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Improvements to the Prototypal Approach to Rural Social Housing in Colombia Using Life Cycle Analysis

Evaluation of alternative construction envelopes for six different prototypes

Supervisor:
Jean-Marc TULLIANI
Co-Supervisor:
Roberto GIORDANO

Candidate:
Daniel MANTILLA ARIZA

Abstract:

The current investigation suggests a solution by employing an LCA or Life Cycle Assessment methodology in the approach to prototypes for the rural social housing context in Colombia. It evaluates the LCA as a tool in the decision-making process of material modifications to six different cases located in different regions of the country and proposes a holistic evaluation of different parameters that range from environmental impact, user comfort, local weather information and project localization which aid the analysis and showcases the potential for quality-of-life improvements for said projects.

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2. Introduction

2.1 Context

Social housing in Colombia has historically been managed in diverse ways by the government. Initially, it was managed and promoted through initiatives such as the ICT[1] or public entities like the BCH[2], which not only financed projects for the construction and improvement of social housing, even in rural contexts, but also promoted them and ensured their integral development. However, starting in the 1990s, the state changes its role from being a promoter to being a regulator of the housing market (Ceballos, 2006). Instead of alleviating the existing deficit, this worsened the situation, as the quality and state of housing began to be driven by market dynamics, fostering a housing deficit that is not only quantitative but also qualitative (Ramos, 2012), DANE (2022). This research proposes to address this issue through the application of Life Cycle Assessment (LCA) to the prototypal approach to the formulation of rural social housing.

Therefore, this research is framed within the field of rural social housing in Colombia, which, historically, has been precisely subject to a qualitative deficit (Saldarriaga & Fonseca, 1980), which is exacerbated by forementioned problematics, and has not been possible to resolve. Currently, of the rural housing deficit in Colombia, which stands at 68.2%, 47.5% is qualitative, and 20.7% is quantitative, according to the latest quality of life survey by DANE (2022). Consequently, one of the approaches that the state has faced in this situation was to create a public policy designed to subsidize rural housing projects known as PPVISR[3]. It also produced the National Plan for Construction and Improvement of Rural Social Housing – from now on **PNVISR** as named by MinVivienda[4], (2021). Which proposes various housing prototypes and guidelines for approaching their formulation and general improvement of existing housing.

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[1] Instituto de Crédito Territorial (Territorial Credit Institute)

[2] Banco Central Hipotecario (Central Mortgage Bank)

[3] Política Pública de Vivienda de Interés Social Rural (Public Policy for Rural Social Interest Housing)

[4] Ministry of housing in Colombia

Nonetheless, the PPVISR norm and prototypes within the PNVISR are formulated in a generic way that does not provide a clear formulation path for developing this type of housing, constructions whose development should be especially sensitive to the context and existing conditions as indicated by various authors and the PNVISR itself in one of its sections. This is reprehensible, given that within this plan, it is repeatedly stated that projects must be adapted to the culture and populations of each region, as well as to their specific needs given the geographical conditions (Minvivienda, 2021).

2.2 Investigation avenues

Therefore, this research recognizes vernacular architecture as one of the alternatives to be evaluated in the field, given that literature suggests and intuits how, through this type of architecture, issues associated with social housing can be addressed, as will be elaborated in the present document. Additionally, the fundamental issues recognized within the field of social housing can be defined under the categories of habitability, sustainability, and even cultural value. These issues result from the role that the state has assumed and the management of the industry in general. An added problem is the fact that this area of knowledge in vernacular construction, which has been passed down from generation to generation, is progressively being replaced by industrialized construction methods, process noted by Saldarriaga & Fonseca, (1980) and continues to this day (Anzellini & Garcia-Reyes, 2019).

Therefore, in this project arises the interest in parameterizing and analyzing possible vernacular techniques and incorporating them into the methodology along with other innovations with a higher level of technology, such as lightweight construction with panels and insulation layers, all for the improvement of housing prototypes.

2.3 Unit of analysis

It is worth noting that the non-structural envelope of the house is recognized as the unit of analysis, the artifact on which improvements and changes will be proposed, while the structural elements will remain the same within the study. This is because the structure is rigidly defined by the seismic resistance standard NSR-10 (Asociación Colombiana de Ingeniería Sísmica[5], 2010). Similarly, the proposition of different structural systems would add more variables to the present analysis, detracting from the clarity of the differences that may exist between diverse types of envelopes, which is the focus where the dynamics culminate, as will be discussed in the theoretical framework, reflecting advantages and issues. It should be added that the environmental impact between different structural systems in an LCA study has already been analyzed in works such as that of Zea et al., (2018).

This document will commence by establishing a theoretical framework to elucidate key concepts employed throughout the text. A comprehensive literature review will follow, shedding light on the current state of research within the subject area. The rationale behind the chosen methodologies will be articulated, primarily informed by insights derived from the literature review. Subsequently, we will develop an LCA methodology to evaluate different scenarios relating to rural housing prototypes, culminating in their interpretation and analysis.

