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A Value-Based Framework from Building Stock Model to Retrofit Model

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Abstract

The study has as its original database the decarbonization process initiated in Mexico by the National Commission for the Efficient Use of Energy (CONUEE) as part of its "Savings Program of Electric Power in Buildings of the Federal Public Administration" (PAEIAPF) of 1999. The primary purpose of PAEIAPF was to reduce the levels of electric power consumption in Federal Government buildings. The program has operated for 20 years; however, its scope only reaches operational carbon.

Since 90% of existing buildings will be in use by 2050, the Retrofit Models will be the base to determine solutions for a more resilient living environment that fortifies and extends the grid's capacity and meets climate change mitigation targets.

Secondly, significant socioeconomic and profound environmental impacts are not calculated explicitly in existing tools and are often referred to as "secondary" or Non-Energy Benefits (NEB). "The goal is to give them a measurement value to be considered in the decision-making calculus. It is assumed that soon; such factors will enter the general climate change economy, not unlike carbon in the past decade."

In this context, the proposed research aims to develop a value-based framework that will support a Building Stock Model and subsequent Retrofit Models, documented in a web-tool platform. The framework has three main steps:

A) Building Stock Model: Mapping of selected buildings of the program PAEIAPF in a GIS system. Documentation of the baseline energy consumption and embodied CO2-eq of the existing building.

B) Retrofit Models: Involving a Whole Life Cycle Assessment (WLCA) and Non-Energy Benefits (resilience coefficient, health, productivity).

C) Web Tool Platform: Application and toolset that allows for consistent documentation, environmental impact evaluation of existing building stock, and solution design in identifying energy reduction concepts.

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Keywords

Building Energy Retrofit; Whole Life Cycle Assessment; NEB; Web Tool

1. Introduction

The transformation of existing building stock to enhance energy efficiency by upgrading building structures stands as a well-established and highly effective strategy for mitigating and adapting to climate change. Particularly, the reduction of operational emissions, achieved through energy-efficient building operation and on-site renewable energy generation, is a critical facet of the transition towards clean energy. The pursuit of Building Energy Retrofit (BER) strategies is geared toward achieving substantial reductions in such emissions, constituting a meaningful endeavor across environmental, energy, and societal dimensions.

However, the significance extends beyond operational emissions to encompass Embodied Emissions arising from the complete life cycle of building materials and components, spanning production, procurement, installation, maintenance, and eventual disposal. Notably, the quantity of embodied carbon dioxide equivalent (CO_2-eq) within a typical building surpasses operational CO_2 emissions throughout its lifecycle (69% in residential, 76% in warehouses, and 67% in commercial buildings) (Finch, 2013). Efforts directed towards achieving a net-zero carbon building stock by 2050 entail the reduction of direct building CO_2 emissions by 50% and the decline of indirect building sector emissions through a 60% reduction in power generation emissions by 2030, necessitating a consistent annual decline of around 6% from 2020 to 2030. This context is further emphasized by the 7% reduction in global energy sector CO_2 emissions observed during the pandemic. (Institute for Building Efficiency, 2011)

While much emphasis has been placed on new constructions, it is essential to recognize that achieving the 2050 energy demand reduction targets could largely hinge on the renovation of the existing building stock rather than relying solely on new developments. Generally, the prevalent energy renovation rate encompasses 12% of the building stock per annum, with average energy intensity reductions generally below 15%. To align with the Sustainable Development Scenario (SDS), however, energy renovations would need to achieve energy intensity reductions ranging from 30% to 50%. Moderate refurbishment endeavors within existing buildings have been identified as having the greatest potential to advance the goal of decarbonizing the built environment (Loga, 2015). Furthermore, the building stock emerges as one of the most substantial and yet largely untapped avenues for enhancing energy efficiency and mitigating greenhouse gas emissions.

In the context of Mexico's energy consumption and CO_2 emissions landscape, it is pertinent to note that Mexico ranks as the 11th largest emitter of greenhouse gases (Figure 2). As the second-largest oil producer in Latin America, Mexico's energy mix comprises only 10% from wind and solar sources. Fossil fuels account for more than 80% of Mexico's total energy supply, with oil contributing 45% and natural gas 38% (Figure 1) (Programme for Energy Efficiency in Buildings, 2019). Given these realities, retrofit strategies assume pronounced significance in Mexico's trajectory, particularly when considering the imminent challenges posed by the fossil fuel scenario. Among the paramount reasons underscoring the critical importance of retrofit strategies are the reduction of fossil fuel dependency, the enhancement of energy security, the stimulation of economic benefits, the improvement of indoor comfort, the realization of long-term cost savings, and the fostering of urban planning and renewal efforts. As such, the implementation of retrofit strategies holds the potential to catalyze a transformative shift towards a sustainable and resilient built environment in Mexico.

