Pathway to Net-Zero Carbon Buildings

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Abstract

The construction industry and buildings have a considerable impact on society, ecosystems, and global warming, shaping the way people live, consuming large amounts of materials, and producing abundant GHG emissions. As a result, the building sector plays a crucial role in the fight against climate change by mitigating the industry's impacts and decarbonizing buildings. Therefore, the concept of Net Zero Carbon Buildings (NZCB) emerges as the answer of the sector's researchers and practitioners to eliminate or minimize a building's carbon emissions throughout its entire lifecycle. However, there is no established and clear action plan or set of strategies for construction companies to design, build and operate such buildings. Thus, the purpose of the thesis is to co-design a strategy in collaboration with real-estate development companies to reduce the carbon emissions of their buildings and contribute to reaching NZCBs. For this purpose, this study is based on theories, such as Design for Sustainable Transitions, to comprehend and analyze the industry's composition, its enablers and limitations, and Participatory Design to engage with key actors and co-create an effective solution. Additionally, research, analytical, and participatory methods like interviews, affinity diagrams, and workshops were essential in the design process to gather relevant information and knowledge, examine connections and pathways, and create spaces for creation, discussion, and evaluation. Finally, this journey led us to develop a practical, clear, and tailored Guideline for real-estate development companies to implement design and behavioral strategies that reduce the operational carbon of buildings and encourage them to build their own path toward the decarbonization and resilience of the built environment.

Keywords: net-zero carbon building, construction industry, operational carbon, design strategies.

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INTRODUCTION

We are now facing a climate emergency as the globe is warming at a rapid pace. We are passing the safe operating space of climate change boundaries and their irreversible tipping points. Based on the urgency and importance of this issue, nations worldwide have committed to the Paris Agreement common goal of maintaining the global temperature rise to below 2 °C by the end of the century. The Intergovernmental Panel on Climate Change (IPCC) sixth assessment report stated that global warming is a direct result of greenhouse gas (GHG) emissions generated mainly by human activities (World Economic Forum, 2023).

In particular, the construction sector has a significant impact on global warming and ecosystems, as buildings are globally responsible for 38% of energy-related carbon emissions and 50% of resource consumption (World Green Building Council WGBC, 2021). Consequently, the whole industry has a vital role in achieving the common goal and a huge responsibility in reducing the impacts of the sector and decarbonizing buildings.

Therefore, the sector requires a radical transformation across the building's life cycle and value chain. There must be a radical shift in the way buildings are designed, built, operated, refurbished, and deconstructed, in how professionals plan and design having a whole life cycle approach, and in business models that promote circularity, renewable energies, and innovative operations (World Green Building Council WGBC, 2021). Lastly, there is a need for greater and deeper collaboration, not only across the value chain but also among the public and private sectors, at all jurisdictional levels (GlobalABC; IEA; UNEP, 2020).

The impacts of and challenges for every region vary widely regarding climate, regulations, cultural, economic, and development conditions. In Colombia, the context of the project, building's carbon emissions represent around 7% of total national carbon emissions. Some of the reasons are that the energy grid is dominated by renewable sources (more than 70%, mostly hydropower), and emissions from agriculture, forestry, and land use are much more representative (Universidad de los Andes; Hill Consulting, 2022).

Source: Conaltura

Although the impact is considerably lower than in other regions of the world, the industry faces significant challenges to achieve carbon neutrality, such as high levels of informality, lack of technology, and industrialized processes. These circumstances are further exacerbated by high urbanization rates, urban sprawl and fragmentation, and low public infrastructure (CCCS, 2022; GlobalABC; IEA; UNEP, 2020). Furthermore, the transformation and decarbonization of the construction sector in Colombia are highly relevant and urgent, considering that at least 40% of the housing stock will be built between 2020 and 2050 (Universidad de los Andes; Hill Consulting, 2022). According to the same study, if the industry continues doing business as usual, GHG emissions associated with buildings are expected to increase from 18.9 Mt-CO2eq in 2020 to 32.6 Mt-CO2eq in 2050.

To outline the pathway to a sustainable and efficient buildings regions and countries worldwide have developed strategic roadmaps to set up a common vision. Thus, the Colombian government developed a roadmap, in collaboration with over 200 stakeholders from the industry, that outlines a range of plans and strategies to develop a sustainable built environment and achieve the goal of Net Zero Carbon Buildings (NZCB) by 2050 (CCCS, 2022). As a result, the national roadmap defined NZCB as “a highly efficient and climate change resilient building that, in its life cycle and interaction with the environment, generates well-being for its occupants and a net zero carbon emissions balance.” (CCCS, 2022, p. 21). Therefore, to develop such buildings, it is essential to adopt a whole life cycle approach, considering all emissions, impacts, and actors involved in each phase.

A building’s lifecycle comprises five phases: the product phase, the construction process phase, the use phase, the end of life, and the next product system. Over its lifetime, a building’s carbon footprint includes embodied carbon from the manufacture and processing of building materials and construction processes, as well as the operational carbon from the energy use of its operations (GlobalABC; IEA; UNEP, 2020). While both carbon emissions need to be reduced to achieve carbon neutrality, this project will focus on reducing operational carbon, as it accounts for the largest portion of carbon emissions in buildings, primarily due to their extended lifetime.

However, neither the national roadmap nor other international frameworks propose a specific action plan or guide for building developer companies to implement in order to reduce operational carbon and achieve the goal of NZCB. Therefore, this study aims to investigate and analyze the construction industry’s current state, as well as map innovations, strategies, barriers, and enablers of sustainable initiatives to create an action-based solution for such companies to implement. For this purpose, the design team has collaborated with a Colombian real-estate development company named Conaltura, which designs and constructs high-rise residential buildings (Conaltura S.A., 2021). The organization is a national leader in sustainable construction and buildings but has not yet implemented a carbon emission reduction approach and plan.

Consequently, the research question this thesis wants to answer is:

How to co-design a strategy for real-estate development companies to reduce the operational carbon of their buildings and thus contribute to achieve the goal of NZCB?".

To argue for the final solution, this thesis comprises seven sections. First, the literature review introduces the current state of the construction industry, the concept of NZCB and operational carbon, and sustainable theories and methods related to it. The second chapter presents and argues the theories and methods selected to research, analyze, and develop the design process. The third section describes and analyzes the current socio-technical system and the transition pathway required for the industry to decarbonize buildings.

Chapter four shows the research and the collaboration process results and examines the key findings that shaped the solution. The fifth section presents the Pyramid Model and the Building's Operational Carbon Reduction Toolkit as the solution, together with its strengths and weaknesses. In chapter 6, we discuss severable issues about the process, our contribution to the Sustainable Design Engineering (SDE) field, and future steps to improve the solution. The last section concludes the paper, analyzing the influence of key methods, theories, and findings on the final solution, and gives final considerations about its.

1

LITERATURE RESEARCH

To deepen the research on how to achieve the transition towards NZCB and thus answer our research question, in this chapter, we address the main characteristics and environmental impacts of the construction industry, both globally and in the Colombian context. Besides, we will present the concept of NZCB and operational Carbon, introduce our collaborator partner, and explain sustainable theories and methods currently used to address the challenges of global warming and GHG.

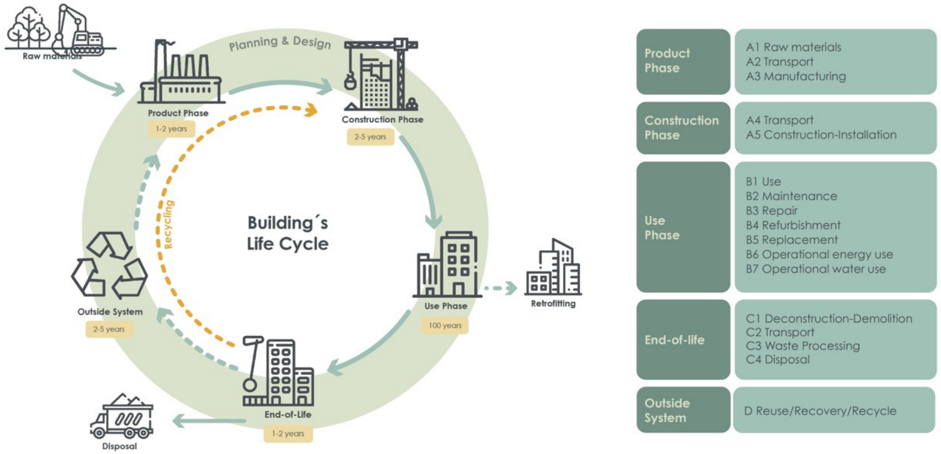
1.1. Construction Industry

In the context of the climate emergency, the construction sector has a crucial role, being responsible for 39% of global energy-related carbon emissions (GlobalABC; IEA; UNEP, 2020). This situation can be explained because the processes involved in building development are energy-intensive, such as the production and transportation of building materials and the energy used during building operations. For example, cement production, a crucial building component, accounts for around 8% of global carbon emissions. In addition, the construction sector is also responsible for a significant portion of global material use, accounting for approximately 50% of the consumption of all materials extracted globally (CCCS, 2022).

Additionally, it is estimated that by the year 2050, the built park will double its current size to meet the housing demands of the increasing world population. This means that the construction industry will need to build the equivalent of the current global building stock in the next three decades, increasing the burden of its impacts on the environment. Thus, with current trends, the global building sector would generate the entire budget for GHG emissions that the IPCC considers would allow reaching the scenario of a limit increase of 2 degrees (World GBC & GBCe, 2022).

1.1.1. Building life cycle

The construction industry holds significant responsibility for several environmental impacts. Adopting a holistic approach that examines the entire life cycle of buildings is essential to address these effects comprehensively. This entails going beyond the finished building and considering crucial elements such as design, construction, demolition, and waste management. According to the European standard EN 15978, the life cycle of a building is divided into five distinct phases: the product phase, construction process phase, use phase, end-of-life phase, and the subsequent product system (Kanafani et al., 2019), see Figure 1.



Product Phase	A1 Raw materials A2 Transport A3 Manufacturing
Construction Phase	A4 Transport A5 Construction-Installation
Use Phase	B1 Use B2 Maintenance B3 Repair B4 Refurbishment B5 Replacement B6 Operational energy use B7 Operational water use
End-of-life	C1 Deconstruction-Demolition C2 Transport C3 Waste Processing C4 Disposal
Outside System	D Reuse/Recovery/Recycle

Figure 1. Building's lifecycle and its phases. Source: Kanafani et al. (own illustration)

Therefore, when adopting a life cycle approach, carbon emissions associated with buildings are categorized based on the respective phases of their occurrence. These emissions are referred to as embodied and operational carbon, and both contribute to the overall carbon footprint of a building, commonly known as whole-life carbon (CCCS, 2022). However, they originate from different sources and at distinct stages throughout the building's life cycle, see Figure 2.

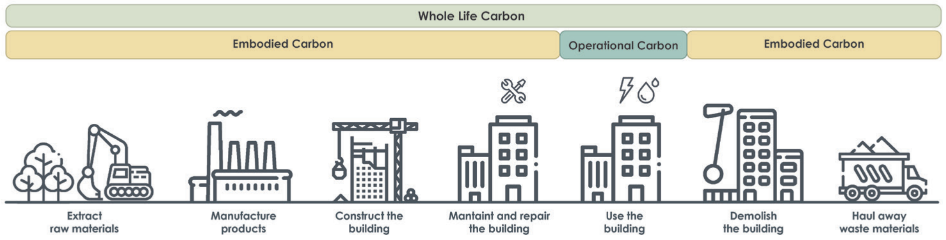


Figure 2. Carbon emissions during the building's life cycle. Source: World Economic Forum (own illustration)

Embodied carbon emissions are attributed to the manufacturing and transportation of construction materials and the construction and demolition processes of the building. It includes, for example, the emissions associated with the manufacturing of cement, steel, and glass and the emissions from the construction process itself, including excavation, transportation of materials, and the energy used to power construction equipment (World Green Building Council, 2021).

On the other hand, operational carbon refers to the carbon emissions associated with the energy utilized for the daily operation of the building, ensuring comfortable living conditions. This encompasses emissions from heating, cooling, and lighting systems, as well as from household appliances and other electrical equipment. These emissions occur once the building is occupied (World Green Building Council, 2021).

Globally, buildings are responsible for 38% of global energy-related carbon emissions. Out of this total, operational carbon emissions contribute to 28%, while materials and construction processes (embodied carbon) account for the remaining 10% (World Economic Forum, 2021); see Figure 3.

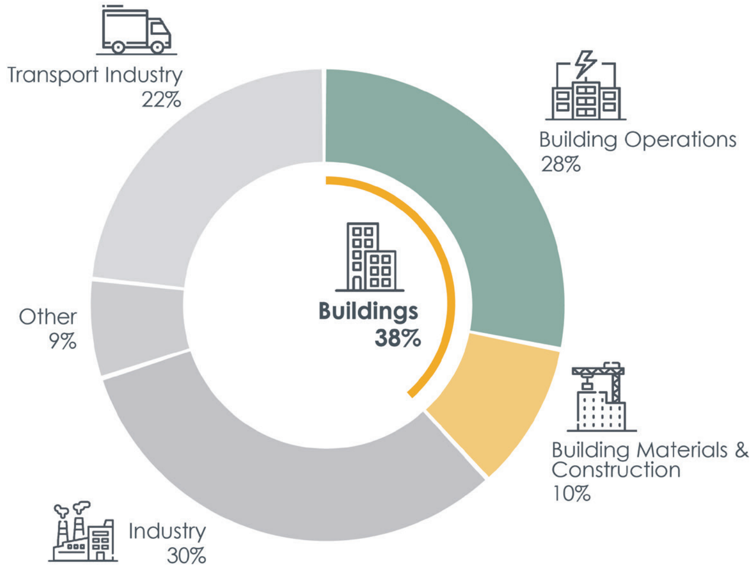


Figure 3. Global carbon emissions by sector. Source: World Economic Forum (own illustration)

Although embodied carbon emissions are associated with various stages of the building's life cycle, they constitute a relatively small portion of the overall emissions due to their short duration compared to the use phase. Considering buildings have a lifespan ranging from eighty to one hundred years, the use phase plays a prominent role, contributing more than 70% of the total emissions from buildings (Kanafani et al., 2019).

1.1.2. Challenges of the industry

Therefore, to align with the objectives outlined in the Paris Agreement and effectively reduce GHG emissions, the construction sector must commit to reshaping the future of the built environment. Moreover, addressing decarbonization in this sector requires a comprehensive approach that encompasses both operational and embodied carbon, as well as direct and indirect emissions (World GBC & GBCe, 2022). In line with this, the International Energy Agency (IEA) estimates that to achieve industry decarbonization by 2050, direct carbon emissions from buildings must be reduced by 50% in 2030, while indirect emissions from the building sector should be reduced by 60%.

However, the Global Status Report by the Global ABC highlights that current progress in emission reduction is insufficient, as the growth of built-up areas and increasing demand outpaces advancements in energy efficiency (GlobalABC; IEA; UNEP, 2020). Consequently, the building sector faces a profound and transformative challenge. On the one hand, there is a social obligation to ensure habitable conditions. On the other hand, an ambitious goal must be pursued: the substantial reduction of GHG emissions from buildings to achieve climate neutrality by 2050.

Furthermore, due to its highly fragmented and localized nature, the building industry poses a significant challenge to decarbonization. No single group of actors has substantial control over the stock and value chain. Instead, the industry involves a plurality of participants throughout all life cycle phases, including designers, contractors, developers, suppliers, and owners, among others. This fragmentation creates coordination and communication challenges, impeding innovation and hindering the widespread implementation of new sustainable practices across the construction process. Moreover, the lack of a common and internationally shared vision among actors in the construction sector adds to the complexity of the situation (GlobalABC; IEA; UNEP, 2020).