[5] Colombian Association of Seismic Engineering

3. Theoretical Framework and Hypothesis

3.1 Hypothesis

From the issues, evidenced in the literature review and official sources, arises the hypothesis that Life Cycle Assessment (LCA) can be implemented in the prototypal approach to the formulation of rural social housing to support design decisions that enhance living conditions for users and mitigate its environmental impact.

However, in this statement, there are terms that are worth reviewing and defining to have a clear concept of their use and context throughout this text.

3.2 Definition of the Life Cycle Assessment and its use in Colombia

Life Cycle Assessment (LCA) in Colombia is still a frontier in the field of research and knowledge production. The ISO 14040:2006 standard defines it as the collection and evaluation of inputs, outputs, and possible environmental impacts of a product system throughout its life cycle. Similarly, this approach is used by the European directive 2010 31 /EU (EPBD recast) and the subsequent regulation 244 2012, which defines energy efficiency as an objective to be achieved during the life cycle of a construction. "The four steps of this methodology are defined as: goal and scope definition, inventory analysis, impact assessment, and interpretation" (International Standard Organization, 2006).

In the Colombian context, the Energy Efficiency Law EE n. 697 of 2001 is developed, stating: "The Rational and Efficient Use of Energy (URE) is declared a matter of social, public, and national convenience." However, there is no mention of the life cycle concept, and no foundations are established for the evaluation of energy efficiency, especially in the specific field of construction. This absence may be one of the potential reasons for the current scarcity in Colombian research regarding the LCA approach in the housing construction sector. Similarly, in regulations associated with the development of rural social housing in Colombia, there is no mention of this law or the concept of energy efficiency.

3.3 Definition of Rural Social Housing and its regulatory management

Under the regulatory framework, the State defines rural social housing as "The social interest housing located on land classified as rural (…) that adjusts to the ways of life in the countryside and recognizes the characteristics of the rural population " (MinVivienda, 2020). This definition is vague, as it allows it to be defined solely by its value and location. In contrast, Saldarriaga & Fonseca (1980) discuss how rural housing in Colombia is defined not only by its value but also by the composition of the household, ways of living, building, and interacting with the environment of each region. They finally recognize that a housing unit is not just that; it is also a productive and cultural unit. Sánchez-Quintanar and Jiménez find something similar when they speak of rural housing as an "eminently active and interactive organism with the natural, built, and community environment, constituting an inheritance, not only cultural but also emotional and cohesive support for families" (2010 p. 175). It becomes evident that the State's definition of rural housing is insufficient, an assertion reached by Acevedo & Hurtado (2022, p. 110).

Additionally, this recent definition of rural housing is not the only issue that has arisen from the government regarding the management of this type of housing. Guardiola and Velandia (2020) discuss how during the period from 2014 to 2018, the management of this administration occurred in a disjointed manner, mainly because it was not under the responsibility of the Ministry of Housing. Instead, it was managed by the Ministry of Agriculture, where it was one of several initiatives overseen by this government entity. Initially, there was a single proposed prototype of rural housing. Later, under the approach of the Ministry of Housing and the PNVISR, six reported prototypes emerged, formulated from 105 community workshops involving 960 actors from various sectors. The proposed prototypes are homogeneous in terms of architectural language, the wall configuration is similar but plausible to replace with varied materials. The six prototypes only present differences in their programmatic distribution and vertical and horizontal dimensions.

3.4 Vernacular Constructions and their context in Colombia

The emergence of vernacular constructions is inherent to all places globally; however, in each location, it develops with highly distinct characteristics, responding to its context and conditions (Rudofsky, 1967). Anzellini & García-Reyes (2018) add to this statement by saying, "Rural vernacular architecture is not necessarily 'architecture without architects'; it is architecture slowly and respectfully inserted into the territory, integrating into the landscape without changing or obstructing it" (p. 45). The vernacular refers to the local but also to the cultural, as the built environment logically responds to modes of living and the conditions and resources offered by the natural environment. The modes of living are the sphere in which culture is embedded (Saldarriaga, 2010) & (Sánchez, 2007).

In Colombia, the use of earth is predominant in vernacular constructions, either from a pre-Columbian perspective (Sánchez 2007) or in the present day, as indicated by Angulo & Carreño (2017): "In our country, wattle and daub, rammed earth, adobe, and Compressed Earth Block (hereinafter CEB) are prevalent, and with these techniques, 90% of our country's vernacular heritage has been built" (p. 33). It is precisely the use of earth techniques that the State initially leveraged in 1957 to create prototypes of rural houses for the highlands, in collaboration with the Inter-American Housing Center.

Figure 1: Photography – Traditional rural house wall construction with adobe block technology - Sogamoso, Boyacá, 2022

3.5 The envelope of architecture

The concept of the envelope in architecture is explored by various authors, with one of the most prominent being Peter Zumthor (2006). He discusses architecture as a body that has skin, where this skin, beyond being a surface, is a membrane, a fabric, or velvet that divides the universe between exterior and interior. This aligns with Semper's (1860) textile definition of architecture, describing architectural practice as a textile one, where the primary action is weaving elements that form a barrier and construct the architectural body. Additionally, Villazón & Rodríguez (2020) refer to the envelope as the barrier that translates external environmental actions into tangible indicators: structural function, acoustic comfort, lighting comfort, thermal comfort, and air tightness.