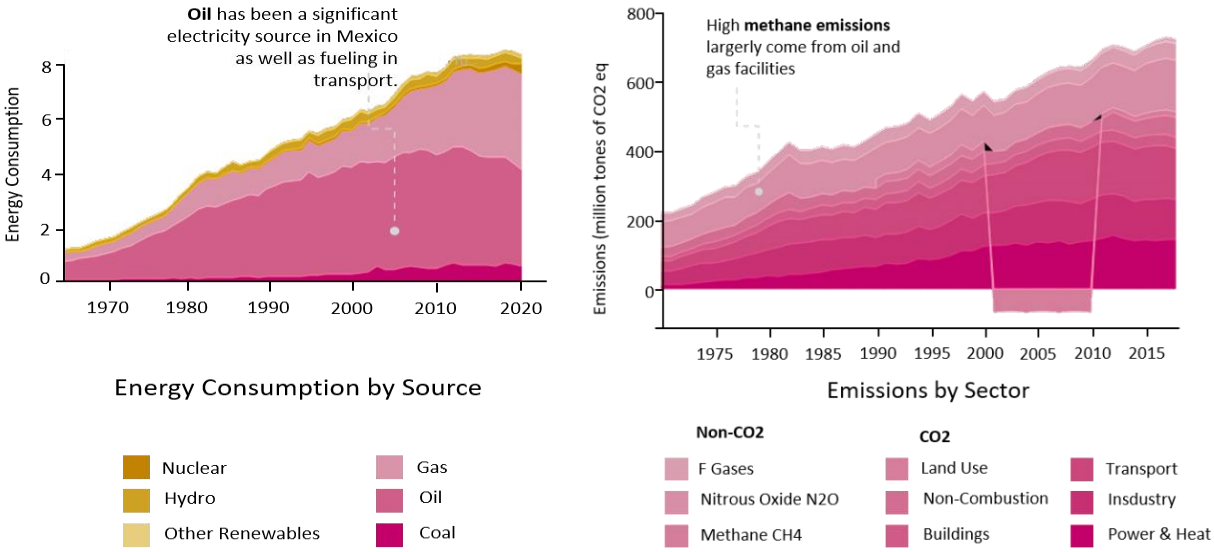

Figure 1: Energy Consumption by source and Emissions by sector in Mexico. Carbon Brief Profile 2023.

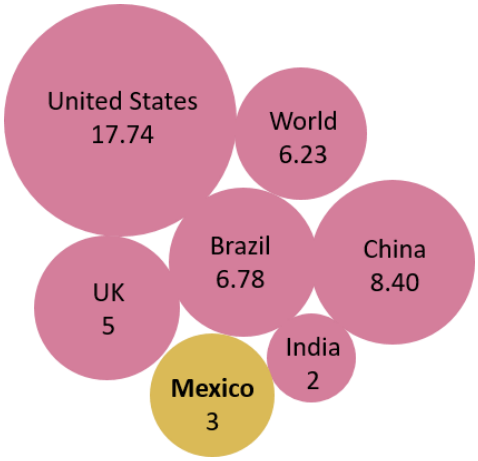

Figure 2: Emissions per capita (tpy).

2. Justification

The dearth of information presents a current constraint when endeavoring to assess the performance of public and private buildings for informed urban energy decision-making. To address this gap, it will be drawn upon data curated by the National Commission for the Efficient Use of Energy (CONUEE), which spearheaded a comprehensive Energy Efficiency Program within the Mexican Federal Public Administration Buildings for a 26-year span (Comisión Nacional para el uso Eficiente de la Energía, 2020). This initiative yielded valuable insights into building performance pre and post-implementation of energy-saving strategies, culminating in a 21% reduction in energy consumption. However, it's noteworthy that the program's scope did not encompass a holistic Whole Life Cycle Assessment, thereby neglecting the evaluation of embodied carbon associated with the executed strategies. Within the expansive portfolio of 2,076 buildings spanning Mexico, a subset of sixty-five structures located in the Cuahtemoc District of Mexico City has been meticulously selected for inclusion in this study.

Drawing from projections by the International Energy Agency highlighting that 90% of existing buildings will persist through 2050 (International Energy Agency, 2015), a cogent rationale emerges for the prioritization of Retrofit Strategies. While new constructions inherently possess the advantage of optimizing CO2 savings from inception, Retrofit Strategies stand as the compelling pathway for enhancing the environmental performance of existing buildings. Scholarly references, including seminal works by Nishimwe et al (2021), Yamaguchi et al (2022), and Hirvonen et al (2021), document remarkable energy savings of 66%, 50%, and 75%, respectively. However, prevalent tools for building evaluation inadequately account for paramount socio-economic and environmental implications, often termed "secondary" or Non-Energy Benefits (Smith, 2018).