From the imperative of reducing carbon emissions to integrating sustainable strategies throughout the building life cycle, these challenges demand a holistic and collaborative approach. Therefore, it is paramount that all stakeholders engaged in the construction process actively participate in a concerted effort. This collaborative paradigm will facilitate the development of a shared vision, implementing effective long-term strategies and seamlessly integrating emerging and innovative technologies into everyday construction practices.

Embracing this collaborative approach holds the potential to overcome obstacles and pave the way for a sustainable and resilient future.

1.2. Net Zero Carbon Buildings

Within the current context, the concept of NZCB emerges as an innovative approach to mitigate the harmful effects of the building sector. Governments and companies worldwide are actively implementing this concept within their territories and portfolios, going beyond 'business as usual' and devising strategies and roadmaps to achieve it. However, a universally shared definition for NZCB is lacking despite its widespread adoption. In this study, we adopt the definition provided by the Colombian Government's roadmap, which characterizes NZCB as:

> **"A highly efficient and resilient building to climate change that, in its life cycle and interaction with the environment, generates well-being for its occupants and a net balance of carbon emissions equal to zero"** (CCCS, 2022, p. 21).

NZCBs embody a fundamental goal in sustainable construction practices, aspiring to achieve a whole-life carbon of zero GHG emissions. NZCBs accomplish this not only by reducing energy and material demands but also by actively avoiding carbon emissions through the integration of renewable energy sources. Such buildings significantly curtail operational carbon emissions by prioritizing energy efficiency, optimizing building envelopes and systems, and harnessing renewable energies. Additionally, reducing embodied carbon becomes essential, focusing on materials efficiency and utilizing low-carbon alternatives. Furthermore, NZCBs recognize the role of carbon offsets to compensate for residual emissions, thereby enhancing their carbon neutrality (World Economic Forum, 2021).

In conclusion, NZCB are highly complex systems that entail a holistic approach encompassing multiple strategies and technologies, along with the active collaboration of the entire industry. The collaborative efforts of all stakeholders are paramount in successfully implementing these strategies, as they bring together diverse expertise, resources, and perspectives on how buildings are designed, constructed, and operated. By embracing these strategies, NZCBs exemplify a paradigm shift towards sustainable construction, ultimately fostering a resilient and low-carbon built environment.

1.2.1. Operational carbon

Operational carbon accounts for over two-thirds of the environmental impacts attributed to buildings and represents nearly one-third of global final energy consumption (World Economic Forum, 2021). Recognizing the tremendous impact of operational carbon emissions and the transformative potential to reduce them, the project will focus on this aspect to develop a solution. Thus, comprehending and managing energy consumption throughout the use phase becomes imperative in pursuing the primary goal of NZCBs.

The energy consumption of buildings encompasses various aspects, including heating, cooling, lighting, ventilation, cooking, food storage, domestic hot water, and household appliances, as well as communal services like elevators, public lighting, and social facilities (Sun et al., 2022). Among these activities, some are primarily influenced by building materials, design, and building envelope, such as heating and cooling, while others are more closely linked to user habits, such as cooking and water heating. Thus, these actions can be categorized into three distinct groups: indoor environmental energy consumption, user behavior energy consumption, and public utility energy consumption, as outlined in Appendix 11 (Sun et al., 2022).

Based on global averages, space heating accounts for the highest energy consumption in buildings, representing 32% of the total energy use, followed by cooking at 29% and heating water at 24% (Guo et al., 2017). However, energy consumption patterns in the building sector vary significantly across countries and regions. This disparity can be attributed to many factors, including climate conditions, population density, income levels, economic development, household size, technological availability, and cultural practices. The regional climate emerges as a key determinant among these factors, directly shaping residents' energy needs and behaviors. For instance, in colder climates, a significant portion of energy consumption is dedicated to space heating, whereas in warmer regions, it is associated with water heating and cooking (International Energy Agency, 2013), see Figure 4.

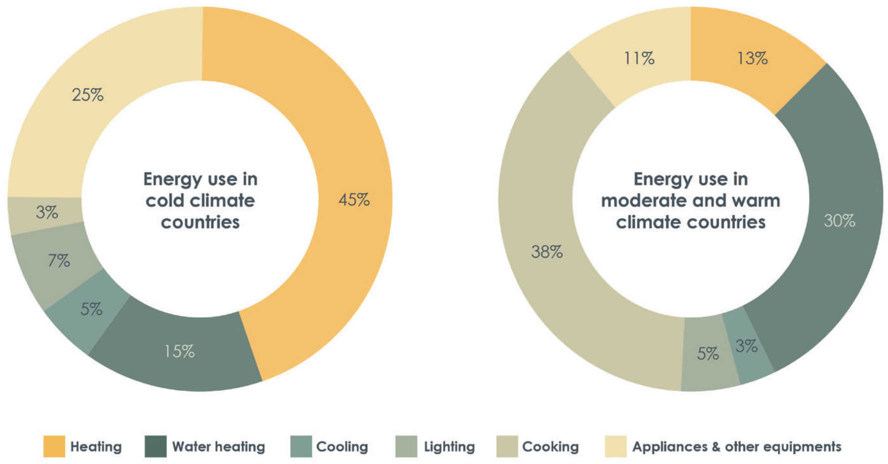


Figure 4. End-use energy consumption of buildings in cold and warm climates.
Source: International Energy Agency (own illustration)

With the projected global population expected to increase by 2.5 billion people by 2050 and rising resource consumption driven by economic development and improved living standards, energy consumption in the building sector is set to rise by 50% (International Energy Agency, 2013).

To address this challenge, the widespread adoption of energy-efficient buildings becomes essential in achieving a more sustainable future. In particular, NZCBs have the potential to significantly reduce energy demand, along with associated

GHG emissions and other pollutants (World Resources Institute, 2016). Therefore, developing strategies linked to energy-efficient building envelopes and systems, and promoting environmentally conscious decisions concerning site selection, building design, and water use, emerge as critical aspects to involve in the design process of buildings and companies.

1.3. Current methods in the industry

Within this context, there are numerous frameworks and concepts used by different actors in the construction industry, aiming to enhance the energy efficiency of buildings. These schemes approach energy efficiency from three aspects: the design and construction of the building, encompassing aspects such as the structural components, envelope, and windows. The conception and selection of technical systems, including energy and water systems, heating, ventilation, air conditioning (HVAC), water heating, and lighting. And finally, the integration of both on-site and off-site renewable energy sources. These frameworks were also utilized as literature for the project, delivering practical and measurable strategies for companies to implement. The most relevant schemes are:

1 **LEED Certification**, which stands for Leadership in Energy & Environmental Design, is the most widely used and well-recognized green building rating system worldwide. It aims to address sustainability in all types of buildings and construction phases. LEED incorporates strategies related to energy efficiency, the use of alternative energies, improvement of indoor environmental quality, efficiency in water consumption, sustainable development of space, and the selection of materials (U.S. Green Building Council, n.d.).

2 **EDGE Certification,** which stands for Excellence in Design for Greater Efficiencies, is a green building certification system developed by the International Finance Corporation (IFC). This certification system was created to reduce and mitigate the environmental impact of buildings in three areas: direct energy consumption, water consumption, and the energy footprint of construction materials (EDGE, n.d.).

3 **Passivhaus Institute (PHI) and Certification** is an independent research institute that has taken a leadership position in the research and development of building concepts and components, planning tools, and quality assurance for energy-efficient buildings. As a result, Passivhaus is a building standard that is energy efficient, comfortable, and affordable while focusing less on systems, and more on architecture, planning and design strategies (Passivhaus Insitute, n.d.).

4 **Active Buildings** is a design concept developed by Specific, one of seven Innovation and Knowledge Centers in the United Kingdom. This concept takes the

principles of the Passive House scheme and combines them with energy-efficient systems and on-site renewable energy generation. An Active Building goes one step beyond energy efficiency and incorporates intelligent control strategies, both to control building systems and to manage interaction and commerce within the network. This is achieved through consistent data capture and continuous feedback (Clarke, 2020).

In addition to these schemes, there are tools that allow more informed and well-founded decision-making for the incorporation of efficient measures and strategies. These tools allow assessments, project modeling, energy and site simulations, and systems control. The objective is to generate and analyze data, allowing a project team to identify the environmental impacts of different stages of the building, energy consumption throughout its lifetime, site conditions, and the possibility of incorporating all this data in a single system. Within the construction industry, there are abundant technological tools and software; some of the most recognized and with the greatest potential are:

1 **Life Cycle Assessment (LCA)** is a decision-making tool for evaluating the environmental impacts associated with the complete life cycle of products, processes, or services. This comprehensive approach is especially valuable from a sustainability standpoint, as it ensures that environmental considerations are not simply shifted to other stages or locations (Jolliet et al., 2016). By encompassing all life cycle stages, LCA allows for a more holistic assessment. In the context of buildings, specific tools such as One Click LCA or LCAbyg have been developed to facilitate this analysis and provide a focused examination of environmental impacts.

2 **Building Information Modeling (BIM)** is a collaborative work methodology for the creation and management of construction projects, whose objective is to centralize all the information in a digital information model. Today, BIM is recognized as an essential way to improve the entire value chain in the construction industry and, in turn, facilitate more effective energy modeling and multidisciplinary collaborations with a total lifecycle and supply chain integration perspective (Petri et al., 2017)

3 **DesignBuilder** is an advanced software tool that offers comprehensive analysis capabilities for any building project. Whether utilizing imported BIM models or creating models within DesignBuilder, the software enables detailed performance evaluations encompassing energy efficiency, occupant comfort, HVAC systems, daylighting, cost analysis, design optimization, and certification requirements. With DesignBuilder, users can efficiently compare various building designs, assess their functionality and performance, and deliver timely and cost-effective results (DesignBuilder, n.d.).

Building Management Systems (BMS) is a computer system installed in a building that allows communication with the building equipment. The surveillance owner can control its facilities and systems, such as air conditioning, heating, ventilation, lighting, alarms, access control, or energy supply management systems. Today, BMS tends to be part of a broader approach, as it is BIM (Hajdukiewicz et al., 2015). 4

1.4. Prevailing theories in the industry

Researchers, policymakers, and practitioners have been actively addressing the multifaceted challenges of climate change, characterized by long-term shifts in temperature and weather patterns resulting from GHG emissions. Their efforts are driven by the recognition that climate change poses the greatest threat to humanity, unfairly impacting the most vulnerable communities (United Nations, n.d.).

In response to this urgent issue, these stakeholders have sought out various theories to comprehend and tackle the complex nature of climate change, introducing strategies that enable substantial carbon emission reductions. Among the literature on carbon mitigation, there is a range of approaches, from technological advancements to policy frameworks and behavioral change theories. In this sense, two prominent frameworks have gained considerable attention in addressing the problem of climate change within the construction sector: the Sustainable Development Goals (SDGs) and the Planetary Boundaries.

1.4.1. Sustainable Development Goals

The SDGs, adopted by the United Nations in 2015, provide a comprehensive framework that integrates social, economic, and environmental dimensions to guide sustainable development efforts worldwide (United Nations, n.d.).

Within the building industry, the SDGs are critical to address carbon emissions and promote sustainable practices. They emphasize the urgency of taking action to combat climate change and its impact, making it imperative for the industry to prioritize carbon reduction strategies and contribute to global climate targets. By aligning with SDG targets, the building industry can contribute significantly to the global fight against climate change while driving sustainable development. Among the SDGs, several targets are particularly relevant to the building sector's endeavors in reducing carbon emissions:

SDG 7 Affordable and Clean Energy, emphasizes the need for energy efficiency and the adoption of renewable energy sources in buildings to mitigate carbon emissions associated with energy consumption (United Nations, 2015).

SDG 11

Sustainable Cities and Communities, highlights the importance of sustainable urbanization, including energy-efficient buildings, resilient infrastructure, and sustainable urban systems (United Nations, 2015).

SDG 13

Climate Action, stands out as the most critical in addressing the challenges related to carbon emissions. With its call for urgent action, it becomes imperative for the building industry to prioritize carbon reduction strategies and actively contribute to global climate targets (United Nations, 2015).

1.4.2. Planetary boundaries

The urgency and importance of addressing climate change are evident within the framework of planetary boundaries, which assesses the state of nine essential earth system processes crucial for the endurance of future generations (Steffen et al., 2015).

Among these limits, climate change stands out as one of the three most critical factors, alongside biodiversity loss and the introduction of novel entities into the environment. Within the construction industry, the concept of planetary boundaries becomes particularly relevant as it emphasizes the need to respect the safe limit of GHG emissions to avoid detrimental environmental consequences. Unfortunately, as the IPCC states, we have already surpassed the planetary boundary for climate change, putting immense pressure on the Earth's natural systems (IPCC, 2022).

Hence, to align with the planetary boundary of climate change, reducing the concentration of GHG emissions in the atmosphere is crucial, ensuring they remain within the defined safe operating space. The construction industry plays a vital role in this endeavor by embracing sustainable construction practices and actively participating in and implementing carbon reduction initiatives, such as NZCBs and reduction roadmaps. By doing so, the industry can contribute significantly to stabilizing Earth's systems and work within the safe operating zone of climate change.

1.5. Colombian context

Our project takes place within the context of Colombia, as our collaborating partner is based and operates in this country. In line with global efforts to mitigate climate change, Colombia has established a significant agenda on climate action, including developing a National Roadmap to decarbonize the building industry and formulating a long-term strategy known as Estrategia 2050 (E2050). Therefore, given the building sector's pivotal role in the national economy and its immense potential for emission reduction throughout all stages of the life cycle, it becomes imperative to prioritize this sector in order to accomplish the set objectives (CCCS, 2022).

However, the construction industry in Colombia encounters significant challenges in achieving emission reductions throughout all stages of the building life cycle. Firstly, limited access to advanced technologies impedes the widespread adoption of clean energy and energy efficiency measures across buildings. Additionally, compared to other countries, the sector is far behind in using technological tools, such as energy and thermal simulations and LCA, for informed decision-making during project planning and design. Furthermore, the construction processes in the industry predominantly rely on low-tech approaches, lacking prefabricated or industrialized systems, and are characterized by a high degree of informality in working conditions (CCCS, 2022). Consequently, these limitations must be considered in developing a suitable and impactful solution for encouraging sustainable and energy-efficient design processes and construction practices.

Similar to the global context, emissions from buildings' operational stage far surpass those attributed to embodied carbon. For example, findings from studies conducted by Universidad de los Andes and Hill Consulting reveal that in 2020, operational carbon accounted for 63% of the total emissions from national buildings, while embodied carbon contributed to 37% (2022). However, as depicted in Figure 5, if the industry maintains a 'business as usual' approach, the proportion of operational carbon in the overall emissions will escalate further, with operational carbon comprising 80% and embodied carbon making up 20% of the total share.