3.6 Current Environmental Issues and Rural Housing in Colombia

As indicated by the UN report, the construction sector is responsible for 37% of CO_2 emissions on the planet, and 46% of the energy used annually is allocated to construction. On the other hand, Acevedo & Hurtado (2022) state that the serialization of rural housing under current regulations leads to the use of common industry materials (concrete, steel, fired clay bricks), which have an embedded CO_2 emission load that negatively impacts the environment. Susunaga (2013) and Luna (2014) also mention that the use of these materials creates environmental issues, involving the pollution of water sources and the removal of the upper vegetal layer, exposing chemicals and heavy metals that adversely affect the development of plant and animal life. In a previous study, Acevedo et al. (2012) note that 20% of the total energy consumed by a building is used during its construction, which is why changes in this process can lead to significant improvements in terms of total energy consumption and pollution.

Figure 2: Photography - Industrialized Materials used in the construction of housing in rural areas - Acacías, Meta, 2022

3.7 Previous Works

The quest for adaptations in the field of social housing has been explored previously. Flórez (2017) conducted research to assess the bioclimatics of peripheral affordable housing and potential enhancements through the implementation of prefabricated panels. Likewise, Calderón (2019) explored the possibility of improving thermal comfort in self-built environments using sustainable materials, even proposing it through earthen materials.

Innovation in earthen construction has also been addressed. Yamin et al. (2007) worked on adaptations for houses made with these materials, making them safer in the event of an earthquake. Astudillo & Vacacela (2015) similarly seek to reconnect the industry with traditional construction techniques like bahareque by proposing a prefabricated panel, which also serves a load-bearing function. In Ráquira, Colombia, Beaudu & Conforti (2017) reached a similar proposal. Through available information and workshops with the community, they suggested a wattle and daub or bahareque panel, the frame of which can be prefabricated in a workshop and then transported on-site to be completed by the community and local skilled workers.

Regarding the development of Life Cycle Assessment (LCA) in the construction sector in Colombia, four main works with relevance to the current research were found:

The first of these is particularly significant: Ortiz et al. (2006) compared a house in Spain with one in Colombia, using generic databases and generalized energy models for both countries. This work is referenced by authors like Rivera (2020), who conducted an LCA in Bogotá to predict carbon emissions caused by the construction of affordable housing within the metropolitan area. Since the number of Environmental Product Declarations (EPD) in the local construction product sector is still scarce, the use of generic databases like *Ecoinvent* plays a crucial role. These are generic but localized data, meaning they apply the specific electricity mix of Colombia as well as specific data on transportation and energy in the region.

Another relevant work is that of Zea et al., entitled "Industrial or Traditional Bamboo Construction? Comparative Life Cycle Assessment (LCA) of Bamboo-Based Buildings." This study implements a comparative approach between different construction technologies such as bamboo and concrete. An important aspect is the consideration of different transport distances from production centers of the various materials used. This geographical knowledge about the economic systems of each region is also reflected in the work of Suárez et al. (2021) when analyzing the environmental impact of Construction and Demolition Waste (CDW).

4. Literature Review

4.1 Habitability of Rural Social Housing and its management by the State

In addition to the approach based on PPVISR, the State has taken an architectural prototype approach that has been evident since 1957 (Sánchez, 2007) and has continued to the present day, as evidenced by Guardiola & Velandia (2018). They identify various prototypes created by the Ministry of Agriculture and the Agricultural Bank; entities responsible for their design but faced implementation challenges. This situation persisted until a change in management, where the Ministry of Housing took control of rural housing development. A similar strategy is currently employed by MinVivienda, supporting projects proposing prototypes for municipalities or regions with VISR and VIPR[6] subsidies. However, the issues arising from this approach are noted by Acevedo & Hurtado (2022), indicating that regional generalization leads to decontextualized architectures with habitability problems.

Following the same line, Manrique (2021) points out how these prototypes should improve the habitability and health conditions of their inhabitants, creating homes that, in his words, are biosafe. Giraldo (1992) also had contributions to that idea previously, by stating that rural homes should also be equipped with spaces for communal activities that encourage interpersonal relationships and constructive leisure. The initiative to generate suitable housing prototypes is also reflected in the PNVISR produced by the Ministry of Housing (2021). It demonstrates a justified and clear intention to establish precise guidelines for the construction of VISR, such as climatic and geographical adaptability, acoustic and thermal comfort, durability, construction systems related to cultural context, and minimal maintenance costs (p. 67).

Thus, Ceballos (2006) asserts that the habitability conditions in social housing are precarious, a fact also highlighted by Ramos (2012) when discussing low-cost housing conditions, and even Saldarriaga & Fonseca (1980) when stating that the

[6] Social interest rural housing and Priority interest social housing respectively

housing deficit in rural areas is not quantitative as in urban contexts but largely qualitative, concerning the quality of the space. Acevedo & Hurtado (2022) make a similar claim; the generic design of spaces requires users to make adaptations for them to be usable. For instance, in the indigenous reserve in Apartadó, residents often had to construct volumes attached to the original building or even cook outside their homes due to the precarious habitability conditions of the provided constructions. In terms of adaptation, this aligns with the statements of Flórez (2017), who discusses how bioclimatic solutions in social housing are often inefficient, leading users to make adaptations such as adding active heating systems in the best cases.