These encompass pivotal facets such as improved Indoor Air Quality (IAQ), bolstered resiliency, enhanced health, and heightened productivity. Regrettably, these factors remain largely absent in projected adaptation scenarios and decision-making calculations. Notwithstanding the intricacies of quantification and monetization, this proposal presupposes that these dimensions will inevitably assume greater prominence in the evolving climate change economy, analogous to the trajectory of carbon-related concerns in the previous decade.

Insights from the European Academies Science Advisory Council emphasize the significance of embodied Green House Gas (GHG) emissions within building life cycles. They reveal that typical values of embodied GHG emissions per square meter for new buildings fall within the range of 250 to 400 kg of CO2eq./m2, while operational GHG emissions from existing buildings hover between 30 and 50 kg CO2eq./m2 per year (European Academics Science Advisory Council, 2021). Furthermore, studies underscore that the incorporation of embodied emissions from the renovation of existing buildings, contingent upon renovation scope and materials, usually accounts for less than 50% of the embodied emissions associated with new constructions (International Energy Agency, 2016).

The overarching goal of this study is to contribute to the body of knowledge by formulating a robust framework and evaluation method system for retrofit models tailored to temperate climates akin to the conditions prevalent in Mexico City throughout the year. This research endeavors to bridge the existing gaps in understanding, ultimately guiding the formulation of effective retrofit strategies that align with the city's unique environmental context.

3. Problem Statement

The current landscape of Building Retrofit Models presents several limitations that have given rise to misinterpretations in the pursuit of Energy Efficiency improvements and decarbonization. These limitations encompass critical aspects including:

- Balancing Energy Efficiency, Embodied Carbon, and the "Energy of Architecture": The absence of a clear coefficient to harmonize Energy Efficiency savings, embodied carbon considerations, and the broader architectural context has led to fragmented approaches in retrofit strategies.
- Methods for Whole Life Cycle Assessment (WLCA) on an Urban Scale: The absence of robust methodologies to calculate WLCA for existing buildings at an urban scale poses a significant challenge. This gap hinders comprehensive assessments of the environmental impacts associated with retrofit interventions.
- Baseline Calculation Challenges: The lack of accessible and standardized information to calculate a reliable baseline for evaluating retrofit impacts contributes to the ambiguity surrounding retrofit outcomes.
- Urban Scale vs. Architectural Scale Accuracy Coefficient: The disparity in accuracy between urban-scale retrofit models and architectural-scale analysis further complicates effective decision-making, inhibiting the adoption of impactful retrofit strategies.
- Integration of Non-Energy Benefits: The current retrofit models inadequately account for non-energy benefits, such as improved indoor air quality, occupant health, and resilience, which are integral to assessing the holistic value of retrofit interventions.

Addressing these challenges is pivotal to developing a comprehensive and accurate approach to Building Retrofit Models. This research considers these limitations as essential components within a Value-based Framework designed to enhance the efficacy of retrofit strategies. The scope of the problem can be delineated into two primary dimensions:

- Renewable Sources of Energy: This facet acknowledges Mexico's heavy reliance on fossil fuels and the projected doubling of its energy consumption before 2050 (Programme for Energy Efficiency in Buildings, 2019). Recognizing the practicalities of the scenario, which envisions a distributed effort towards reducing greenhouse gas emissions, the gradual integration of Renewable Energy Sources becomes a significant consideration. The research will explore potential scenarios for incorporating Renewable Energy Sources under these conditions.
- Selection Criteria of Buildings: The representative sample for this study will encompass sixty-five Office

Buildings drawn from the pool of the National Commission for the Efficient Use of Energy (CONUEE) (Figure 3). The selection criteria will include factors such as Climate Zone 3A, a humid tropical climate, the typical footprint size of government office buildings, and the specific location within the Cuauhtemoc District in Mexico City. These criteria provide a targeted focus for the research's investigation into retrofit strategies.

The identified limitations and challenges in Building Retrofit Models underscore the urgency and importance of this research. By addressing these issues and delving into the intricacies of Renewable Sources of Energy and building selection criteria, this study aims to contribute to a more informed, effective, and holistic approach to retrofit strategies in the context of energy efficiency and decarbonization.

Figure 3: Selected buildings mapping

4. Research Objectives

The research objectives of this study are strategically designed to address the gaps and challenges identified within the realm of Building Retrofit Models, with a clear focus on enhancing energy efficiency and decarbonization strategies. These objectives are formulated to guide the research towards meaningful contributions that will drive transformative changes in the field:

- Developing a Robust Building Stock Model Framework: One of the primary objectives of this research is to establish a comprehensive and robust Building Stock Model framework. This framework will be intricately tied to a Baseline Approach, enabling accurate comparisons and assessments of retrofit interventions. By creating a systematic and standardized model, this objective aims to provide a reliable foundation for evaluating the energy efficiency and decarbonization potential of existing buildings.
- Whole Life Carbon Calculation of Existing Buildings: This study recognizes the crucial significance of considering the entire lifecycle of buildings, including their embodied carbon and operational emissions. To address this, an essential research objective is to formulate a method for the Whole Life Carbon calculation of existing buildings. This involves conducting thorough assessments that encompass various stages of a building's lifecycle, thereby providing a holistic perspective on its environmental impact.
- Developing a Retrofit Model Framework as a Library of Solutions: The development of an effective Retrofit Model framework is another core objective of this research. This framework will function as a dynamic "Library of Solutions," (Jemtrud, 2021) offering a diverse range of retrofit strategies tailored to specific

contexts. Through meticulous research and analysis, this objective aims to compile a comprehensive repository of technically sound and environmentally impactful retrofit options.

5. State of the Art

The review of the current state-of-the-art in the field of Building Retrofit Models reveals key concepts and research works that have significantly influenced and provided valuable insights into the development of this study:

- Retrofit Strategies Implementation for Existing Buildings:

  A noteworthy observation from the current body of literature is the prevalence of tools and methods designed to facilitate energy-efficient features primarily during the design and predesign phases of existing buildings. However, the literature is considerably reduced when it is related to developing retrofit strategies for existing buildings, especially on an urban scale. In this context, the research of Claudio Nägeli et al. holds substantial importance, particularly, their works titled "Towards agent-based building stock modeling: Bottom-up modeling of long-term stock dynamics affecting the energy and climate impact of building stocks, Energy and Buildings" (Nägeli, 2020) and "Synthetic building stocks as a way to assess the energy demand and greenhouse gas emissions of national building stocks. Energy and Buildings" (Nägeli, 2018) have offered critical insights into retrofit strategies through their case studies, such as the retrofit study conducted in Switzerland. Furthermore, Claudio Nägeli et al.'s article "Methodologies for Synthetic Spatial, Building Stock Modelling: Data-Availability-Adapted Approaches for the Spatial Analysis of Building Stock Energy Demand" forms the foundational basis for my forthcoming synthetic urban-scale analysis.

- Data-Driven Analysis Tools for Building Retrofit Models:

  The development of effective Building Retrofit Models is significantly influenced by the availability of instruments and tools. In shaping my model as a Data-Driven Analysis Tool, the work of C. Szum et al. has provided valuable guidance. Their research, especially the texts "Data-Driven Analysis Tool Plays Critical Role in Climate Neutral Buildings. Advances in Applied Energy" (Ding, 2021) and "Targeting Building Energy Efficiency Opportunities - An Open-source Analytical and Benchmarking Tool," (Li, 2019) offers insights into open-source analytical tools that play a pivotal role in advancing climate-neutral building practices.

- Building Stock Models and Retrofit Focus in Latin America:

  While the research landscape is rich with studies focusing on retrofit strategies in the residential and non-residential sectors across European and North American countries, the perspective is notably limited in the context of Latin America, particularly Mexico. In this regard, the works of researchers such as Luis Eduardo Medrano-Gómez et al. (2017), Miguel Flores et al. (2022), Itzell Torres et al. (2023), and Rodrigo Mercado Fernández et al. (2022) have emerged as pivotal resources. Their research, including non-domestic Passivhaus retrofit proposals, addresses the unique challenges and opportunities of retrofitting in the Latin American context.

In summary, the review of the state-of-the-art literature underscores the critical influence of existing research in shaping the trajectory of this Ph.D. study. By drawing from the insights and methodologies of scholars like Claudio Nägeli, C. Szum, and Latin American researchers specializing in retrofit strategies, the aim of this research is to contribute to the field by developing a holistic and effective Building Retrofit Model that addresses the distinct challenges and opportunities present in the Mexican urban context.

6. Theoretical Framework

As the base framework, it will be taken the process involved in the Whole Life Cycle Assessment (WLCA) (Royal Institution of Chartered Surveyors, 2017). Where the emphasis will be in stage B, considering renovation strategies.

WLCA is used in the assessment of the carbon emissions associated with a building throughout its entire lifecycle, from construction and operation to end-of-life scenarios. This assessment takes into account both operational carbon emissions (related to energy consumption during the building's use) and embodied carbon emissions (associated with the construction and maintenance of the building). When applied to existing buildings, the Whole Life Carbon

Assessment focuses on evaluating the carbon impact of the building's ongoing operation, maintenance, and any potential retrofit activities, which is STAGE B, from 1 to 6 (Figure 4).

This assessment is used to inform decisions about energy efficiency improvements, retrofit strategies, and other interventions that aim to reduce the building's carbon footprint over time.