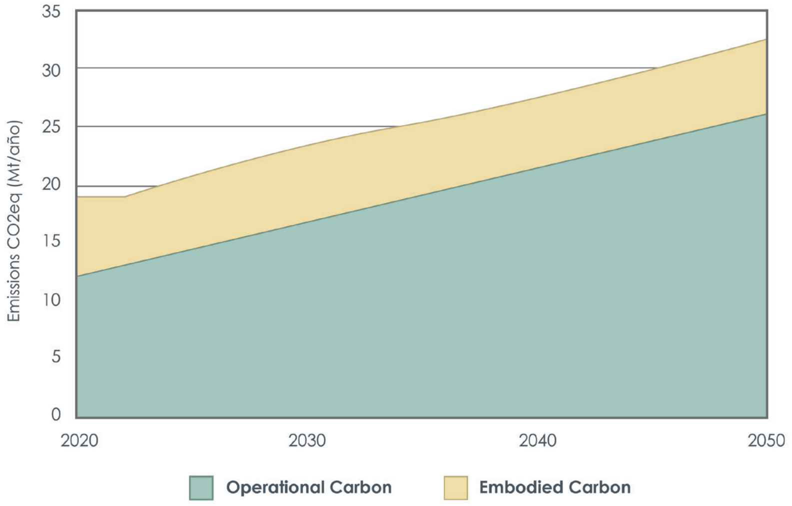


Figure 5. Projection of GHG emissions of buildings in Colombia (2020-2050). Source: Colombian Roadmap to NZCB (own illustration)

Regarding operational carbon, the residential sector ranks as the third-largest energy consumer in the country, representing 19.2% of the total final energy consumption. Among residential activities, cooking exhibits the highest energy intensity, accounting for 46% of energy usage, followed by appliances and systems at 24%, and lighting at 11% (Gobierno de Colombia, Ministerio de Minas y Energia, 2022). These considerations are essential when evaluating the impact of strategies and methods targeted to reduce energy consumption and operational carbon emissions.

Furthermore, Colombia possesses a renewable-dominated energy grid, with hydroelectric power contributing to over 70% of total electricity generation (IEA, 2022). Despite this advantageous energy mix, the country faces a considerable challenge concerning inefficient energy utilization. As highlighted in the National Energy Plan (PEN) 2020-2050, Colombia's overall energy efficiency stands at 31%. Particularly concerning is the residential sector, which demonstrates an alarming rate of 18% efficiency, indicating a substantial energy consumption inefficiency of approximately 82%. Consequently, enhancing energy efficiency becomes critical for achieving significant savings and substantially reducing the carbon footprint associated with buildings (Gobierno de Colombia, Ministerio de Minas y Energia, 2022).

1.6. Collaboration partner: Conaltura

Conaltura is among Colombia's 20 largest real estate developing companies, with over 30 years of experience and over 20.000 homes built (Galeria Inmobiliaria, 2022). They develop high-rise residential buildings in four major cities in Colombia: Bogotá, Medellín, Barranquilla, and Cartagena, and conduct four processes of a project: design, management, sales, and construction (Conaltura S.A., 2021).

The company has been part of the established regime of the construction sector in Colombia, as its business model involves designing and building residential projects and selling apartments directly to the final user or investors. In addition, their projects comprise traditional high-rise residential buildings, mainly executed with load-bearing wall systems, which is a quick and low-cost process, but with reduced flexibility. Regarding materiality, their product relies mainly on concrete, steel, and bricks, and apartments are usually delivered with minimal architectural finishes and basic HVAC and lighting equipment. Most of Conaltura's projects are directed to a medium-low social stratum market, with several client archetypes in terms of age, family, and marital conformation (Conaltura S.A., 2021).

Although Conaltura has mainly done business as usual, we chose the company as a collaboration partner because they are transforming their business model through innovation, sustainability, and technology, both at the strategic and product levels (Conaltura S.A., 2021). Furthermore, due to the several accomplishments within sustainability, the company is considered a national leader in the field, and its commitment to building a better world for future generations encourages them to follow the national roadmap and support transformative projects, such as implementing the concept of NZCB (Hidrón, 2023).

Since the creation of the sustainability and innovation department in 2017, sustainability has represented a pillar of Conaltura's corporate strategy. Their management and operations align with the SDG framework, specifically with goals 7, 8, 9, 11, 12, and 13 (see Figure 6). This has enabled them to work collaboratively with relevant actors in the industry and transversally across all areas of the company. In 2022, Conaltura obtained the B Corp certification, which awards companies that use their business to positively impact the world by solving social and environmental problems (Conaltura S.A., 2021).

Figure 6. Sustainable Development Goals used by Conaltura. Source: United Nations

In addition, Conaltura created its own certification scheme for sustainable projects, called VIO, which integrates six key principles of the building's lifecycle, see Figure 7. To date, the company has certified eight projects as sustainable and aims to complete 44 certifications in the coming years, both with local and international schemes, such as LEED and EDGE. In addition, Conaltura created a program called "Siembra desde ya tu futuro" (Planting your future now), which strengthens a sustainable culture in their clients through educational and participative events, including activities such as tree planting, talks about sustainable operation of the apartments, waste management, and responsible behavior (Conaltura S.A., 2021).

Conclusively, Conaltura is aligned with local and global sustainability goals and has implemented several schemes and strategies around sustainable construction and buildings. However, the concept of NZCB is still new for the company, and there is no current plan aiming to reduce operational carbon in their buildings. Moreover, considering that usual real-estate development companies are not directly responsible for the day-to-day operation of the buildings, addressing operational carbon is particularly challenging for actors like Conaltura. Therefore, co-creating an action-based strategy to reduce operational carbon buildings is very valuable and necessary for real-estate development companies to achieve the goal of NZCB.

Figure 7. VIO sustainability scheme by Conaltura. Source: Conaltura S.A.

2

THEORIES & METHODS

In this chapter, we will explain and argue the sustainability theories and the definition used to support the project and the designed solution. Afterward, we will present the design theories that helped us navigate the design process and guided us through selecting accurate methods. Finally, we will introduce the methods and tools used to understand and analyze the problem statement, collaborate with the company, and co-create and develop the final solution.

2.1. Sustainability approach

The notion of sustainability began to gain recognition in 1987 when the Brundtland Commission conceived the term ‘sustainable development,’ defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland Commission, 1987, p. 41). However, this definition presents two contradictory concerns. On the one hand, the notion of ‘development’ indicates socio-economic progress in our current society. On the other, the mission of preserving the environment and ecosystems so that future societies can thrive (Kuhlman & Farrington, 2010).

Since then, innumerable contributions, conventions, and assemblies have been made on the subject. One of the major developments in the concept of sustainability is the distinction of the three pillars or dimensions of sustainability: economic, social, and environmental, also known as the Triple Bottom Line. Today, this interpretation is so widely accepted that the United Nations incorporates it into its 2030 Agenda for Sustainable Development, where they affirm that they “are committed to achieving sustainable development in its three dimensions -economic, social and environmental- in a balanced and integrated manner” (United Nations, 2015, p. 3). In addition, the Agenda sets out 17 SDGs in which they reaffirm the search for an equilibrium of the three dimensions of sustainable development.

These definitions and concepts of sustainability present a comprehensive approach in which socio-economic well-being, and environmental protection are integrated. However, they present different views. For example, the Brundtland report offers a view where socio-economic development should not occur at the expense of future generations, which is a ‘strong sustainability’ approach. Instead, the triple bottom line concept presents a ‘weak sustainability’ approach that balances the economic, social, and environmental components necessary to satisfy human needs (Kuhlman & Farrington, 2010).

Keeping this distinction in mind, our project adopts a sustainability approach that aligns with the principles outlined in the Brundtland definition. This approach, rooted in strong sustainability theory, acknowledges the intrinsic value of nature and the crucial role of ecological integrity (Kuhlman & Farrington, 2010). By prioritizing emissions reduction more than economic growth, we aim to secure the resilience and integrity of ecosystems and natural resources. Furthermore, this focus on strong sustainability allows us to adopt a long-term perspective, considering the needs of both present and future generations and recognizing that economic growth should not come at the expense of environmental degradation.

Although our project embraces a strong sustainability approach, it is essential to acknowledge that it may not provide a comprehensive understanding of the entire climate change issue. Climate change extends beyond environmental consequences and has significant societal and economic implications. It affects vulnerable sectors of society and is exacerbated by both societal practices and the pursuit of economic growth (United Nations, n.d.). It is crucial to recognize that our project focuses solely on carbon emissions within the building sector, and we approach it from a perspective that includes, for example, carbon offset mechanisms and technological innovations. This approach could be considered a weak sustainability perspective (Kuhlman & Farrington, 2010), as it addresses the challenge of carbon emissions by seeking an equilibrium among different capitals to pursue the common welfare. Thus, it is crucial to recognize the dichotomy between these two approaches and carefully consider their implications for sustainable decision-making.

2.2. Sustainable design theories

Design for sustainability transitions (DfST) evolved since the 1990s as a practice needed to address emerging environmental challenges through a systemic approach rather than technological adjustments (Ryan et al., 1992). It continued focusing on the transformation of complex socio-technical systems, such as industries or cities, through technological, social, organizational, and institutional innovations (Ceschin & Gaziulusoy, 2020). As a result, achieving this kind of transformation requires radical and long-term changes, given the complexity and entrenched nature of such systems.

The research problem of the project is built around co-creating a strategy to achieve net-zero operational carbon buildings. This target requires not only a serious, synergic, and long-term commitment between several social groups, such as companies, universities, public authorities, and users, but also fundamental shifts in the socio-technical system, including regulations, infrastructure, technologies, user practices, and markets. Hence, to accomplish such a great challenge, DfST is used as the leading theory to guide the project in understanding the required change and identifying the multiple actors and elements involved.

To further understand the socio-technical system and the required change to a sustainable one, the multi-level perspective (MLP) on transitions was also employed. MLP describes how a socio-technical system is actively created, reproduced, and improved by multiple actors and how it is characterized by stability, as it is embedded in society. This approach recognizes three conceptual levels: niche, socio-technical regime, and socio-technical landscape (Geels F. , 2005).

The micro-level is created by the technological niches, formed by low stability and high uncertainty, and where radical novelties arise. The meso-level is formed by the socio-technical regime, which ensures the dynamic stability of the system through routines, core capabilities, binding contracts, lifestyles, and social relationships. Finally, the macro-level comprises the landscape, where external aspects, such as deep cultural patterns, macroeconomics, and politics, affect and influence the system (Geels F. , 2005). These three levels were determined in relation to the construction industry, and their inter-relations were analyzed to understand how the transition should come about and how the dynamics between the different levels are necessary for a more significant breakthrough.

Based on the MLP and its understanding of transitions as consequences of alignments and dealignments between the multiple levels, the framework of four transition pathways developed by Geels and Schot was also implemented in the project. They developed a typology of four transition pathways based on multi-level interactions, adding two criteria: the timing and the nature of the interactions (2007). Depending on the timing of the interactions, particularly the landscape pressure on regimes in relation to the development state of the niches, the transformation process can result differently. On the other hand, they differentiate if niche innovations and landscape developments have reinforcing or disruptive relationships with the regime, having stabilizing/symbiotic or competitive effects (Geels & Schot, 2007).

Moreover, they use four types of environmental change proposed by Suarez and Olivia (2005) to explain the possible landscape dynamics further. This typology entails regular change, which refers to frequent but gradual and low-intensity transformations. Specific shock describes rapid and intense environmental changes that occur infrequently and has a limited scope. Third, disruptive change entails sporadic changes that develop gradually but significantly impact a single dimension. Finally, Avalanche change rarely occurs but is characterized by high intensity, rapid speed, and simultaneous effects on multiple dimensions of the environment (Geels & Schot, 2007).

Combining the two criteria and the four environmental changes, Geels & Schot developed four propositions of transition pathways: transformation, reconfiguration, technological substitution, and de-alignment and re-alignment. This approach is implemented in the project in order to identify and analyze the type of transition the construction industry is experiencing, an understanding of the relationship between the three levels and their agency within the change process to create a better solution and plan for the collaborator company to achieve the target of net zero operational carbon. Finally, we propose a type of transition path, that the industry and Conaltura should follow to reach a fundamental transformation, see chapter 3.

2.3. Design theories and design process

There are three approaches to design that are being used in the project: design for system innovation and transitions, participatory design, and design thinking.

First, the project's goal requires maintaining sight of the big picture, moving from product thinking to system thinking, as

NZCB needs the transformation of the whole system. In other words, it focuses not only on buildings as the design objective and means of change but also on the processes, cultural meaning, user practices, and policies. Consequently, the first approach is Design for System Innovation and Transitions. This understanding focuses on transforming systems by supporting the creation of long-term visions and connecting those visions to actions and strategic plans (Ceschin & Gaziulusoy, 2016).

To promote such a transformation process, designers should create perspectives for transition, improve present ideas of change, modify their mindsets and perspectives, and create novel ways of designing (Irwin, 2015). We considered not only the company's postures but also other relevant stakeholders, using and trying new design methods and creating solutions that holistically target sustainability. Therefore, we have co-created a clear and comprehensive vision of the transformation process with an action-based approach, including specific strategies and future goals for the company.

Next, as the project exists in collaboration with a company (Conaltura), the second understanding of design is as a participatory practice. The strength of this approach lies in the capacity to congregate in different communities of practice and communicate across their professional boundaries (Sanoff, 2007). Especially when working with sustainability challenges, such as NZCB, this approach is very relevant as it includes and integrates different but critical perspectives to understand complex issues and co-create innovative plans and projects to target such matters.

Hence, to develop the optimal outcome for the company and the project, we recognize employees as the experts in their fields, and our role relates more to facilitators and consultants. This means that we decentralized the role of designers as the ones that hold the knowledge to become those who facilitate the co-creation of solutions through various methods (Valderrama et al., 2018). Thus, participants are not merely considered informants but authentic and valuable designers because they hold the knowledge. In this design approach, information exchange takes a backseat, and mutual learning, the construction of knowledge, and understanding different perspectives are more important for the process (Luck, 2018).

Finally, Design Thinking is non-linear and iterative process designers utilize to comprehend users, question assumptions, redefine problems, and generate innovative solutions that can be prototyped and tested (Interaction Design Foundation, 2022). The design team used this approach as it is particularly effective in addressing complex problems. By utilizing Design Thinking, the design team could reframe the problems and focus on addressing the correct issues before diving into the solution development, increasing the likelihood of finding effective and impactful solutions.

Based on this approach, we used the double diamond method for the design process, see Figure 8. The diamonds symbolize two similar divergent and convergent phases in which the specific problem is first discovered and then defined. In the second, the right solution is first developed and finally delivered.

The double diamond illustrates how the design process goes from concrete to abstract thinking and back again, combining the generation of new ideas with their analysis and evaluation in the specific context of use (Han, 2022). This approach sees design as a solution-based field in which key features include integrative thinking, creativity, empathy, collaboration, and willingness to fail (Braun, 2008).

2.4. Methods

Considering the design approach, the design team implemented research methods, such as interviews and literature review; analysis methods, including affinity diagrams, conceptual maps, and stakeholder analysis; and participatory methods, such as collaborative workshops and brainstorming.

2.4.1. Research methods

Systematic literature review

> *“The Systematic Literature review is a qualitative research method that helps to provide a broad picture of the current view on a research domain. It includes all types of scientific sources, like journals or collections and interpretations of data.”* (Paul y Barari, 2022)

First, a systematic literature review was conducted by the design team, firstly to gain a broad understanding of the problem statement and then to focus on specific topics, namely, the construction industry (globally, in Latin America and Colombia), roadmaps to the decarbonization of the construction sector, sustainable buildings, the lifecycle of buildings, carbon emissions, NZCB, Active Buildings, operational carbon, energy reduction measures, and energy efficiency. See Appendix 1 for the literature database.

Scientific articles, websites, roadmaps, and reports from sources such as the International Energy Agency (IEA), the World Resources Institute (WRI), Global Alliance for Buildings and Construction (Global ABC), United Nations (UN), the Intergovernmental Panel on Climate Change (IPCC) and the Colombian Council for Sustainable Construction (CCCS) were highly relevant to extract reliable knowledge around these complex topics. The investigation allowed us to identify key actors, barriers, enablers, ideas, and progress to set a pathway for the project.