On the other hand, Flórez (2017) and Calderón (2019) propose the use of the ASHRAE measurement system for the hygrothermal qualities of spaces in social housing. They find that this method considers a range of factors affecting human comfort in the space, such as temperature, thermal radiation, humidity, and even air velocity. Another measurement alternative is reflected in the EDGE platform, created to increase the accessibility of users to apply to the *Excellence in Design for Greater Efficiencies* EDGE certification, increasingly used in the Colombian context due to certification opportunities (Beltrán & Bakht 2018). Similarly, within the platform it is possible to assess the thermal comfort of users, this time through the calculation of the thermal transmittance of the materials in the built environment and the local climate. These parameters impact the hours of comfort depending on the user type and are reflected as energy demand. Marzouk (2023) describes this tool as convenient and accessible due to its iterative nature and ease of model construction.

4.2 User well-being and health related to its living conditions

Regarding the well-being of users, consulted authors have a clear stance when it comes to the role of architecture, firstly, health and well-being is considered the final goal for all constructions, since the real purpose is for users to inhabit them, as Manrique, et al. (2021) put it: ”The hygiene and health conditions both inside and outside the home determine the application of envelope systems that generate optimal microenvironmental conditions to ensure human health and establish mechanisms of protection against harmful external agents to health" (p, 61) where it is exemplified how the health conditions of users should the driving factor behind the rest of decisions made regarding the development of housing, and not a byproduct of decisions made with other purposes such as; but not limited to, monetary gain as Ceballos, (2006) points. Additionally, Flórez (2017) also points to the idea of specifically social housing being made with this in mind, since the search for economic feasibility endangers the capability of the home to provide well-being for its users.

4.3 Environmental Sustainability of Rural Social Housing

For the evaluation of sustainability in social housing, multiple methodologies are used. Initially, there is an approach through certifications such as the LEED (Leadership in Energy & Environmental Design), which have been implemented in the country and have motivated the construction industry to incorporate innovations towards sustainability (Susunaga, 2013). Besides its widespread use worldwide, there is certain criticism in the sector. Firstly, Suzer (2015) questions the LEED certification ability to evaluate sustainability in a context outside of North America since environmental concerns differ depending global location and its application is generalized with little adaptations to the assessment method. Additionally, Giannetti et al., (2018) find that, in this specific context, evaluating sustainability solely based on the certification approach is ineffective when considering the varied factors that influence the development of rural social housing, which can escape the scope of a weighted point system that awards credits based on specifical goals.

On the other hand, there are holistic approaches, such as emergy accounting. This concept is defined by Odum (1996) as: "the total amount of available energy (or exergy) of one kind that is used up directly or indirectly in a process to deliver an output product, flow, or service". Said author also proposes this methodology because it is useful for comprehensively evaluating systems with various inputs and outputs of energy, waste, and products. Gianetti et al., (2018) use it to compare the impact of different rural housing projects in Brazil. Along the same line, Reza (2014) uses Em-LCA (Emergy Accounting integrated with LCA) for the analysis of single-family and multi-unit homes, also facilitating a holistic and comparative approach to different housing projects.

Alternatively, Lárraga et al. (2014) use the distance to construction resources as a sustainability parameter, whether it is the distance to natural resources or the distance to industrial material production centers. This aligns with Giannetti et al. (2018) since the distance to resources implies how much energy it will take to transport them and what type of resources they are, consistent with the work of Zea et al. (2018), who through this idea, confirms that industrial production centers are not commonly closer than local natural resources, as also affirmed by Acevedo et al., (2012).

The distance to resources and production plants analyzed through the LCA methodology, as discussed in this document, is a common scope across the different reviewed works, such as Ortiz et al., (2018, p. 2441), Rivera, (2020, p. 30), and Zea et al., (2018, p.4). In some of these cases, the LCA approach allowed highlighting how even if the CO_2 load increases due to transportation associated with the reuse of materials before or after their use in each project, their recycling positively favors the net results of the respective impact categories, as evidenced in the work of Suárez et al. (2021) and previously mentioned Zea, in which the reuse of stone materials is crucial to improving the analysis results.

4.4 Vernacular Architecture

A vital component of rural housing, as mentioned by Saldarriaga (2010), is culture. Similarly, Rudofsky (1964) speaks of ancestral knowledge passed down through generations, related to how to inhabit and build the environment, which is specific to each region. Heidegger (1951) precisely discusses how inhabiting an environment or space is constructing it and how this implies nourishing this space over time. Thus, to inhabit a space optimally, one would have to build and care for it with that vision. This aligns with the findings of Anzellini and García-Reyes (2019) when they discuss the rootedness generated through community participation in the construction of their environment and how this participation creates a connection with the territory and their own culture. All these perspectives contribute to the definition of Vernacular Architecture.