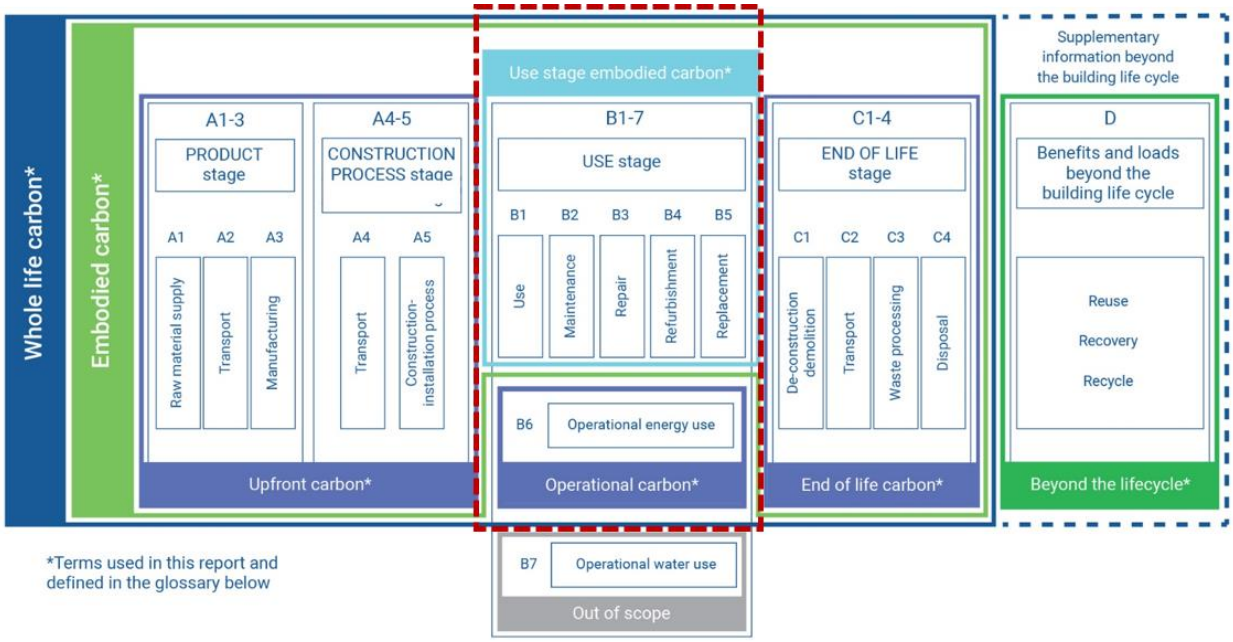

Figure 4: WLCA. World Green Building Council.

7. Methodology

This section outlines the methodology employed to address the complexities inherent in assessing building energy demand and greenhouse gas emissions at an urban scale, particularly in the face of limited information availability. The method is structured into three primary steps, collectively aimed at the creation of an "Archetype Building Information" framework. These steps are conducted iteratively, guided by the pursuit of uncovering an accurate representation of the urban context (Figure 5).

Step 1 – Synthetic Stock Generation: The initial step entails the transition from the architectural to the urban scale, necessitating a paradigm shift to cope with information scarcity. Buildings are treated as fundamental model entities, forming the basis for further analysis. This step's foundational concepts are rooted in the dynamics of building ownership, user behavior, and the probabilistic nature of renovation decisions. The Synthetic Stock Generation process is further divided into three essential components:

- Characterization of the Buildings: This involves defining the key attributes that distinguish one building unit from another. These attributes encompass physical features, usage patterns, and potential retrofit possibilities.
- Building Agents: Incorporating the human element, building owners, and users, into the model adds a layer of realism. Their behavior, preferences, and decisions play a pivotal role in shaping retrofit choices and energy-related strategies.
- Building Stock Initiation: Recognizing the need for efficiency, this substep involves categorizing the urban building stock based on critical characteristics. The integration of sixty-seven buildings from the urban approach aids in refining the process and streamlining subsequent stages.