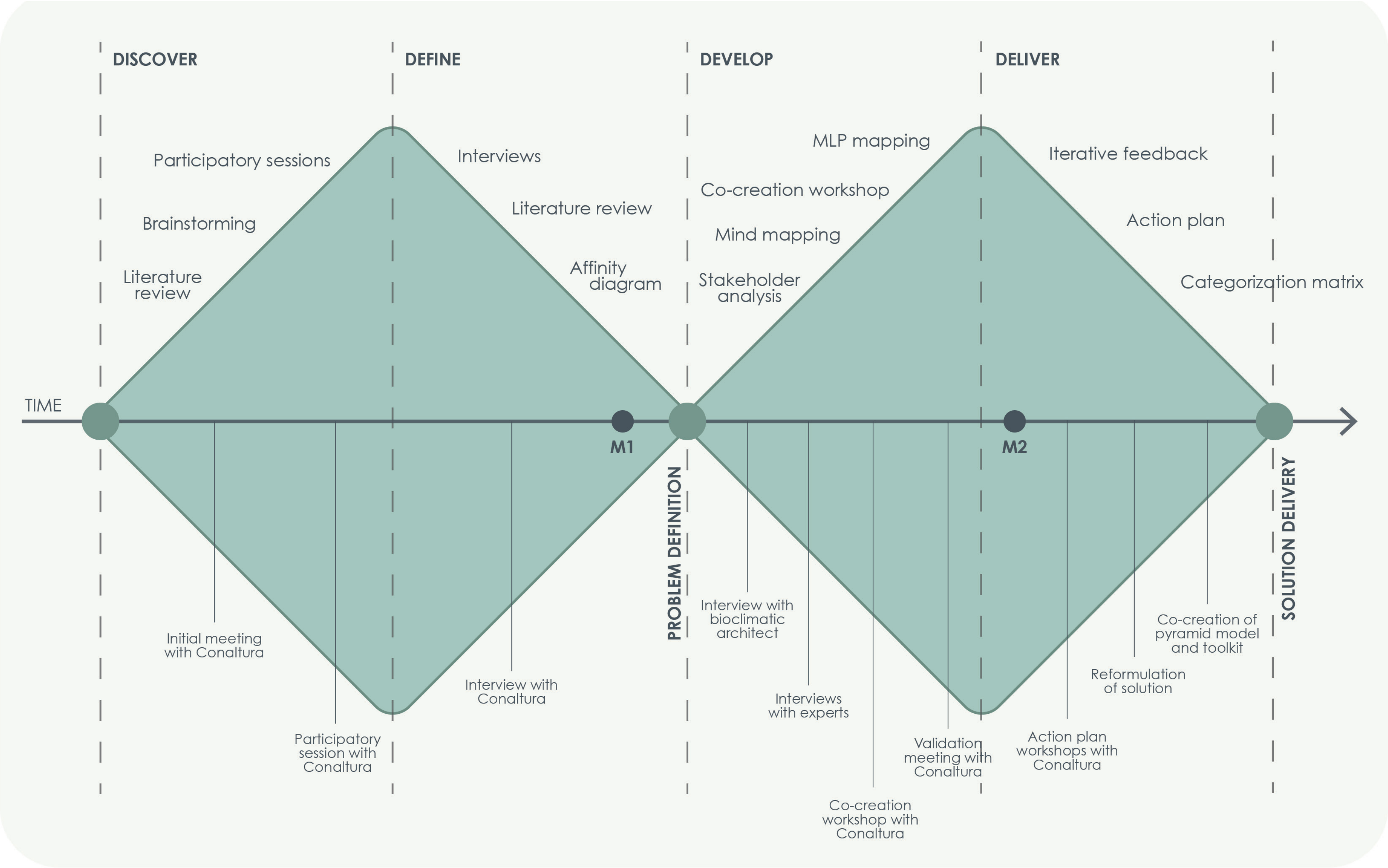


Figure 8. Double Diamond Method for the design process (own illustration)

Interviews

> *“Interviews serve as an ethnographic research method that produces ‘authentic experiences’ and thus, delivers an understanding of the language and culture of the interviewee.”* (Silverman, 2011)

Several interviews with company employees were conducted to understand the current status of the sustainability journey in the company, their approach, and their plan for future projects around NZCB (see Appendix 2, 3, 4, 5, and 6). In addition, some interviews with external experts in different fields within the construction industry were carried out to expand specific topics, validate information, get inspiration, and have a different perspective to contrast statements and ideas (see Appendix 7, 8, and 9).

2.4.2. Analysis methods

Affinity diagram

> *“An Affinity diagram is a grouping method to identify relevant actors’ needs or general information for the implementation of a new product or service.”* (Takai y Ishii, 2010)

The affinity diagram was used to visually map out general information about the construction industry, sustainable construction, and Conaltura’s practices, as well as more specific data about energy use and design strategies for efficient buildings gathered through the literature review and interviews, see appendixes 10 and 11. In addition, this method allowed organizing the data in a structured way to identify connection points between topics, create groups and thus identify a potential direction and scope to follow in the project.

Mind mapping

> *“Mind mapping is a creative tool to relate ideas by centralizing a visual or problem area and then letting spontaneous associations appear, leading to new concept ideas.”* (Davies, 2011)

Mind mapping is a tool that visually represents information, ideas, and concepts hierarchically and interconnectedly. It involves creating a diagram or map that starts with a central topic and then branches into subtopics, related concepts, and associated thoughts. The process includes using keywords or images to organize information in a non-linear and flexible format, highlighting the connection and hierarchies between topics.

This tool was used to organize strategies that reduce operational carbon in buildings into four groups, see Appendix 12 and 13. This arrangement gave us a clearer understanding of the range of possibilities to target the problem and a structure to build the first co-creation workshop with Conaltura, where more strategies. were added. It also encouraged the holistic comprehension of the complex topic, exploring different angles and associating the related strategies.

Stakeholder analysis

> *"Mind mapping is a creative tool to relate ideas by centralizing a visual or problem area and then letting spontaneous associations appear, leading to new concept ideas."* (Davies, 2011)

For radical transitions to occur, the involvement and interaction of various actors and groups from different levels and spheres are needed. Therefore, it is vital to understand their agency, interest, and capabilities in the transition process. A range of relevant actors in the construction industry was determined and analyzed with a stakeholder analysis to understand their needed contribution, interest, and agency in the change process (see Appendix 14). This method was also helpful in anticipating future opportunities or obstacles for the design solution and planning several strategies to influence them.

2.4.3. Participatory methods

Participatory methods were used to help actors share their thoughts and information, communicate with each other to create a shared vision, and join discussions to foster learning. Several workshops were carried out with employees from different areas of the company (sustainability, construction, architecture, sales, and budget), not only because they will all be involved in the implementation of the solution but also to consider several perspectives and understandings of the challenges and co-create ideas to improve the solution.

As Conaltura is a Colombian-based company, the whole collaboration process was held online through platforms such as Teams for interviews and meetings and Miro for interactive activities and workshops.

Brainstorming

> *"Brainstorming is structured by four rules: 1) generate as many solutions as possible; 2) defer judgment about solutions until the end of the generating session; 3) try to come up with original ideas; and 4) combine and build on existing ideas.* (Bonnardel y Didier, 2020)

This method was used during the first co-creation workshop with the company as a way to bring everyone's knowledge together and open a space for creativity and learning. The first brainstorming session helped the group think about and examine strategies to reduce building operational carbon (see Appendix 15). The second brainstorming comprised exploring and discussing enablers and limitations for each operational carbon reduction group (see Appendix 16).

This method was helpful for the design process because it encouraged the collaboration team to explore ideas outside their comfort zone, creating spaces for discussion to finally deliver a rich outcome. Moreover, this method allows us to discuss and generate innovative ideas without time, budget, and other project-related limitations, as it encourages us to think and explore "out-of-the-box" and challenge established assumptions.

Impact-feasibility analysis (XY matrix)

> *In order to set priorities on what actions to take first, the tool "impact-feasibility analysis" helps to facilitate a group discussion of options that have the highest benefit or impact for the least effort or cost in terms of both time and expense.* (Drury, 2023)

This method was also used during the first co-creation workshop as a tool to evaluate the four operational carbon reduction groups (see Appendix 17). This method served as a practical way of determining the feasibility of each group of strategies within the capabilities and agency of the company and the impact in terms of carbon emissions the strategies could have. This activity proposed a direction to follow in the design process, either by choosing the most viable group to facilitate the action of the company or the group with the highest impact to create a more significant change.

3

SYSTEM & TRANSITION PATHWAY ANALYSIS

In this chapter, we will present the current socio-technical system of the construction industry in Colombia, using the MLP as a framework and thereby describing each of the three levels: the landscape, the regime, and the niches. Next, based on the present situation, we will explain the enablers and limitations that Conaltura encounters to shift to a sustainable and net-zero building company. Finally, we will introduce our proposition of the transition pathway that the regime should follow for this radical change to be achieved, based on the four transition pathways by Geels and Schot.

3.1. Multi-level Perspective

In order to design a viable and applicable strategy for the company and therefore guide them to the transition toward NZCB, it is vital to comprehend the different elements of the socio-technical system. In addition, to understand how the different components interact and foresee possible connections, the design team illustrated a dynamic MLP graphic of the current socio-technical system of the construction industry in Colombia, see Figure 9.

First, identifying key components of the landscape level is fundamental to understanding how they can put pressure on the regime and support the shift towards a zero-carbon industry. Global warming is determined as the factor that exerts more weight because it is recognized globally as the most urgent challenge that humanity needs to face and target (IPCC, 2022). Repercussions are already evident across all regions, including the warming of the atmosphere and oceans, the reduction in snow and ice coverage and volume, the rising sea levels, and alterations in weather patterns. In fact, global warming is also affecting buildings and the construction industry directly. Thus, the investment in qualified and resilient materials, the search for specific construction locations, and bioclimatic design are more relevant than ever since buildings are more vulnerable to extreme weather conditions (Chalmers, 2014).

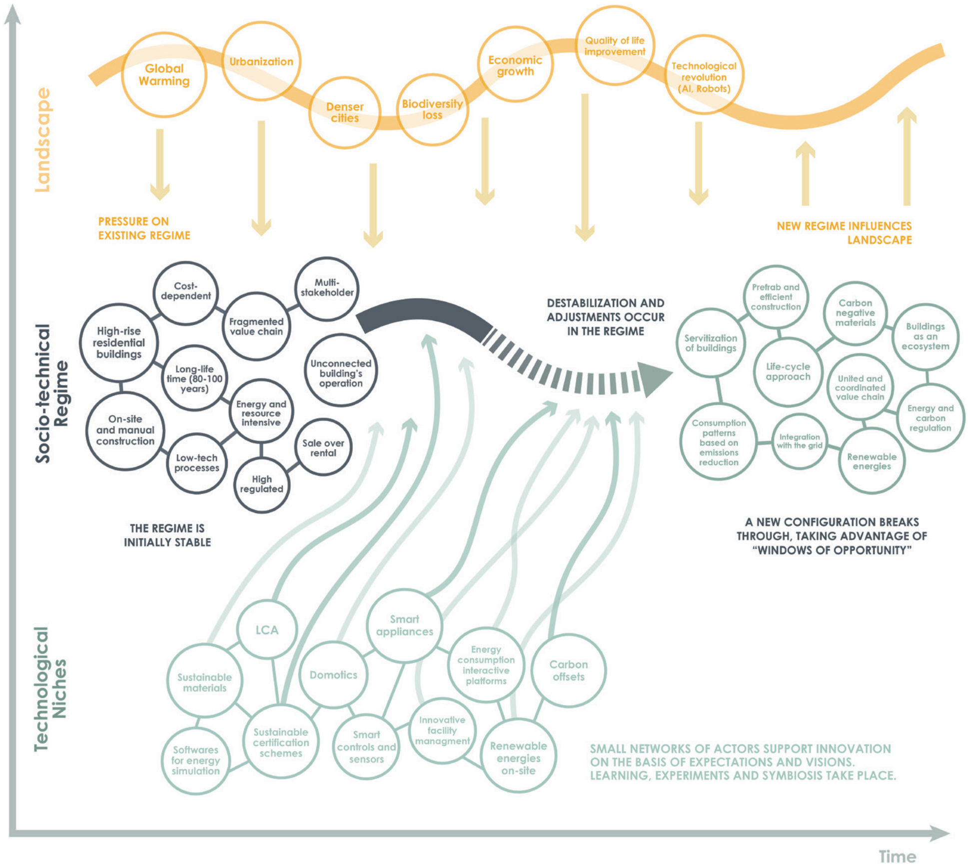


Figure 9. Dynamic multi-level perspective of construction industry's transition (own illustration). Source: Geels (2005)

Furthermore, the economic growth and, thus, the improvement in the quality of life in many households, especially in developing countries like Colombia, create a higher energy demand and the utilization of more equipment, HVAC, and lighting systems (Ferro, 2021). These conditions influence buildings as energy systems must be more stable and integrated to support the increasing requirements. Another essential component of the landscape is the technological revolution. With the advent of new technologies, such as artificial intelligence (AI), 3D printing, drones, and robotic equipment, the design and construction processes are faster and more efficient (e-architect, 2022). This influences the availability of new design tools and software for bioclimatic design and simulations and the reduction of the use of materials and energy in the construction and use-phase of the buildings.

On the meso-level, the current regime is dominated by a complex and fragmented value chain composed of multiple stakeholders. In addition, projects usually involve various disciplines and actors that do not necessarily have a contractual relationship, and processes are carried out rapidly and as silos, where information, learnings, and goals are barely shared across groups (CCCS, 2022). This influences how projects are developed, leaving minimum room for innovation without a systemic and lifecycle approach, thus hampering sustainability strategies that permeate across areas. Moreover, as thoroughly exposed in Section 1, construction processes are typically low-tech, leading to informality and scarce use of prefab and industrialized methods (GlobalABC; IEA; UNEP, 2020).

What is more, buildings possess a very long lifespan (between 80 and 100 years) which creates a risk of energy use “lock-in” with the consequences of current low ambitions and cost-related decisions lingering for decades (Chalmers, 2014). Besides, the current business model of most real estate development companies is about selling apartment units directly to clients and investors. Accordingly, the building operation passes over a third party, a facility managing company, usually contracted by the community and not linked to the constructor. Hence, real estate development companies have reduced influence over how buildings are operated, hindering energy efficiency measures, using renewable energies, sensors, controls, and interactive platforms to reduce energy consumption.

Finally, identifying key and thriving technological niches is decisive for such transitions to succeed because they can provide spaces for innovation and social networks, eventually breaking through the established regime. Currently, sustainable certification schemes (e.g., LEED, EDGE) represent novel but reliable entities that promote the progress of other technological niches, such as LCA tools, sustainable materials, and sustainable design software. For a few years, this group of niches has incited the development of several certified residential projects in the market, including higher energy efficiency standards, lower carbon emissions, water savings, and a better relationship with the community and the environment (Pérez, 2023). Although this type of building is still far from becoming NZCB, companies from the regime are learning lessons, exploring new possibilities, and paving the path toward the required sustainable transition.

Additional niche developments, such as smart appliances, intelligent controls, sensors, and home domotics, offer interconnected, interactive, responsive, and integral solutions for users to know their energy consumption, thereby contributing to reducing it and creating consciousness. However, these niches are still weak and unstable since they are very costly for the market demand, and main users usually create resistance over novel technological features. There are also facility managers creating new ways of operating buildings and collaborating with residents, for example, by using interactive apps to share data and feedback, create recycling and compost strategies, and foster sustainability within the community (Pérez, 2023). Although this model is still scarce in the regime, this type of company would facilitate the implementation of other niche developments, such as using renewable energy on-site, integrating with the grid, and finally, carbon off-sets.