In parallel, in rural social housing, there is a gap in terms of this cultural connection, as the homogenization of houses, as proposed by the government, produces architectures that are foreign to the landscape (Anzellini & García-Reyes, 2019). This was also pointed out by Saldarriaga & Fonseca (1980) when observing the trend of industrialization in rural housing. They warned that the construction knowledge specific to each region could disappear, and consequently, the cultural value of housing along with it. Following the same line, Acevedo, & Hurtado (2022) note that the current practices promote a lack of recognition of regional construction technology. In their case study area, they found that there is a heritage associated with construction techniques such as 'bahareque' wattle and daub, compressed earth block, and bamboo construction. This heritage was not taken into account by the housing promoter in the studied region, according to their on-site studies.

Additionally, vernacular construction has a historical relationship with the country's culture, as mentioned by Sánchez (2007). The Spanish settlers imported an adobe construction culture, enriched by indigenous wattle and daub construction techniques. In contrast, Zuleta (2011) puts vernacular construction in an international context, providing examples of how it is significant for the culture of other regions and how it produces architecture that is durable over time. On the other hand, Vargas-Rubiano et al., (2007) illustrate the context of adaptations of earthen construction in the country by incorporating cement as a stabilizer to achieve more resistance in the earth components used in construction. This exemplifies the adaptation of techniques discussed by Fathy (1986), explaining that architecture can be renewed and enriched by modern techniques while simultaneously validating traditional methods established by our ancestors.

The adaptive intention reflected in Fathy's work (1986) can also be observed in specific cases in Colombia. Arroyave et al. (2021) primarily studied the positive environmental impact generated by the implementation of Compressed Earth Block (CEB) in rural housing construction. The vernacular architecture is not necessarily something "untamed" (Rudofsky, 1964). On the contrary, Anzellini and García-Reyes

(2019) demonstrated that the knowledge of a region can be articulated with the academic, disciplinary, and technical knowledge of architects and engineers. Moreover, if done appropriately, it can even be safe against seismic movements, as proven by the earthquake-resistant adaptations of Lacouture et al. (2007) whose experiments proved that adding simple modifications such as a welded mesh, which will perform efficiently under tensile stress, can improve the envelope’s behavior under seismic movements. Similarly, the "domestication" of traditional and vernacular construction techniques is evident in the work of Zea et al. (2018), who expose the technology and industrialization of materials such as bamboo and its use in an industrialized environment.

Figure 3: Photography - Bamboo construction present in the rural context of Colombia - Acacías, Meta, 2022

4.5 The Envelope of Rural Social Housing and Experimentations

Both Beaudu & Conforti (2017) and Astudillo & Vacacela (2015) proposed experimental prototypes for social housing in Ráquira, Colombia, and Cuenca, Ecuador, respectively. Both arrived at prefabricated prototypes of wattle panels, as a common goal was to reach a versatile construction system. The main difference between the two is that in the Ráquira study, there was collaboration with the local community, from which key knowledge emerged to propose the prototype, while in Cuenca, the study took place in a laboratory, testing materials and choosing the configuration that resulted in better hygrothermal conditions.

5. Justification

5.1 Main and Specific Research Questions

From the presented literature review specific questions arise, most importantly, the main question is the following:

How can the prototypal approach to rural social housing in Colombia be enhanced?

This main question arises from concerns generated by the authors at various points in the review, as well as from the repeated attempts by the government to implement a prototypal methodology for rural housing in Colombia, making it worthwhile to reevaluate this process and seek alternatives for its improvement. Following this main question, subsequent secondary questions are pondered:

- What technologies can be implemented in the envelope of rural social housing to improve its sustainability and thermal comfort conditions?
- What virtues exist in the envelope of vernacular construction as improvement strategies for the qualitative deficit of rural social housing?
- What indicators can be used to measure and quantify parameters of sustainability and thermal comfort?
- In what way can each prototype be informed by its immediate context and respond to specific needs of each region?

With the goal of addressing these concerns, the following justification points are elaborated:

5.2 Prototype Evaluation and improvement.

In this project, the prototypes of housing proposed by the state in the PNVISR will be evaluated, as they represent the most recent proposal for rural housing made by a public entity. It provides a robust number of options, six in total, for units to be evaluated. As mentioned earlier, these prototypal units are proposed homogeneously, diversifying only the horizontal distribution of the program, which presents various typologies across the different options. It is appropriate to assess improvements and changes to these prototypes considering the local conditions in which they will be located. These conditions are inspired by participative workshops conducted by the government, where representatives from various departments had the opportunity to vote for the prototype to be applied in their respective regions.

Consequently, the act of choosing prototypes for each region can be understood as a representative and not necessarily significant act since each prototype has similar materiality and program conditions, with form and distribution being their only differences. Nevertheless, this research will consider these locations resulting from participation as a starting point for the six possible locations of the different prototypes. This approach operationalizes the previous participative exercise, evaluating the conditions that each base prototype would adopt in its respective region. As Giraldo aptly mentions: "There is a noticeable belief that the improvement of housing comes spontaneously with economic progress, which is a mistake. This improvement must be planned and programmed with the participation of the rural inhabitants" (1992, p. 14).