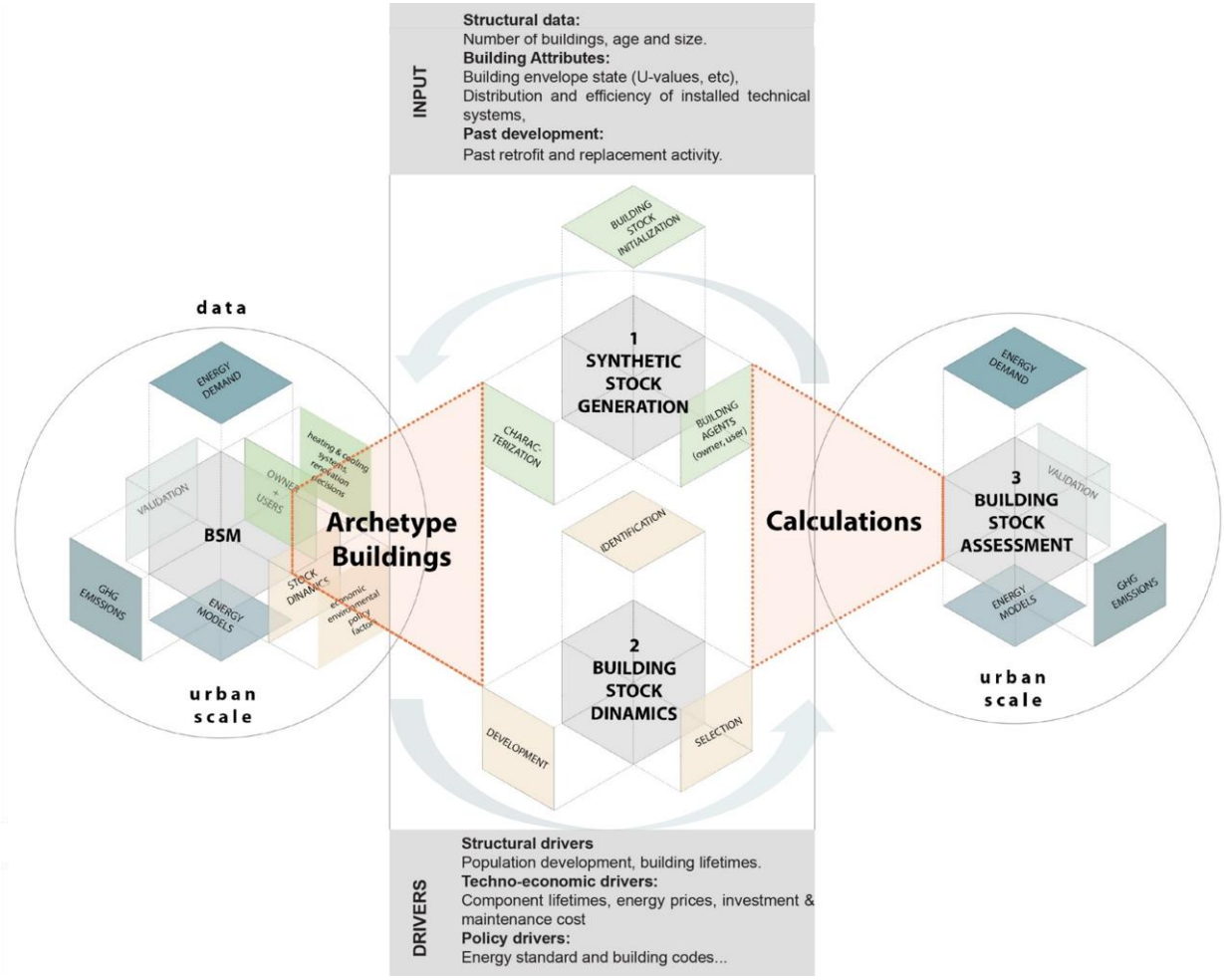

Figure 5: Methodology

Step 2 – Building Stock Dynamics: The second step delves into the dynamic interplay within the urban building stock and its relation to the surrounding environment. The intricacies of this step are informed by economic, environmental, and policy considerations, all of which are intrinsically tied to stock dynamics. Three distinct facets constitute this step:

- Identification of Retrofit Strategy: Each building unit is subjected to a meticulous analysis to identify the most suitable retrofit strategy. Tailoring these strategies to the individual attributes of buildings ensures a contextually appropriate approach.
- Selection of Retrofit Strategy: The benefit-to-cost ratio guides the selection process, underlining the significance of economic feasibility. This step aligns retrofit strategies with broader urban sustainability goals.
- Development of Retrofit Strategy: This aspect considers technological feasibility, policy restrictions, and the availability of market options. A comprehensive strategy emerges from this multifaceted evaluation.

Step 3 – Building Stock Assessment: The final step involves validating the synthesized data and refining the Archetype Building Information framework. This step ensures the alignment of the framework with real-world data and its accuracy in reflecting urban building stock dynamics. The iterative nature of this research process is essential, as it embodies a continuous quest for the most accurate representation of the urban context. The methodology's journey from Step 1 through Step 3 is characterized by iterative refinement, aiming to uncover the inherent truths within the urban building stock dynamics and retrofit strategies. Zooming in on the Building Stock Model, a detailed analysis reveals the fundamental parameters governing energy demand and greenhouse gas emissions.

The pivotal concepts leading to Step 1 revolve around "Owners and Users," their decision-making processes, and their role in shaping the built environment. In contrast, the concepts guiding Step 2 center on "Stock Dynamics," encompassing the intricate web of economic, environmental, and policy factors shaping the urban building landscape.

In summary, this methodology blends quantitative analysis with qualitative human factors, positioning it as a holistic approach to tackle the challenges posed by urban-scale building assessments.

Through these methodological steps, the study aspires to offer decision-makers a robust framework for devising effective retrofit strategies to enhance energy efficiency and mitigate greenhouse gas emissions in urban environments.