3.2. Barriers and Enablers Conaltura

As explained in Chapter 1, Conaltura is part of the established regime, and its business model and operations follow the current trend. However, they are in the process of transforming their buildings and company toward sustainability and are also targeting to achieve the goal of NZCB in the future. As a result of the relation and influence between the three levels and the own internal affairs the company encounters, there are several barriers and enablers (see Table 1 and Table 2) that are either hindering or enhancing the transition pathway. These were recognized and discussed throughout the numerous meetings held with the sustainability team and the co-creation workshop. Identifying and analyzing these conditions is vital for the collaboration process and the development of an appropriate and promising solution.

Money and time are the main barriers, which subsequently impact most of the other constraints. Given that the company's target audience and project types are reliant on costs, it is crucial for the design, planning, construction, and sales processes to be highly efficient. Therefore, the standardization of designs, processes, and commercial tactics, the restricted budget, and the construction system are hindering the transversality of the sustainability department and the implementation of novel and diverse strategies. In addition, employees have limited time to interact in innovation plans and learning programs around sustainability and NZCB, which impacts the required skillset that employees need to develop new strategies.

Even though global warming is creating pressure on governments, organizations, and individuals, the cultural meaning around the real estate market still values economics, location, and esthetic more than sustainability (Pérez, 2023). Unfortunately, most clients follow this traditional mindset, and introducing sustainable, energy reduction, or bioclimatic strategies becomes more complicated as they are more resistant to novelties. Moreover, Conaltura has struggled with effective and targeted customer communication and educational strategies. This has caused, for example, incorrect functioning of water and energy-saving equipment in homes and the rejection of design modifications to improve natural ventilation (Pérez, 2023).

	Barriers
✗	The standardization of processes and designs cause that novel proposals or methodologies, which are out of the normal course of a project, are likely to be rejected.
✗	Most of the company's projects have a very limited budget, which does not allow room for the implementation of new low-carbon or recycled materials, efficient equipment and more technological systems, due to their price.
✗	The construction process (load-bearing wall system) is very rigid and does not facilitate the implementation of new architectural design proposals that are bioclimatic or energy efficient.
✗	The culture around the building market is very traditional and resistant to substantial changes, such as biomimetic architecture, interactive and integrated technologies, smart materials and equipment, etc.
✗	The knowledge and skills of the company's employees are still very limited, in terms of general knowledge about NZCB, bioclimatic strategies, software for simulations and LCA, etc.
✗	The sustainability and innovation area does not function as a transversal area for the company's processes and projects, making it difficult to implement its strategies and plans.
✗	Conaltura does not operate the buildings that designs and builds, so strategies that require monitoring and control of energy use during operation are more difficult to achieve.
✗	There is not a widespread culture in the real estate market based on sustainability, energy savings, and emissions reduction.
✗	The relationship with the client is limited and lacking in trust, which makes it difficult to strategically communicate sustainability issues and strategies.
✗	Currently, there is not enough availability and good cost-benefit solutions, technologies, and materials to reduce the operational carbon of buildings.
✗	There is a lack of knowledge in the management of intellectual property that hinders the co-creation of strategies and projects that promote the implementation of NZCB.

Table 1. Barriers of Conaltura to achieving the goal of NZCB (own illustration)

On the other hand, the predominant enabler consists of the interest in managing areas in the company in engaging with sustainability through the creation of the sustainability and innovation department, the certification of several buildings, the investment in technological tools, and the achievement of becoming a B Corp. This commitment has expanded to most areas of the company and employees, creating an internal sustainability culture and a general awareness of the importance of transforming into a sustainable business (Hidrón, 2023). This situation has, in turn, favored the partnership between sustainable companies and start-ups of the industry (many on the niche level), as well as public and private institutions, to plan and develop innovative projects with sustainable potential.

	Enablers
✓	The company and employee commitment to sustainability provides motivation to transform internal processes and advocate for the development of sustainable projects.
✓	There are good relationships with other actors in the value chain (suppliers, banks, investors, service companies, etc.), which facilitates future alliances.
✓	There is progress and interest in the investment and use of technology in the company's processes, e.g. BIM is used in all projects, the creation of the analytics area.
✓	The company has experience in the design and construction of sustainable buildings through the certification of several projects with schemes such as LEED and EDGE.
✓	The company has a strong influence on the product as they design, manage, construct and sell the buildings, contributing to the sustainable transformation of other actors in the value chain.
✓	There are favorable financial, tax and technical incentives for sustainable construction.
✓	Global warming and sustainable construction are high on the national and international agenda, and stakeholders are proposing new solutions and ideas that support NZCB's development.

Table 2. Enablers of Conaltura for achieving the goal of NZCB (own illustration)

In conclusion, the main barriers and enablers must be considered to successfully answer the research question of co-designing a strategy for real-estate development companies to reduce their building's operational carbon and thus contribute to achieving the goal of net-zero carbon buildings. The solution must recognize the dynamic and rapid evolution of the design process and encourage the integration of the sustainability department with other company areas. Besides, the strategy must take advantage of employees' enthusiasm and commitment and the company's favorable interconnections with other stakeholders.

3.3. Transition Pathway

Implementing the transition pathway approach in the project aims to comprehend the roles of the three socio-technical levels in the change process to identify and analyze the type of transition occurring in the construction industry and Conaltura.

Currently, the industry experiences moderate landscape pressure, as NZCB is targeted for 2050, and buildings have no mandatory energy codes (GlobalABC; IEA; UNEP, 2020). Further, although not all technological niches are fully developed and mature, they have symbiotic relationships with larger actors of the stable regime to solve internal problems and create innovative solutions. For instance, Conaltura and a few more companies have implemented sustainable building certification schemes to validate their sustainability effort and gain recognition in the industry. This has leveraged the further development of other niches-innovations because they can offer services and products that big companies cannot. In this sense, Conaltura has collaborated with small start-ups to co-create a low-carbon cement with ash residues and for the sustainable and integral operation of their buildings by entrepreneurial facility managers.

At the moment, regime rules of the construction industry are still unchanged because the landscape pressure is not strong enough, and most actors are doing business as usual. Consequently, if the elemental architecture of the regime remains equal, the transition path could become a Transformation Pathway (P1). As Geels and Schot (2007) explain, introducing niche-innovations alone is insufficient for reconfiguring the regime. To achieve significant regime changes, these novelties should lead to technical modifications or shifts in user behaviors, perceptions, and decision-making approaches.

Hence, the transition into a zero carbon, resilient, and sustainable industry must endure radical and long-term shifts, and for this to happen, the regime's basic architecture must undergo substantial changes. Consequently, the Reconfiguration Pathway (P4) is considered the optimal course to follow, where sequences of minor and major component changes can lead to an architectural reconfiguration of the socio-technical regime (Geels & Schot, 2007). Although a radical change is definitely needed, it must be accomplished through incremental steps that strengthen the empowerment of actors in the transition process and the accomplishment of significant milestones.

Conclusively, the interplay of multiple technologies and innovations with the regime is especially relevant to encourage this type of transition. After all, developing NZCB will not be possible through a single breakthrough novelty but by the establishment and adaptation of manifold niche-innovations that can eventually enable significant changes in the architecture of the building industry. Thus, such transformations not only need the commitment of all stakeholders in the value chain but the reconfiguration of the market, user conducts, technologies, materials, processes, and regulations.

4

RESULTS & ANALYSIS

In this chapter, we will present the data produced for the project, describe the methods used to gather the information, and analyze the contribution of the results in the solution. It is through collaboration, participatory and creative methods that we can contribute the most to the transformation process of real estate development companies and the industry. Therefore, the most valuable data was created through a co-creation workshop with the company and the mind mapping method that finally gathered all the knowledge.

4.1. Creation of categories to reduce operational carbon emissions

After the literature review and interviews, both with external experts and internal collaborators of the company, the design team created four categories to organize and group all the design strategies to reduce operational carbon emissions during the operation phase of buildings. The strategies within each group were drawn mainly from scientific papers and sustainable building certification schemes, namely Active Buildings, LEED, and EDGE. The categories are building envelope & design, efficient appliances & systems, user behavior, and renewable energies, see Figure 10.

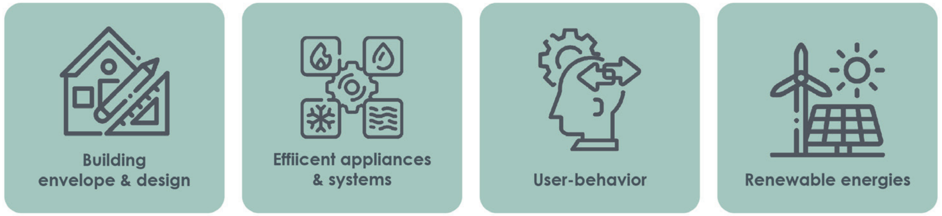


Figure 10. Categories for strategies to reduce operational carbon emissions in buildings (own illustration)

1 **Building Envelope & Design** relates to an integrated approach to engineering and architectural design, which includes building orientation and location, envelope and structural efficiency, and light and natural ventilation, following the principles of passive and intelligent design. For example, this group uses strategies to consider the sun's path to place and orient the building or uses materials with high insulation values to reduce heat loss.

2 **Efficient Appliances & Systems** describe intelligent control and energy efficiency systems to minimize heating, cooling, ventilation, lighting, and vertical transportation loads. This category includes control measures, monitoring, adaptation to changes, and integration with the network. Managing the temperature, lighting, and household appliances through an intelligent energy-saving system is a strategy connected to this category.

3 **User Behavior** presents strategies focused on communication and user education to create awareness, change habits, incentives for consumption, and responsible use of the building, equipment, and systems. As an example, creating user manuals that educate and encourage users to operate equipment correctly and responsibly and reduce their energy consumption is a strategy included in this group.

4 **Renewable Energies** concern the generation and use of renewable energy both on-site and off-site. Renewable technologies should be selected holistically, considering site conditions and building energy profiles. A strategy linked to this category is the alliance with a third party to generate renewable energy on-site and supply the building through a novel business model.

This categorization allowed us to organize the information and gave us an understanding of the wide range of possibilities to target operational carbon reduction. Additionally, they served as action groups for the co-creation workshop with Conaltura.

4.2. Co-creation Workshop

The co-creation workshop comprised a shared space between the design team and six collaborators from different company areas. The main goal of this activity was to involve relevant and varied actors of Conaltura to collectively explore ideas, create a zone of discussion and dialogue, and discover each other's perspectives about operational carbon emissions in buildings. Considering the location of the participants, the workshop was held online through Teams as the communication platform and Miro as the development canvas for the exercises to be more attractive and dynamic.

The participation team was selected according to the critical areas for reducing operational carbon emissions in buildings. The departments are sustainability (at strategic and building levels), architecture (related to bioclimatic and BIM), construction, and after-sale services. Each collaborator was carefully analyzed and chosen regarding their features and strengths to support productive and active cooperation and provide relevant and creative knowledge to the table.

The workshop included three distinct moments. In the first part, the design team presented the thesis theme and the context of the project, focusing on explaining operational carbon, which activities generate it, and the four main groups of strategies to reduce it. Then the participatory phase held three activities: a brainstorming session to explore strategies to reduce operational carbon; second, an analysis activity to identify enablers and limitations, and a discussion stage of evaluating the groups of strategies. Finally, we facilitated a conclusive discussion to hear the last ideas and feedback of the workshop. A specific method and tool were used for each activity, and a unique and valuable outcome was generated.

4.2.1. Activity 1: Brainstorming of strategies

Objective

The first activity encompasses a brainstorming session, where participants were asked to think about strategies or ideas to reduce operational carbon emissions in buildings. To develop this exercise, we used a board with four categories: building envelope and design, efficient appliances and systems, user behavior, and renewable energies (see Figure 11). This activity aimed to complement the strategies found in the research phase with new ideas from different experts within the company.

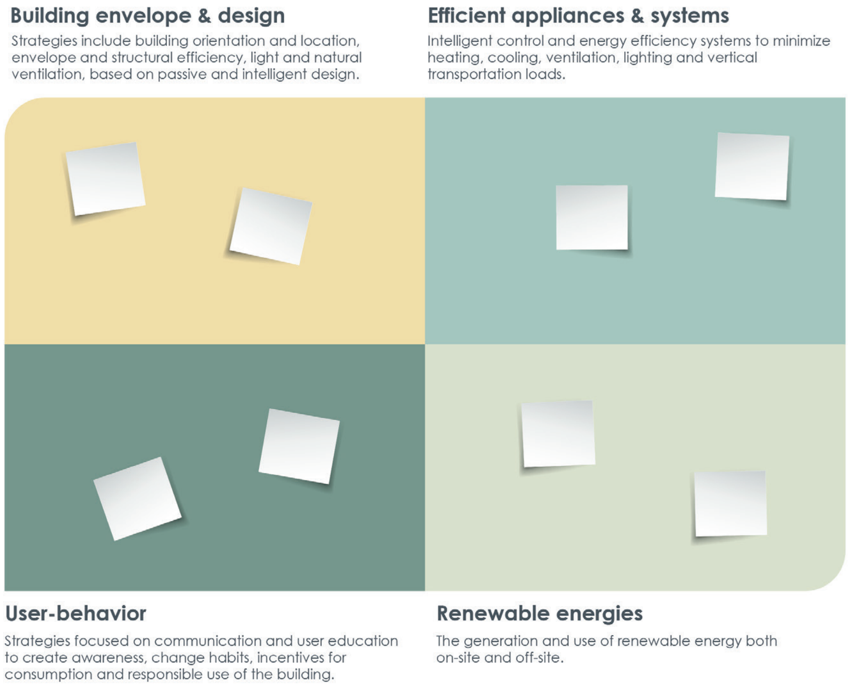


Figure 11. Board activity 1: How can we reduce operational carbon emissions in buildings? (own illustration)

Method

Each participant was asked to join a Miro board, created specifically for the workshop, where they would find all the templates. Everyone had 8 minutes to (individually) generate as many ideas as possible for each group with the help of digital post-its. For this exercise, we encouraged the collaborators to forget about limitations (cost, time, actors) and the other's perspectives to embrace creativity and originality.

Key findings

The activity supported the exploration and discussion of new strategies that have a practical and local perspective (see Appendix 15 for the full outcome). Noteworthy findings comprise the variation in façade and apartments designs based on the building orientation to benefit from the site conditions, as well as establishing partnerships with home appliances companies to offer energy-efficient equipment packages. Furthermore, relevant ideas related to user behavior include including children in sustainability awareness campaigns and using platforms to facilitate the implementation of renewable energies on-site.

The outcome was beneficial for us to grasp the company's understanding of the issue and thus have a complete list of strategies to build the solution. The first, second, and third categories were easier for the participants to generate new ideas, as these areas are where they have more experience and are part of the company's business model. The fourth category was more difficult, as the implementation of renewable energies is still new for Colombia's real estate market.

4.2.2. Activity 2: Enablers and limitations

Objective

The second exercise consisted of a joint brainstorming discussion, where collaborators were asked to develop facilitators and restraints that Conaltura as a company or each department have to implement each group of strategies. This task aimed to map out potential enablers of the solution (e.g., partners, regulations, incentives, technologies), as well as limitations that could hinder the implementation of the strategies, both as a process inside the company and in the buildings.