5.3 LCA Methodology implementation

As evidenced in the literature review and the theoretical framework section, there is a scarcity of studies that have implemented life cycle analysis in Colombia in the field of construction. One of the purposes of this research is to advance this existing frontier in the academic field and, with greater justification, apply it to the context of rural housing prototypes in Colombia. These prototypes can benefit significantly from implementing a system that allows evaluating local conditions concerning geographical position, climate, and available materials. Additionally, contrasting this information with data associated with thermal comfort, viewed in terms of energy demand, can provide greater insights into the various feasible options, and assess the existing condition of each prototype.

Furthermore, a life cycle analysis (LCA) approach relies on information existing in the industry in Environmental Product Declarations (EPDs) that each manufacturer produces with the intention of achieving certification (Andersen et al., 2019). Therefore, encouraging the sector to increasingly adopt such proposals can be beneficial. Housing development stakeholders could begin to see the results of implementing these models, especially considering the growing interest in sustainability and certifications in the sector. This would drive producers and distributors of products to apply for certificates and produce more EPDs, enriching and making the LCA analysis more accurate. To date, in developing countries, it relies on standardized and localized data under statistical models, as evidenced by the works of Zea et al. (2018), Suárez et al. (2021), Rivera (2018), and Ortiz (2006).

Finally, the dimension of time within LCA is what defines it; the ability to analyze different scenarios in the future is crucial in the context of rural social housing and sustainability. LCA can precisely provide information about the impacts of each phase of project development, which, in itself, is beneficial for the environment, promoters (Cruz & Finnegan, 2021, p. 8), and even end-users. Given the context of housing, these end-users exhibit a degree of vulnerability that warrants decent and optimal living conditions, as asserted by Ceballos (2006) and Ramos (2012).

5.4 Changes in the Housing Envelope

Therefore, in the present research, the LCA model will be used as a framework for decision-making since it provides the ability to compare different futures that a project can assume, primarily by changing construction technology and material usage strategies both in its initial phase and at the end of its life cycle. In the context of prototypes, this is enriching as it allows for the comparison of different prototype options and reaching an optimal decision, informed by the following parameters: user comfort, location, access to materials, local climate, and environmental impact.

Specifically, the proposal and changes to be evaluated will focus on the envelope of the dwelling rather than any other component of the architectural object, as it is from this component that one can infer the performance of each housing unit in the parameters described above as defined in the theoretical section. Moreover, it is a component that can be replaced without structurally affecting the construction. With the added value of having the capacity of implementing changes in a progressive way since the envelope can be replaced on different instances.

6. Methodology

6.1 Presentation of Prototypes and their context

VSRL	VSRC1	VSRC2	VSRT	VSRU	VSRA
					

Figure 4: Overview of Existing Prototypes proposed in the PNVISR.

In this research, improvements will be evaluated and proposed for the six prototypes presented in the PNVISR: VSRL, VSRC1, VSRC2, VSRT, VSRU, VSRA, located in six different rural areas in Colombian territory. This selection of areas was determined by the participative process involved in the development of the PNVISR. However, this selection is understood as non-binding and instead, the present study aims to have a diverse and representative sample of the various climates existing in Colombia. In the case of this investigation, a region did not have an assigned prototype in the current plan and was given one, as in the case of Guainía.

Initially, digital models of the prototypes were developed using information obtained from the annex to the PNVISR, where floor plans and information about the program of each dwelling in square meters were obtained. These models were developed using BIM software, with the aim of extracting information primarily associated with material quantities, both volumetric and in terms of weight, area, and length, respectively. Each prototype's main characteristics and materials are represented in the following way:

VSRA - Villagarzón, Putmayo

This prototype as well as the rest are projected for 6 users in total and with three bedrooms. This one specifically has the quirk of having an open corridor with no envelope, making the actual exterior walls also appear on top of the slab in the middle of the construction. Located in Villagarzón, Putumayo. A zone of tropical monsoon “Am” climate in the Koppen classification, located in the andean amazon foothills.

Areas

Bedroom	22 m²
Toilet	2.8 m²
Kitchen	6 m²
Living	5 m²
Corridor	10 m²
Laundry	1.2 m²
Tool room	1.2 m²

