 5 V, -165 DBm, MTK3339 Chipset’ <https://octopart.com/746-adafruit+industries-32978860> [accessed 1 March 2020].

[504] Davis Instruments, ‘Anemometer’ <https://www.davisinstruments.com/product/anemometer-for-vantage-pro2-vantage-pro/> [accessed 1 February 2020].

[505] Hydreon, ‘Hydreon Optical Rain Sensor’.

[506] Adafruit Industries, ‘Adafruit PCF8523 Real Time Clock Assembled Breakout Board’ <https://octopart.com/3295-adafruit+industries-76371051> [accessed 1 March 2020].

Atmospheric Sensor Breakout - BME280: This sensor offers a simple method to record barometric pressure, temperature, and humidity readings.

DS18B20 Waterproof Wire Temperature Sensor: A very simple wire sensor that measures temperature in a huge range, with high accuracy. It can return values from a range of –55°C to +125°C, with a precision of +/-0.5C.[507]

High Dynamic Range Digital Light Sensor: The TSL2591 is an ultra-high-range luminance sensor offering I^2C compatibility, and can perceive light levels from 188μLux up to 88000 Lux.[508]

Two 5v – 1W Solar Panels: The solar panels were meant to be used to approximate the direct and diffuse solar irradiance by transforming the energy absorbed from the sun into electromagnetic radiation in the measuring instrument's wavelength range.

[507] OctopPart, 'Waterproof Digital Temperature Sensor' <https://octopart.com/sen-11050-sparkfun-66786795> [accessed 1 March 2020].

[508] Adafruit Industries, 'Adafruit TSL2591 High Dynamic Range Digital Light Sensor' <https://octopart.com/1980-adafruit+industries-50010413> [accessed 1 March 2020].