Method

For this activity, participants were asked to collectively think about the facilitators and restraints of each category, considering internal and external factors, such as market trends, regulations, incentives, relationships with stakeholders, cultural meanings, etc. This task was also developed in Miro, with four templates in which each category had two quadrants with a blank Post-it for participants to write their proposals, see Figure 12. In each category, we gave collaborators 5-10 minutes to write enablers and limitations, and at the end, we ignited discussions around the ideas through questions and remarks.

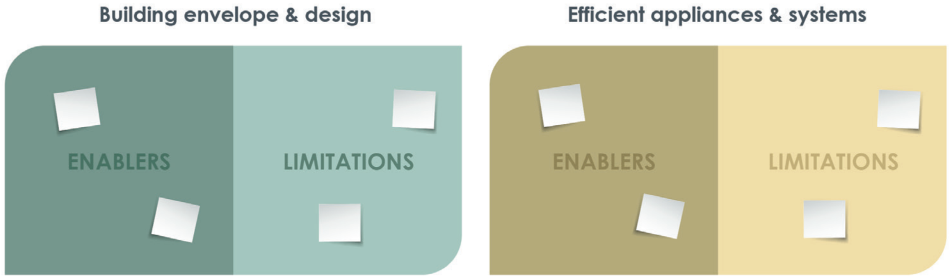


Figure 12. Board activity 2: Enablers & Limitations for each category (own illustration)

Key findings

Through the second activity, we gained insights into the company's perspective on the difficulty level and ease of implementing each group of strategies. The results of this exercise were relatively balanced between constraints and enablers (see Appendix 16 for the entire outcome). Among the most recurrent facilitators were key alliances, closeness to other actors in the value chain, technological availability of equipment and systems, and the sustainability awareness of new generations. The most frequently mentioned constraints were costs, traditional culture resisting change, lack of enough economic aid, and weak client relationships.

As participants possess expertise in their respective fields, this task was very useful since they shared new and valuable contextual knowledge regarding the application of the strategies. This information will aid us in designing a more tailored and effective solution for companies of this nature. Furthermore, the exercise allowed us to anticipate potential challenges and identify potential collaborators, thereby enhancing the likelihood of developing a solution that can succeed.

4.2.3. Activity 3: Evaluation of categories

Objective

The last activity consisted of positioning each group of strategies in a matrix with the variables of impact and feasibility. The objective was to know the point of view of the expert team concerning what they saw as the most viable to implement in the short and medium term and the possible impact it could have on reducing operational carbon emissions in buildings.

Method

For this activity, a digital x-y matrix was used, where participants had to give their individual viewpoints on the impact and feasibility of each category. They were asked to discuss the similarities and discrepancies of their thoughts and collectively place each category in the matrix.

Key findings

The result of the valuation activity can be seen in see Figure 13. During the activity, Building Envelope & Design was rated with high impact, considering the energy-saving benefits it brings, but medium-low feasibility due to the current costs of specialized materials, immature market, the speed, and standardization of the design process within the company. On the contrary, Efficient Equipment & Systems was seen with medium-high feasibility and medium impact since they considered efficient technologies already exist and there is a good and close relationship with suppliers, which facilitates alliances to develop efficient equipment packages and strategies. Considering the technological advancement and the high investment these strategies require, this result was unforeseen by the design team.

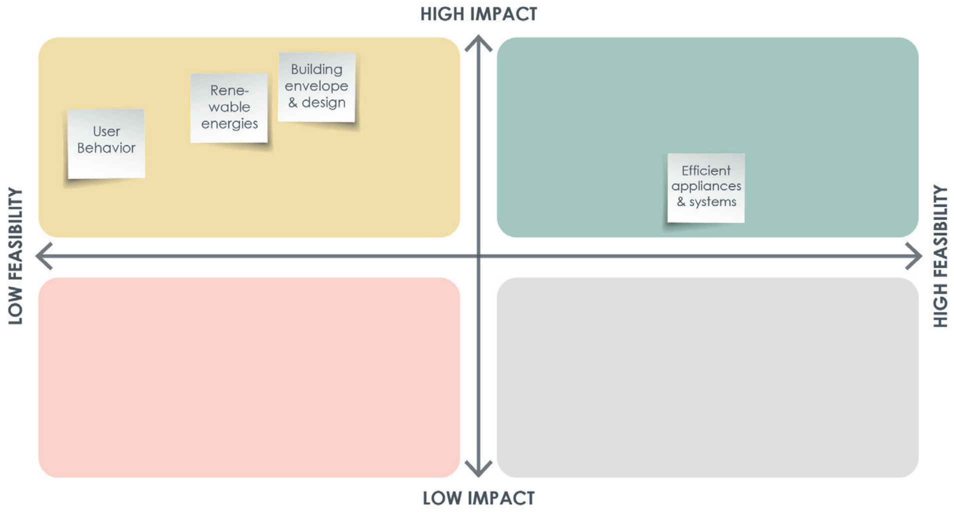


Figure 13. Activity 3: Impact and feasibility of implementing strategies of each category in the company in the short-term (own illustration)

Customer Behavior was recognized as the category with less feasibility due to the limited relation with users, poor sustainability culture around lifestyle, and weak communication and educational strategies with clients. However, the participants considered user behavior to have a medium to high impact because a change in their habits would support the reduction and well-functioning of other categories. The low feasibility of this category was also surprising since building a communication and education plan with users does not need considerable high resources. Lastly, Renewable Energies was placed high in impact but medium to low in feasibility since it has a lot of legal barriers, lack of an appropriate business model, high investment costs, and lack of incentives for the constructor.

Conclusively, the co-creation workshop was an ideal scenario for building a shared vision of a possible pathway toward NZCB, learning about the opportunities and limitations of the company within the construction industry, and to start planting the seed of change within crucial departments. In addition, it taught us about the unexpected results that are normal in a co-creation process, where perspectives and expectations are reframed all the time, and multiple design iterations must be done regularly.

4.3. Four Mind Maps

Objective

After the workshop, we chose the mind mapping method to organize and represent all the strategies from the literature review, interviews, and the co-creation process, see Appendix 12 and 13. These maps aimed to create visual and interconnected diagrams to identify related strategies and subgroups within each category easily.

Method

Each category was placed at the center of the map, and then several subtopics were branched and related to specific strategies to reduce operational carbon emissions in buildings. A darker color was used to represent strategies from the literature research, and a lighter color for ideas from the workshop.

Key findings

For Building Envelope & Design, we generated three subgroups related to benefit from the building's location, explicitly sitting and orientation of the building and its envelope. These strategies are essential for every building that targets carbon neutrality and should be considered at the beginning of the design process. Moreover, four more subgroups associated with climate conditions were added to the map, see Figure 14.

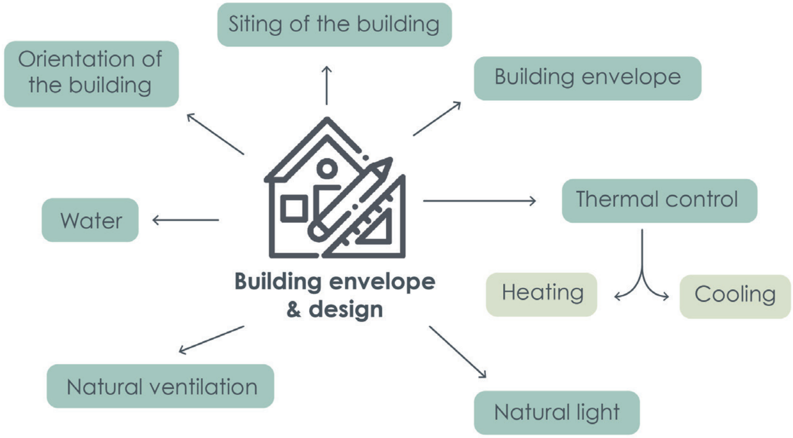


Figure 14. Mind map: Building Envelope & Design

These subgroups are also found in the second mind map for Efficient Appliances & Systems because indoor conditions can be controlled or manipulated by passive strategies or mechanical equipment (see Figure 15). In addition, other sections linked to the nature and function of the appliances and systems, such as adaptable and smart were created. Other category features include combining systems, retrofitting, and control strategies.

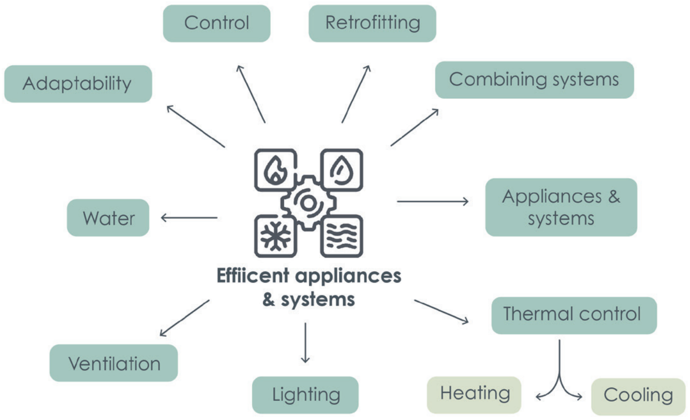


Figure 15. Mind map: Efficient Appliances & Systems

For user behavior, the type of relation with users was organized into subgroups, for instance, through instructions, educational programs, community management, incentives, and platforms. Other strategies related to design changes and strategic allies to influence user conduct were also added, see Figure 16.

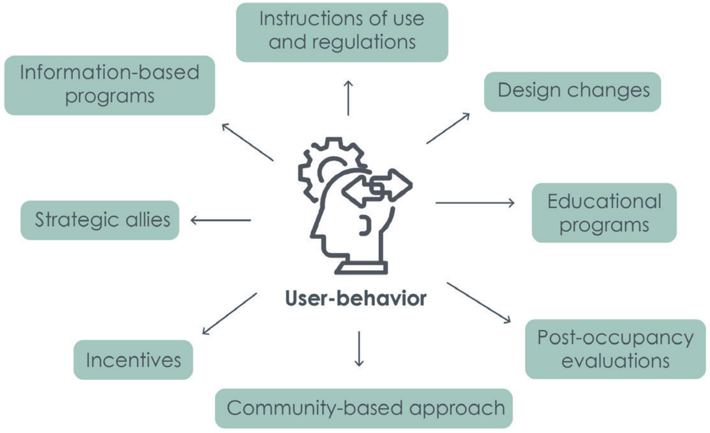


Figure 16. Mind map: User-behavior

At last, Renewable Energy was arranged into three sectors. Two are connected to the location of the energy generation, whether on-site or off-site, and some consideration within each subgroup, and lastly, the third is related to the types of energy available to create carbon-free power, as observed in Figure 17.

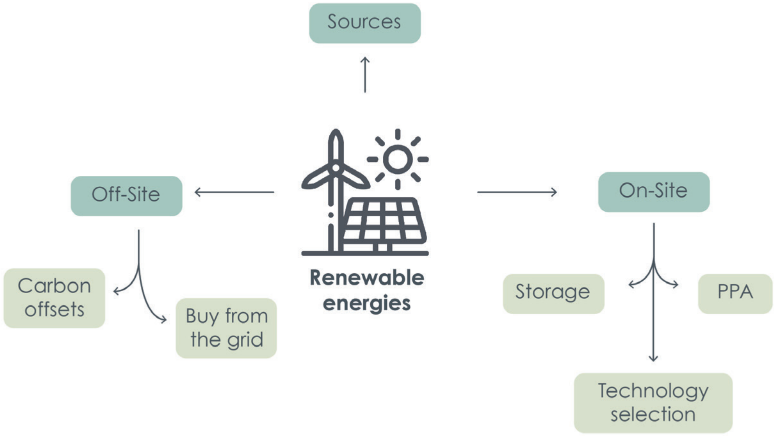


Figure 17. Mind map: Renewable Energies

In conclusion, the four categories, with their subgroups created through the mind mapping method, served as a base to refine the strategies further and start building a guide and action-based solution for the company to implement.

5

SOLUTION

This chapter will present the final solution that emerged from our research and collaboration process with Conaltura. First, we will introduce the Energy Pyramid Model as the theoretical framework of the solution. Then, we will provide an overview of the failed implementation strategy that shaped our journey, highlighting the challenges and insights gained along the way. Finally, through a process of iterative development, we develop a practical and flexible Toolkit that addresses the identified gaps in the literature and meets the specific needs of real estate development companies.

This chapter reflects on the process behind creating the solution, defined as The Guideline toward the Decarbonization of Buildings. The Guideline was developed and designed as a separate document for the examination and assessment of the company and can be found in an additional appendix.

5.1. The Energy Pyramid Model

Background

Integrating insights from the literature review, interviews with external experts, and professionals from Conaltura has culminated in the development of a comprehensive model known as the Energy Pyramid Model (see Figure 18). This Model evolved from the four categories created during the research process (see Section 4.1). Inspired by established models in the field, the Model presents a hierarchical structure comprising interconnected levels of energy considerations.

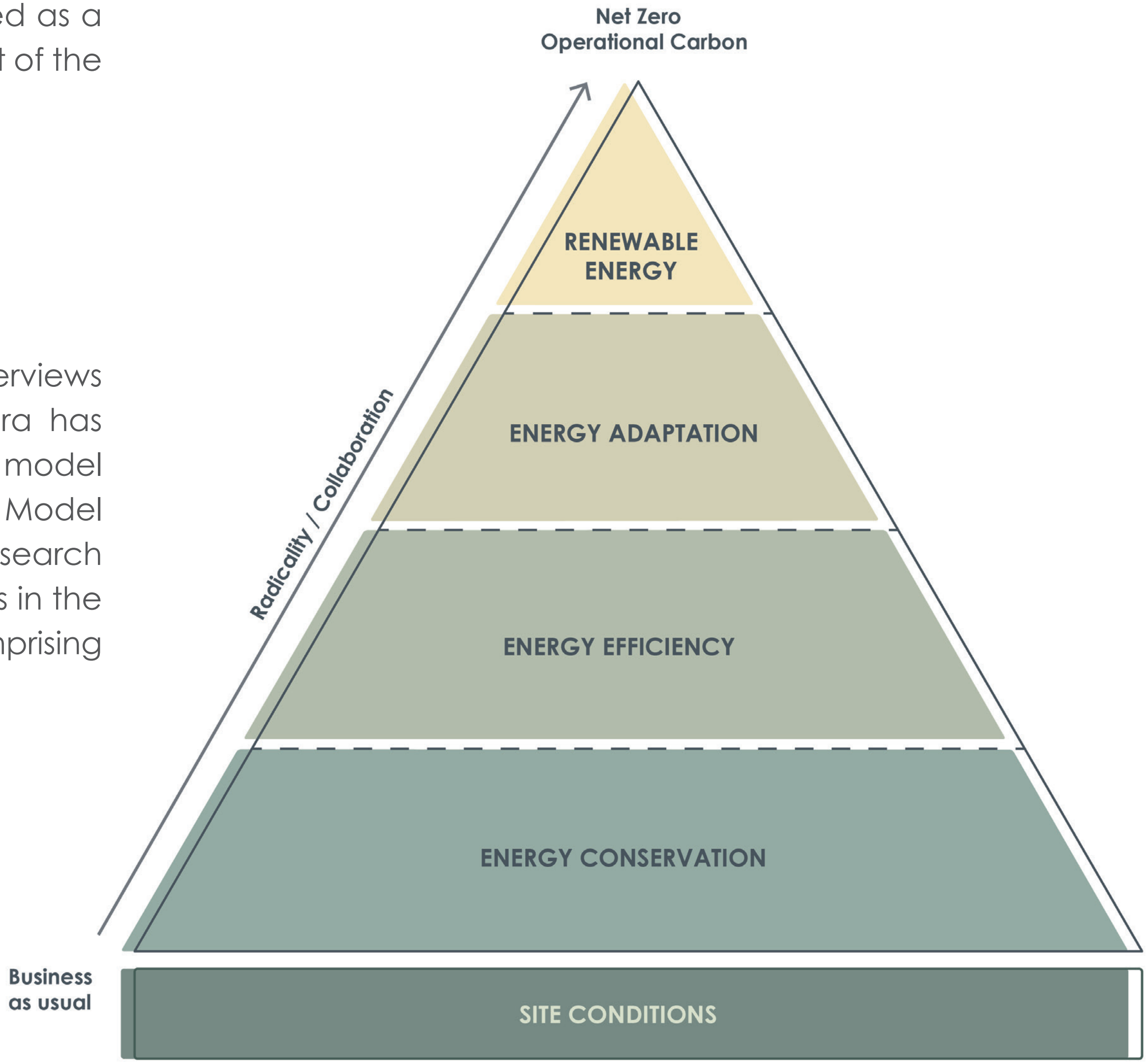


Figure 18. The Energy Pyramid Model (own illustration)

A referent contributing to the Model is the Energy Hierarchy Pyramid introduced by NHS England. This framework emphasizes a systematic approach to reducing energy consumption across four key levels (NHS England, 2020).