Here we have the location and distribution of the Study cases at the Urban Scale, which will be synthetically constructed. They are sixty-seven buildings property of the federal government, located in the Cuauhtemoc District, in the North of Mexico City.

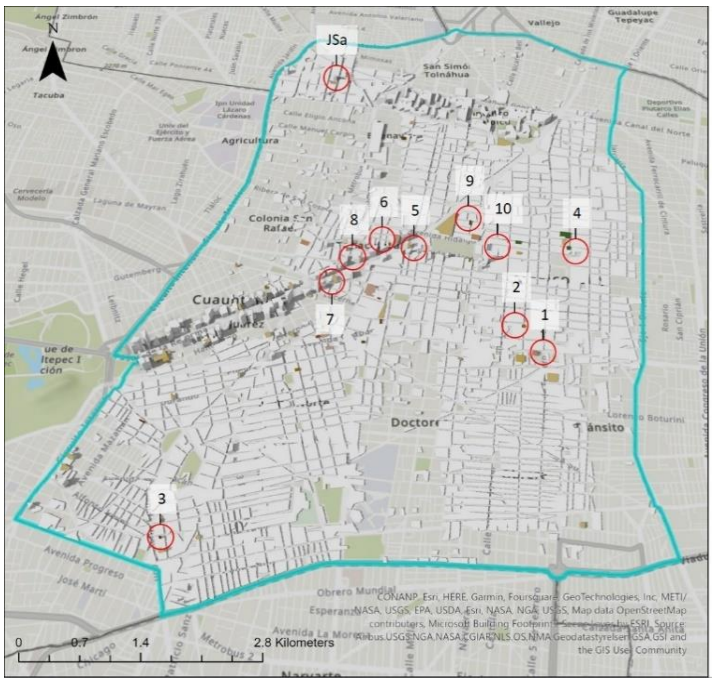

Figure 6: 10 selected study cases

10 BUILDING CASES		Synthetically Modeled	
No.	LOCATION & CONSTRUCTION SYSTEM	IMAGE	FACADE TYPOLOGY & MECHANICAL SYSTEM
1	Fray Servando T. de Mier 135. The facade is made of precast concrete and clear glass. Sides of the building, precast concrete slabs. Steel Structure, slab system made of joists and beams.		3 exposed facades + NO HVAC T3
2	Izazaga 74. Piso 5. The facade is made of precast concrete and clear glass. Sides of the building, precast concrete slabs. Steel Structure, slab system made of joists and beams.		2 exposed facades + HVAC T2
3	Tlaxcala 208. Facade, precast concrete slabs as railings, mirror glass; side of the building, precast concrete slabs. The structure is made of concrete columns, joists, and beams.		1 exposed facade + NO HVAC T1
4	Argentina 12. Stone-based façade, mainly quarry. The structure is made of wooden beams and concrete slab.		2 exposed facades + Historical Building + NO HVAC T2
5	Juárez 101 (Torre Prisma). Facade of mirror glass. Steel Structure, slabs made of joints and beams.		3 exposed facades + HVAC T3
6	Av. de la República 117. Steel Structure, slabs made of joints and beams. Concrete prefab and glass.		2 exposed facades + NO HVAC T2
7	Paseo de la Reforma 116. Facade = Concrete Prefab slabs and tinted black Glass. Steel Structure, slabs made of joints and beams.		4 exposed facades + HVAC T4
8	Paseo de la Reforma 51. Facade = Concrete Prefab slabs and mirror Glass. Steel Structure, slabs made of joints and beams.		4 exposed facades + NO HVAC T4
9	Mina 24. Facade = Concrete blocks covered by textured concrete, blue tinted glass. Concrete Structure, slabs made of joints and beams.		1 exposed facade + HVAC T1
10	Tacuba 1. Facade = stone, mainly quarry, clear glass. Concrete Structure, slab system of joists and beams.		4 exposed facades + Historical Building + HVAC T4

Figure 7: Classification of the 10 selected study cases that will be synthetically Modelled

8. Hypothesis

Within the context of urban sustainability and building stock retrofitting, this study posits that by employing a value-based framework capable of amalgamating building stock performance data with the intricate interplay of Building Stock Dynamics (BSD), municipal decision-making processes can be significantly streamlined. Consequently, the urban environment will be empowered with an efficient approach to assess and compute retrofit scenarios on a citywide scale. The anticipated outcome of this approach is not solely limited to the enhancement of building performance but also extends to encompass Non-Energy Benefits (NEBs) which will be quantitatively appraised, positioning them as indispensable in the evaluation of CO2 emissions.