Total utilized area: 55.2 m²

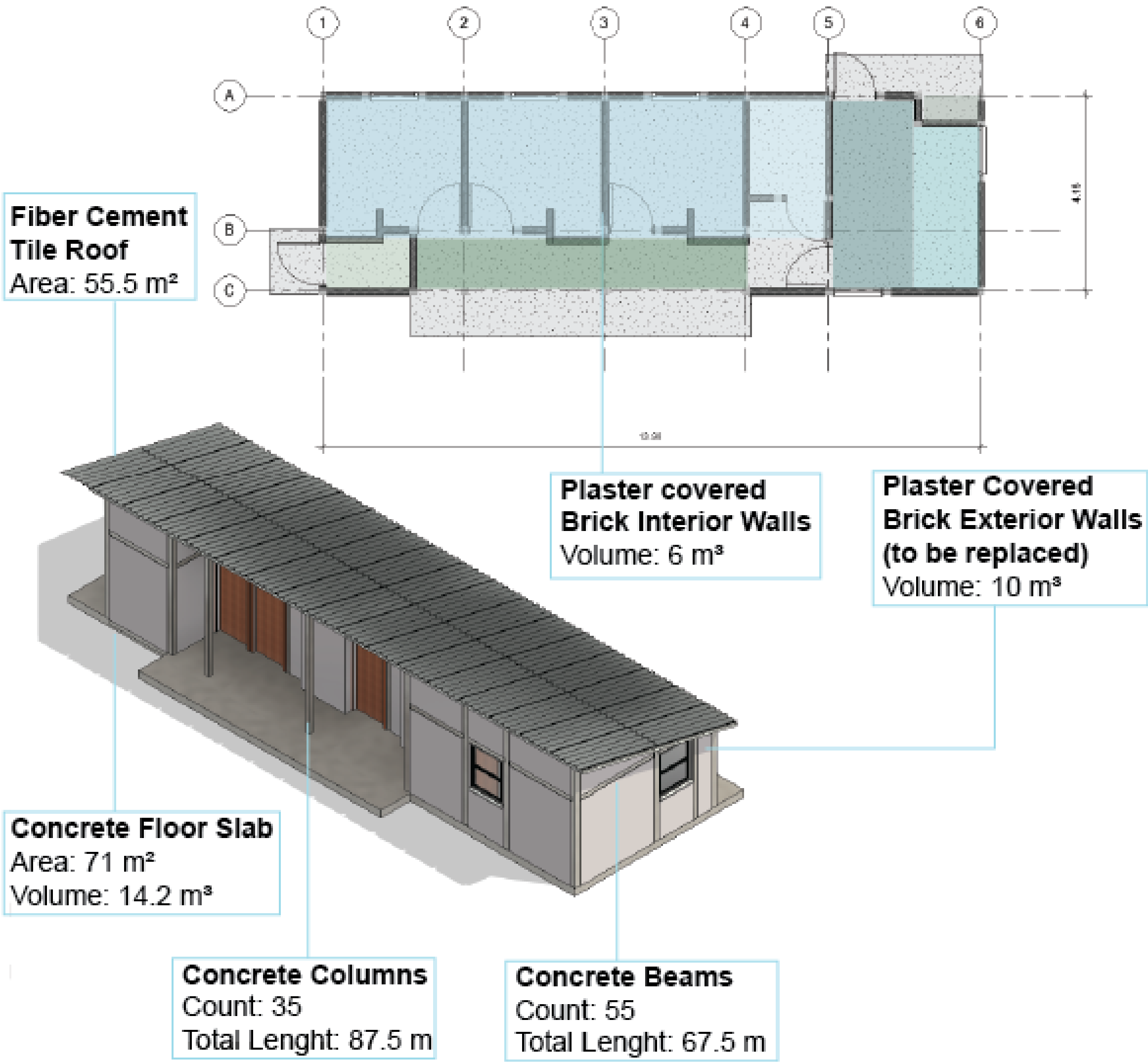

Figure 5: VSRA Prototype information sheet.

In the participative process made by the government, the VSRA prototype was chosen by the region of Putumayo, hence its location in Villagarzón in the current document, a municipality located twenty kilometers away from the region’s main capital, Mocoa. Throughout the year the temperature can vary from 20°C to 30°C, there is no significant variance in weather from typical seasons since the country is located in the tropic zone of the globe. Nonetheless, the region has a hot season ranging from August to October, and a relatively cool season from May to July.

It is also worth noting that while it is true that the municipality has a certain number of comfortable hours yearly, the temperature outside is mostly within the hot uncomfortable range, making it necessary to implement strategies, be it active or passive, to reach a comfort target within buildings.