- The first level, **"be lean"** emphasizes the importance of optimizing energy usage by employing efficient architectural and technical design.
- The second level, **"be clean"** underscores the significance of using energy resources in a highly efficient manner to achieve maximum output.
- The third level, **"be green"** highlights the integration of renewable energy sources as a vital component of sustainable energy systems.
- The fourth level, **"offset"** acknowledges the need to neutralize any remaining carbon emissions.

Additionally, the Energy Pyramid Model draws inspiration from the Pyramid of energy priorities, also called the Energy Conservation Pyramid. This Model shares a common emphasis on three fundamental levels (University of Maryland Extension, n.d.).

- The first level, **energy conservation,** emphasizes on reducing energy consumption through behavioral changes and smart design practices.
- The second level, **energy efficiency**, highlights the importance of employing energy-efficient technologies, systems, and processes to optimize energy use.
- The third level, **renewable energies**, underscores the adoption of renewable energy sources as a primary means of powering operations.

Objective

The creation of this Model aims to provide empirical knowledge on how real estate development companies can achieve operational carbon reduction. Thus, we have developed a comprehensive scheme that offers clear guidance for organizations striving to reach this sustainable goal. The Model outlines the progressive journey from conventional building practices to the achievement of operational net zero-carbon buildings. It contains a base and four levels, each encompassing a unique set of strategies from both design-oriented and user-centric perspectives. By integrating these strategies, we provide a comprehensive solution that can potentially reduce the building's carbon emissions.

Method

In order to effectively organize the strategies identified during the research and collaboration phases within the framework of the Pyramid, we devised a categorization matrix, see Appendix 19. To organize and group the different types of strategies, we developed two separate matrices: one dedicated to design and the other focused on user engagement strategies.

For the first matrix, we developed a set of guiding questions to assign each strategy to a corresponding level within the Pyramid. These questions were carefully formulated based on established descriptions and criteria related to four initial categories.

Energy Conservation

- Does the strategy take advantage of site external conditions?
- Does the strategy reduce the need of mechanical or technological assistance?
- Can the strategy be achieved by architectural design?

Energy Efficiency

- Does the strategy require electricity to function?
- Does the strategy involve a new technology or system?
- Does the strategy require less energy without sacrificing its performance?

Energy Adaptation

- Does the strategy support the reduction of electricity consumption in peak hours?
- Does the strategy support the integration with the grid?
- Can the strategy change or influence patterns of energy consumption?

Renewable Energy

- Does the strategy provide carbon-free energy?
- Does the strategy take advantage of natural resources to produce energy?
- Does the strategy require specific technology on-site to generate energy?

To determine the placement of a strategy, a procedure of yes and no answers to the guiding questions was conducted. Ideally, a strategy that demonstrates alignment with a particular level should receive affirmative answers for all three questions within that level. This ensures that the strategy fulfills the requirements and objectives of that specific group. However, in cases where a strategy generates positive responses on multiple levels, a decision must be made regarding its placement. In such situations, the strategy is assigned to the level that gathers the highest number of yes, indicating the strongest alignment and compatibility.

The categorization process yielded unexpected insights, as specific strategies initially expected to belong to one level were found to be more appropriate for a different one. Moreover, while allocating strategies at the Energy Conservation level was straightforward, complexities arose at the other levels, where some strategies received positive responses across multiple categories. Particularly challenging were the strategies assigned to Energy Adaptation, which demonstrated strong compatibility also with Energy Efficiency. These findings highlight the dynamic nature of the categorization process and underscore the importance of thorough and critical evaluation when allocating strategies.

The second matrix consists of two statements that outline the objectives for each level, considering both Conaltura's responsibilities and the expected actions from users. However, we encountered difficulties using the user-related statement, as we cannot predict user responses but only define the desired outcome. Therefore, our focus was solely on referring to the first statement. When a strategy received a positive response in two levels, we placed it at the lowest level within the Pyramid.

Energy Conservation

- The strategy is aimed at **informing** users about sustainable behavior and operational practices
- Users should **understand** the basic knowledge to operate the building responsibly

Energy Efficiency

- The strategy is aimed at **educating** users about energy efficiency and conscious use of appliances
- Users should **take action** in orderto improve their energy consumption patterns

Energy Adaptation

- The strategy is aimed at **interacting** with users and provide them with feedback on their energy consumption patterns
- Users should **transform** their operational patterns and adapt to changing conditions

Renewable Energy

- The strategy is aimed at **facilitating** the implementation or generation of renewable energies
- Users should **advocate** for the implementation of renewable energies

This strategy evaluation and placement process was essential for maintaining the integrity and coherence of the pyramid model. It allowed for a comprehensive analysis of each strategy's characteristics and enabled transparent decision-making. By following this systematic approach, the design team ensured that each strategy was accurately positioned within the Pyramid, reflecting its potential impact and relevance to achieving net zero operational carbon goals.

The methodological framework also offers companies a clear and structured approach to facilitate the integration of new future strategies. By implementing this systematic and transparent categorization and allocation process, through guiding questions, organizations can effectively navigate and enrich the Energy Pyramid Model and align new strategies with the corresponding levels.

Implementation

The Pyramid serves as a starting point and pathway for new projects, guiding the implementation of operational carbon reduction strategies before proceeding to the design and planning phase. Starting with the Base, a comprehensive analysis of the project site and its specific characteristics should be conducted. This sets the foundation for Level 1, which focuses on energy conservation and utilizes site conditions to minimize reliance on technical solutions while ensuring optimal indoor comfort. Moving forward, Level 2 emphasizes energy efficiency, aiming to optimize equipment, systems, and appliances. Level 3 involves capturing and monitoring energy consumption patterns to gain valuable insights into, for example, the components that consume the most energy. Finally, Level 4 integrates renewable energy sources into the project, preferably on-site or alternatively with off-site alternatives.

It is important to note that the objective is not to implement all mapped strategies at each level but rather the most suitable strategies for the specific project. Factors such as project objectives, feasibility, and potential impact must be considered. Therefore, priority should be given to strategies that have the potential to generate substantial operational carbon reduction. By following this systematic approach, organizations can effectively navigate the pyramid model, tailor their implementation strategies, and achieve significant operational carbon reduction in alignment with the project's goals.

More detailed information about the descriptions and instructions on how to use the Pyramid Model can be found in the Guideline, as it provides comprehensive insights into each level, along with additional considerations, offering a deeper understanding of the Model's content.

5.2. Failed action plan development

Objective

The preliminary approach of the project involved co-creating an action plan to facilitate the implementation of strategies to reduce operational carbon emissions. Due to time constraints, we decided to focus exclusively on creating several action plans for energy conservation strategies, constituting the Pyramid's first level. Additionally, we specifically targeted strategies not currently implemented by Conaltura, either due to a lack of knowledge or because they had not been explored previously. As a result, we aimed to develop detailed action plans for five strategies, outlining specific activities, actors, and resources needed for their implementation.

Method

To ensure the successful development of these action plans, active collaboration and knowledge sharing with Conaltura were essential. With this in mind, we carefully designed a series of workshops, limited to a maximum of four participants, to delve into the details of each action plan. During these workshops, the main focus was identifying the key components necessary for successfully applying the strategies. Thus, the action plans were utilized to implement the strategies, encompassing specific activities, optimal stages within the design process, key stakeholders responsible for implementation, and an analysis of the required resources (see Appendix 18).

Key results

Although the action plan method aligned with the company's expectations, the actual process of creating these plans encountered significant challenges, leading to unexpected outcomes. Initially, we aimed to develop comprehensive and detailed action plans by involving various areas of the company in a series of six two-hour workshops. At this stage, we realized that the level of detail required for each action plan exceeded the time planned for the workshops, preventing us from fully addressing all the strategies.

Furthermore, during the third workshop, it became evident that new strategies delivered similar activities and responses to the previously developed ones. Additionally, the actions did not introduce any novel approaches but rather reflected existing practices already pursued by the sustainability department. As a result, our aim of creating an efficient tool evolved into a discussion about innovation without a clear and specific path to achieving it.

This misalignment between our intentions and the outcomes of the workshops was further emphasized in subsequent conversations with the head of sustainability, who expressed doubts about the tool's effectiveness, see Appendix 6. As a result, we collaborated with her on a collaborative brainstorming session, where we generated new ideas. Through this process, we were able to harness the collective insights and expertise that supported the design of a new solution.

Contribution

The workshops presented unexpected challenges, causing the initial action plan to fall short. However, we viewed these setbacks as opportunities to learn and reframe. By adopting the principles of participation and actively involving the company in the decision-making process, we enhanced our initial solution and developed a more effective and tailored approach. The workshops served as a catalyst for change, challenging us to reassess our approach, incorporate new insights, and ultimately arrive at a solution that is better aligned with the specific needs and goals of the company. As a result, we created a comprehensive Toolkit that addresses the shortcomings and provides practical guidance for achieving net zero operational carbon buildings.

5.3. The Building's Operational Carbon Reduction Toolkit

Background

After formulating the Energy Pyramid Model, which represents a pathway towards zero operational carbon buildings, the next goal was to develop a method that our collaborative partner could effectively utilize to implement the strategies outlined in the Pyramid.

To ensure practicality and seamless integration into new building projects, we prioritized the creation of a solution that would be easily understood and implemented by sustainability teams within real estate development companies like Conaltura. Furthermore, during a meeting with the head of the sustainability department, she emphasized the need for a solution that could be implemented in the short term and that was not overwhelming or overly ambitious in its approach. Considering this feedback, we decided to develop a practical toolkit with a comprehensive set of steps and recommendations tailored to achieve the implementation of the Pyramid's levels and strategies.

Objective

The objective of the Toolkit is to provide our collaborator partner with a valuable resource that addresses the specific needs and conditions of a project and fosters confidence in adopting the strategies outlined in the Pyramid. Furthermore, it aims to facilitate the integration of these strategies into Conaltura's existing practices by promoting cross-functional collaboration and considering the organization's time constraints. Thus, it is designed to be user-friendly and time-efficient to enhance its applicability and the future transition toward operational carbon reduction.

Application

The Toolkit is designed to facilitate a systematic and efficient approach. It comprises a series of sequential activities to guide organizations through selecting and implementing strategies for reducing building operational carbon (see Figure 19). The first activity involves a detailed analysis of the project's conditions and characteristics. Building upon the insights gained from the analysis, the second activity revolves around selecting the objectives of each level that align with the project's specific requirements and conditions. Finally, the last activity evaluates the strategies associated with each selected objective through an Impact/Feasibility matrix.

Figure 19. Step by step of the Toolkit (own illustration)

The successful execution of all activities within the Toolkit necessitates a collaborative effort across multiple departments within the organization. In order to achieve comprehensive and well-informed outcomes, it is imperative to engage teams from diverse areas, including architecture, engineering, bioclimatic design, construction, and other relevant departments. Moreover, activities two and three within the Toolkit have been designed to be conducted in a collaborative workshop setting, intended to foster a collective and participatory approach, leveraging multidisciplinary team members' diverse perspectives and expertise.

Furthermore, the Toolkit provides comprehensive instructions and resources that support organizations in executing the activities effectively. These valuable tools can be found within the Guideline, which contains more detailed information about each step and activity of the Toolkit. In addition, the tools required to perform the activities are organized and available on a Miro board, adding a dynamic and interactive dimension to the Toolkit. This approach ensures that users can access and engage with the resources seamlessly and efficiently, fostering collaboration and interactivity throughout the process.

5.4. Reflection

5.4.1. Strengths

The solution's strengths are rooted in its ability to address the identified gaps in the literature. Firstly, it goes beyond mere theoretical concepts by translating complex ideas into an action-based and practical solution that can be easily implemented in the design process of a project. This transformative aspect of the Model ensures that organizations can move beyond theoretical discussions and take concrete steps toward achieving operational carbon reduction objectives.

Secondly, the entire framework is designed to be adaptable and applicable to various real estate development companies operating in different contexts within Latin America. It is a straightforward and dynamic roadmap, providing clear guidance for organizations on a journey towards net zero operational carbon buildings.

Moreover, the solution stands out for its comprehensive approach. It incorporates various strategies derived from various schemes and frameworks, encompassing crucial aspects like passive design, energy efficiency optimization, renewable energy integration, and active user engagement. By consolidating these elements into a unified and cohesive reference model, the Guideline enables organizations to address the complex challenges of carbon reduction holistically.

5.4.2. Weaknesses

The solution has certain limitations that should be acknowledged. Firstly, it primarily focuses on addressing the operational carbon emissions of buildingswww. Thus, it is essential to recognize that by solely concentrating on this aspect, there is a potential oversight of other significant sources of emissions throughout the entire life cycle of the building.

Secondly, the solution's effectiveness relies on accurately selecting and assessing strategies for each level. While we have developed a Toolkit to guide the selection process based on project data, there is still a degree of subjectivity involved. In order to assess the strategies more accurately, a more scientific basis may be required.

Additionally, successful implementation of the strategies requires sufficient resources, technical expertise, and financial investments. Organizations with limited capacities or budgetary constraints may face challenges in fully developing their potential or may need to prioritize specific strategies over others due to resource limitations.

To fully benefit from the Toolkit, allocating enough time to evaluate the strategies is crucial. However, in fast-paced project environments with tight deadlines and processes, time becomes a significant constraint. Thus, this limitation may hinder the full integration and utilization of the Toolkit.

Finally, as the field of sustainable construction continues to evolve, it is important to recognize that the framework will require regular updates to incorporate emerging research, technologies, and practices. Failing to do so may result in an outdated approach that fails to address future sustainability concerns and goals. Therefore, continuous improvements and adaptations are essential to ensure that the Guideline remains aligned with the latest advancements and valuable in the current context.

6

DISCUSSION

This chapter will reveal the strengths and weaknesses of the project related to the scope, the concept of NZCB, methods, theories, and the collaboration process. It will also discuss the project's primary contributions to sustainable design engineering and propose future lines of research to continue developing a holistic approach for the construction industry. Lastly, we will suggest the following steps to further detail and improve the solution.

6.1. Strengths and limitations of the project

Project scope

The approach taken in this study possesses certain limitations, primarily due to the time constraints imposed by a 5-month thesis project. Given these limitations, we had to find a balance between developing a comprehensive solution and delving into the theoretical discourse on buildings' decarbonization. As a result, the project primarily prioritized addressing operational carbon emissions, intentionally setting aside the equally crucial dimension of embodied carbon.