9. Preliminary Results

The analysis was conducted at two distinct scales: The Architectural level and an initial foray into the synthetic analysis of the selected 10 buildings, which stand as a representative subset of the initial 65-building sample. At the Architectural scale, a comprehensive analysis was undertaken on one of the selected buildings, for which architectural plans were available. This facilitated the input of pertinent information into software platforms like Design Builder and One Click LCA, which were chosen for the analysis. The principal aim was to juxtapose the analysis outcomes with available information against scenarios where information was lacking, thereby illuminating the impact of information availability on the analytical results.

Within the subset of 10 selected buildings, reference data was sourced from the Geographic Information System of Mexico City (CDMX), augmented by direct on-site observations. Key data concepts gathered included Heat Gains, Energy Consumption, Air Velocity, Temperature, and Pressure, as well as Embodied Carbon, Global Warming Potential, Life Cycle Cost, and Life Cycle Assessment (Figure 7). In both cases, the results derived establish the Baseline against which subsequent Retrofit Strategies will be assessed and improved. These forthcoming strategies will constitute the subsequent phase of this research. They will be formulated alongside the consideration of Non-Energy Benefits (NEBs), the Building Stock Drivers influencing Retrofit Strategies (encompassing Economic, Environmental, and Policy considerations), and Building Owner Information—bringing an economic dimension to cooling, envelope enhancements, and system modifications.

Preliminary findings indicate a consistency in energy demand behavior among buildings of similar typologies. This discovery serves as a pivotal point in the methodology to define these shared patterns. The difference ratio between baseline and recommended energy demands by ASHRAE, while variable, exhibits a distinct trend across building types, laying the groundwork for a nuanced understanding of energy consumption within specific architectural contexts.

In sum, the examination conducted on the Architectural scale, as well as the preliminary synthetic analysis of the subset of 10 buildings, has furnished foundational insights. This serves as a springboard for the imminent phase of devising Retrofit Strategies and integrating comprehensive considerations that extend beyond mere energy, delving into the intricate nexus of economic, environmental, and policy drivers that influence the urban building stock. By merging these insights, the study aims to establish a robust framework for enhancing energy efficiency and sustainability across urban building stocks while considering the holistic panorama of impacts and benefits.

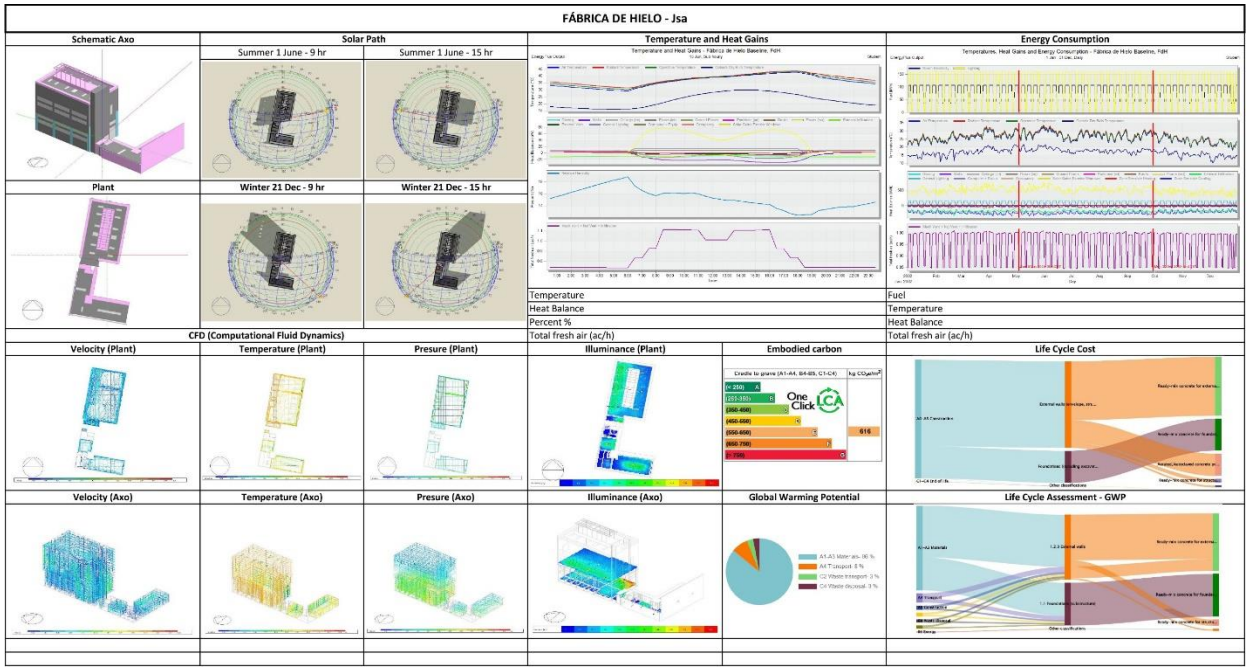

Figure 7: Analysis of the Building on an architectural scale.

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Ethics approval:

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Conflict of interest:

The authors declare that there is no competing interest.

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