While operational carbon plays a significant role in the whole-life carbon emissions of buildings, it is crucial to recognize that they represent just one component of a broader picture. Achieving comprehensive decarbonization of the building sector requires a holistic perspective that encompasses the entire life cycle of buildings and addresses emissions at every stage, from construction to operation and eventually demolition or renovation.

Thus, it becomes relevant to acknowledge that reducing embodied carbon presents an equally complex challenge that requires equal emphasis. Furthermore, as buildings become more energy-efficient, the relative importance of embodied carbon in the overall emissions profile is expected to increase (World Green Building Council, 2019). This emphasizes the need to maintain a long-term vision and understand that achieving zero operational carbon is the initial step in this extensive and transformative journey.

While we recognize the inherent limitations of the approach taken in this study, it is essential to emphasize that these constraints do not diminish our overall aspiration to promote sustainability within the built environment. Instead, we view our work as a stepping stone towards a more comprehensive and holistic approach that encompasses the reduction of operational and embodied carbon across the entire life cycle of buildings.

The concept of NZCB

The concept of NZCB has played a pivotal role in guiding our project toward achieving the decarbonization of the building industry and meeting the commitments outlined in the Paris Agreement. NZCB provides a long-term vision essential for driving systematic transformation within the sector. However, the lack of a standard and universally accepted definition and variations in its scope and factors introduce challenges and complexities in its implementation and interpretation.

In this report, we have adopted the definition of NZCB provided by the Colombian roadmap, which adopts a comprehensive whole-life cycle approach and places a significant emphasis on reducing all carbon emissions associated with buildings.

Alternative definitions focus primarily on energy-related aspects. For instance, the C40 cities definition characterizes NZCB as “green and healthy buildings that use energy ultra-efficiently and are supplied by renewables” (C40 Cities, n.d.). Moreover, the European Commission introduced a similar concept named zero emission building, which is defined as “a building with a very high energy performance, with the very low amount of energy still required fully covered by energy from renewable sources and without on-site carbon emissions from fossil fuels” (European Commission, n.d.).

The absence of a standardized definition for NZCB introduces ambiguity and possible confusion among stakeholders, posing challenges to the effective transition toward a decarbonized industry. To overcome these obstacles, it is imperative to establish a comprehensive and shared understanding of the key criteria required to achieve the long-term vision of NZCB. Furthermore, stakeholders can ensure consistency and comparability across projects and companies by establishing a common vision and framework, fostering collaboration, and facilitating progress toward a decarbonized building sector.

The approach of NZCB

NZCB primarily centers around the reduction of carbon emissions through the balance between man-made an natural resources, aligning with the principles of weak sustainability.

By placing a strong emphasis on mitigating GHG emissions, NZCB acknowledges the pressing need to transition to a low-carbon economy and alleviate the environmental burden associated with buildings. However, to further enhance the comprehensiveness of the framework, it is essential to incorporate the principles of strong sustainability. Strong sustainability emphasizes the recognition that certain thresholds should not be exceeded for long-term sustainability (Kuhlman T. , 2010). Thus, while reducing carbon emissions remains a vital objective, it is equally important to consider other dimensions of sustainability, such as resource consumption and water usage. By adopting this perspective, the analysis scope can be expanded, and the decision-making process can be enriched by considering a wider range of impacts.

Additionally, the theory of DfST also provides valuable insights to advance the NZCB approach. The theory emphasizes the importance of systemic change, innovation, and long-term commitment. By embracing this theory, we recognize that achieving carbon reduction is only one aspect of a broader transformation toward a sustainable built environment. This holistic perspective allows for the integration of innovative technologies and systemic changes to create buildings that not only minimize carbon emissions but also optimize resource use and enhance social well-being.

Theories

Although DfST, MLP, and Transition Pathways are valuable theories for the project used to analyze the sociotechnical system and the type of change required to move toward NZCB, they present some limitations concerning the practical and actionable approach necessary for the transition. For example, as some criticisms of these frameworks reveal, MLP relies greatly on analytical levels and can be unclear on how it should be applied empirically. Moreover, it is a global model that outlines the complete transition process, tending to give less attention to actors and their roles. Therefore, when designing a functional solution, Guideline, or Toolkit for companies to implement, these approaches might fall short.

Additionally, the description and analysis of the transition pathway we envisioned for the construction industry is only a proposal we see viable, considering the current conditions of the landscape, regime, and niche levels. As Geels & Schot (2007) explain, pathways are not deterministic, meaning that the series of events are not automatic and can lead to different and unexpected outcomes. Therefore, transitions rarely occur in their pure and theoretical form, and different types of change can happen simultaneously or sequentially.

Methods

As previously explained, the participation process with Conaltura was held entirely online due to different locations from the design team and the collaborator partner. Hence, specific methods and tools were used to fulfill the cooperation requirements (see Section 2.4.3.): digital diagrams, tables, and matrices through the Miro platform and presentations, graphics, and digital reports through Teams. Even though we consider the co-creation process and the participation of the collaborating team successful and beneficial for the project, the on-site presence could have brought richer feedback and outcomes.

Consequently, the same methods could have led to more creative outcomes or contributed with extra insights like a more detailed analysis of interactions and relations between department teams. Further, additional participatory methods, such as design games, observations, role-playing, and boundary objects, could be used easier in person, as there are more possibilities in terms of tools, materials, and activities to implement and perform.

Collaboration process

Finally, during the participatory process, we had to take different decisions that could favor the company’s wishes or resolve another course of action. Specifically, after the first workshop and the valuation of the four categories (see Section 4.2.3.), the sustainability department wanted the solution to focus on the Efficient Appliances & Systems group as it was classified as the most viable one in the medium-short term. However, we took a different direction based on the literature review, the interviews with experts, and our SDE background. Considering that the category relies heavily on technical and technological advances, it barely includes users in its implementation or profound changes in their organizational practices; we believed that the change within the company would have been more superficial and the effects on achieving the goal of NZCB would have been lower. Thus, we decided to develop a more holistic and integrated framework to push them toward the employment of more transformative and innovative strategies.

On the other hand, we also acknowledge that we were involved in a collaborative process where our project's goal and the company's expectations had to be balanced. Therefore, to develop a suitable and helpful solution for the organization, we had to be empathetic, understand the company's advantages and limitations and analyze all the variables involved. In particular, their biggest concern with the result was its applicability, considering that some of their sustainability strategies and projects are not fully implemented due to time constraints, vocabulary barriers across departments, and usage opportunities.

As a result, we considered the agility of the process, the easy understanding of terms and concepts (through examples, figures, and graphics), and the applicability in the short term as design specifications for the Pyramid Model and the Toolkit. Lastly, the constant reframing of expectations and change of mind are considered an essential part of the collaborative approach, highlighting flexibility, resourcefulness, and adaptation as prominent roles of the designer.

6.2. Thesis' contribution to SDE

Participatory approach

A significant component of the SDE field is the ability to collaborate with other actors, fields, and companies, identifying and analyzing sustainability challenges within their practices to co-design products, systems, models, or solutions and support them in resolving such issues. To realize these collaboration processes, there is a collection of creative, practical, and interactive methods and tools that facilitate and improve the interactions between the design team and the participants and the quality of the outcome. In addition, there are also essential skills needed for sustainable design engineers to assist these participatory processes, such as user involvement, workshop facilitation, knowledge management, and communication.

With this in mind, this project's collaboration process contributes to SDE's established knowledge and methodologies since it breaks the barriers of space and time. The cooperation with a company in a different context from our educational background encourages designers to work across countries, solving diverse sustainability issues and also learning from other particular methods and approaches. Furthermore, by developing the co-creation process online, this project serves as inspiration and reference for other designers to expand their scope and domain of action and gives examples of suitable digital methods and tools to implement in such situations.

Moreover, the project reflects the importance of impersonating an open-minded, empathetic, and flexible role when working across diverse contexts and communities of practice. After all, to achieve the sustainable transformation that humanity requires, sustainability experts should work across barriers and be able to meet the challenges of multidisciplinary and multicultural interactions.

From theory to practice

NZCB has gained significant recognition as a promising approach to addressing carbon emissions in the built environment. However, despite the extensive body of literature, including studies, projects, strategies, roadmaps, and other related documents to promote and implement NZCB, its global application remains limited.

One significant barrier identified during the literature review is the predominance of theoretical discussions surrounding the concept. With various interpretations and definitions, the discourse often revolves around conceptual debate rather than providing practical guidance for implementation. Consequently, private sector companies, particularly those in the real estate market, face challenges translating the NZCB concept into actionable strategies.

To address this research gap, our project seeks to go beyond theoretical discourse and make a meaningful contribution to the knowledge of SDE. Therefore, recognizing the need to go beyond abstract ideas, we strongly emphasize the practicality of our research. By grounding our work in applicability and real-world settings, we confront the complex challenge of decarbonization within the construction industry and effectively showcase a visible path toward carbon reduction strategies.

Thus, our project provides empirical evidence and actionable guidance that industry professionals can readily implement. Through these endeavors, we aspire to stimulate further progress in SDE and foster tangible advancements in the NZCB approach.

6.3. Future research

The solution developed in this study has far-reaching implications for future research in the field of SDE, particularly in the context of achieving NZCB. As stated in past chapters, NZCB considers both operational and embodied carbon. Therefore, future research can contribute to addressing the challenges associated with decarbonizing the built environment, with a particular emphasis on reducing embodied carbon.

There are potential opportunities for a future investigation related to the causes, barriers, and enablers of embodied carbon and its real impacts on buildings. Our study can also serve as an example of developing a practical approach to tackle embodied carbon through strategies, guidelines, models, or toolkits that are easy to implement and understand for companies in the industry. By exploring these research endeavors, scholars can contribute valuable knowledge, methodologies, and recommendations to guide practitioners and policymakers in effectively implementing and prioritizing a pathway to achieve NZCB.

6.4. Next steps

Assessment workshop

Although the solution was co-created with the collaborator company, its success, applicability, and acceptance across areas are not guaranteed. Therefore, as a next step, we planned an additional workshop with several employees from different areas of the organization to share the Guideline and jointly test the Toolkit in an actual project. The objective of this assessment is to evaluate the perception of the Guideline and detect gaps in the Toolkit, especially in terms of the ease of use, the understanding of activities and terms, and the power to encourage interaction. In addition, we would like to identify the implementation time and analyze the discussions surrounding the development of the collaborative activities to improve the tool's impact in the context of Conaltura.

For this workshop, we organized three separate sessions with different company actors. In the first meeting, we will work with the sustainability team to arrange the information on the project needed for the first activity of the Toolkit. The second meeting represents the main workshop, where we will unite key actors to conduct activities two and three of the Toolkit. The design team will facilitate the workshop and have an observant role in getting as many insights as possible. Finally, there will be a last meeting with the sustainability team to get their feedback and recommendations for future improvements and adjustments for the complete Guideline.

Pilot project

Once the solution has been tested and refined, the next step is developing a pilot project by Conaltura. This trial plays a crucial role in assessing the real impact and applicability of the mapped strategies, as well as validating the usability and acceptance of the solution in a contextual setting without the presence of the design team.

Therefore, careful consideration should be given to selecting the most suitable project for the pilot. It is essential to choose a project that offers adequate opportunities to implement a wide range of strategies, ensuring that the solution's full potential can be realized. This strategic selection ensures a comprehensive assessment of the effectiveness of the mapped strategies in reducing operational carbon emissions, considering their impact and combined effects. Simultaneously, it provides a unique opportunity to seamlessly integrate the solution into the actual design process within the company. By doing so, the pilot project becomes a powerful mechanism for assessing the practical impact of the solution and its alignment with the company's existing practices.

Moreover, the pilot project serves as a dynamic learning platform, offering valuable insights into the complexities associated with operational carbon reduction. Lessons learned from the pilot project become the catalyst for continuous improvement, enabling the identification of success factors and areas requiring further enhancement. Thus, the knowledge acquired through the pilot project is a solid foundation for future projects.

CONCLUSION

Globally, governments and organizations have recognized the immense impact the construction industry and buildings have on the environment, specifically on global warming. Therefore, influential public and private institutions have cooperated on the construction of national roadmaps to establish a shared vision and a strategic plan so that diverse actors of the sector can outline their pathway to achieve the goal of NZCB. This framework is vital to tackle climate change and achieve sustainability in the built environment since it aims to reduce GHG emissions by preserving resources, improving residents' well-being, and promoting resilient buildings.

Nevertheless, such roadmaps and frameworks still do not provide specific and practical guidelines or strategies for relevant industry actors, like building development companies, to implement in order to reduce their projects' GHG emissions. Therefore, this thesis aims to co-design a strategy for such companies to effectively reduce the carbon footprint of their buildings and thus contribute to achieving the goal of NZCB.

To answer this question, the design team partnered with Conaltura, a Colombian real-estate development company specialized in residential buildings and experienced in the development of sustainable buildings. Therefore, through an intensive literature review, a collaborative approach, and an iterative design process composed of workshops, creative and analysis methods, this project developed a pragmatic and comprehensive solution that addresses the company's requirements and creates a clear path toward the decarbonization of their buildings.

The research on the construction industry provided relevant sustainable theories, methods, and concepts, such as the life cycle of buildings and the carbon emissions associated with each phase, recognizing operational carbon as the most impactful and challenging for building development companies to reduce. Furthermore, the literature review also gathered essential information on strategies to reduce operational carbon through passive design, efficient appliances and systems, and the use of renewable energies, as well as user behavior strategies to influence their actions and promote sustainable practices within the built environment.

Using DfST and MLP as the theoretical framework of the thesis, we could understand that global warming, economic growth, and the technological revolution are putting pressure on the regime by creating stricter regulations, demanding better living conditions, and offering specialized tools that facilitate sustainable construction. We analyzed that the current architecture of the regime is established by rapid and multidisciplinary design processes that leave small room for innovation and by a business model that hinders the sustainable operation of buildings. Finally, some niches possess symbiotic relationships, providing new services, knowledge, and spaces for innovation, while others still need to mature to supply novel technological and energy-efficient advancements to support the creation of NZCB.

Lastly, a co-creation workshop allowed us to explore the final strategies to reduce the operational carbon of buildings, analyze their strengths and limitations and evaluate their impact and feasibility within the company's practices and context. The collaborative process guided the development and refinement of the final solution: The Guideline toward the Decarbonization of Buildings. The Guideline is an action-based approach composed of the Energy Pyramid Model, the project's theoretical framework that aims to guide companies on a progressive journey to reduce operational carbon emissions. Moreover, a Toolkit that provides a step-by-step procedure to implement carbon reduction strategies associated with the levels of the Pyramid.

The collaboration process played a fundamental role in the creation of the solution, as it continuously shaped the components of the Guideline and defined the method of implementation, considering the characteristics of the company but also of the whole industry. Therefore, analyzing the established regime and how the landscape and niches influence current practices, cultures, processes, and markets in the building industry was also crucial in refining the solution. These considerations will certainly influence the impact and applicability of the strategies by strengthening beneficial relationships among relevant stakeholders or leveraging from new regulations, incentives, and sustainability programs.

Conclusively, the thesis makes an essential contribution to SDE, as it proves the usability of several field-related theories and methods and highlights relevant roles designers must impersonate to unlock the potential of participatory design for sustainability. Most importantly, it contributes to the construction sector and companies by developing a solution that encourages them to take action, familiarize themselves with NZCB and ignite collaboration across disciplines, companies, and industries to create a sustainable and resilient built environment for current and future generations.

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