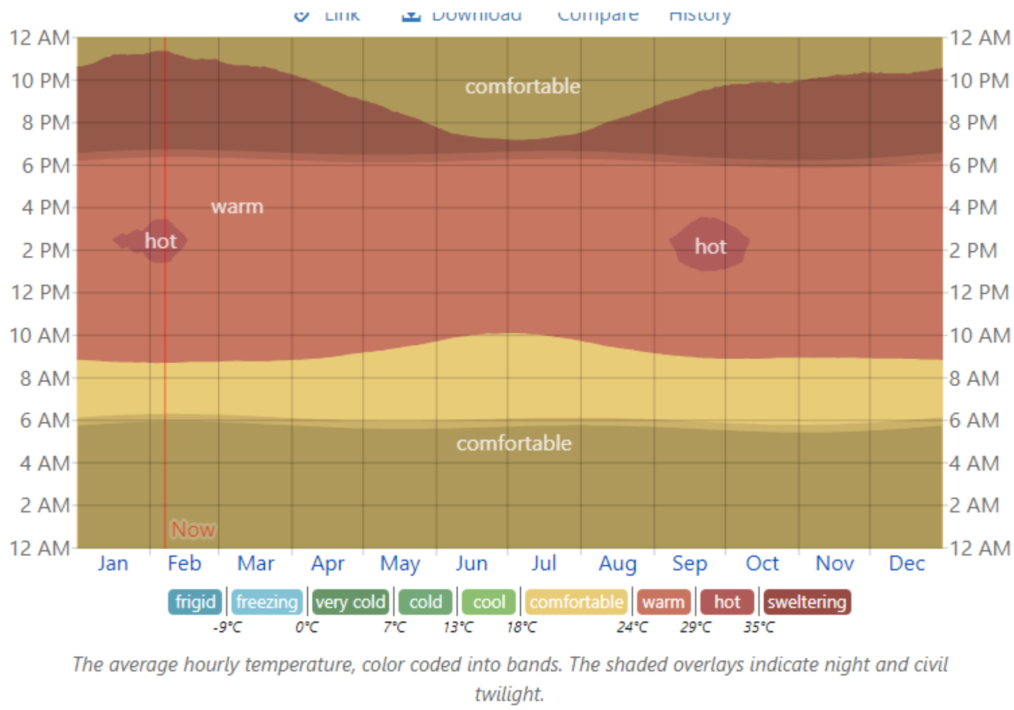

Figure 6: Average Hourly Temperature in Villagarzón, taken from: https://weatherspark.com/y/21461/Average-Weather-in-Villagarz%C3%B3n-Colombia-Year-Round

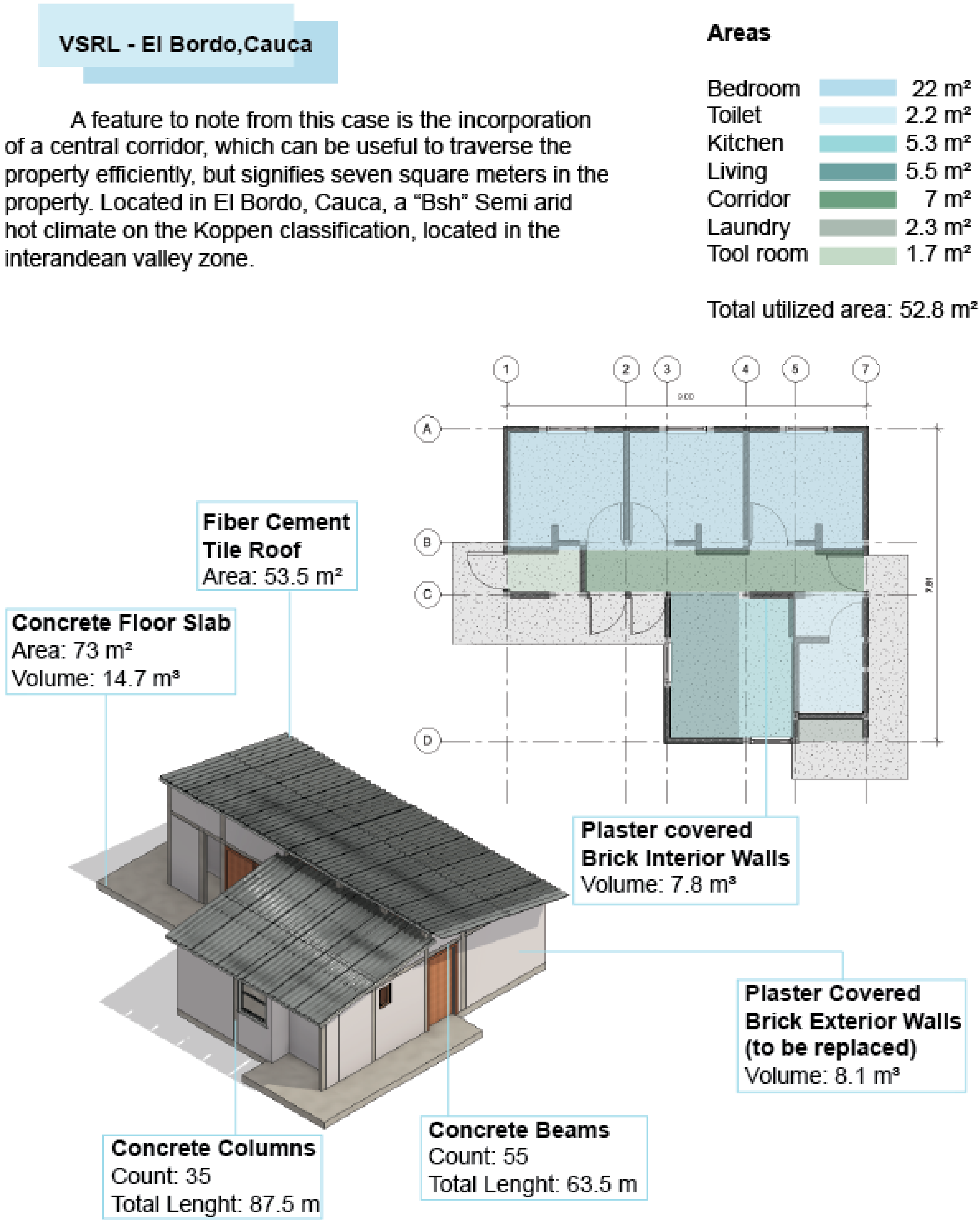

Figure 7: VSRL Prototype information sheet.

The VSRL Prototype location is also defined from the previous participative process done by the government, being the Cauca region one of the regions that opted for this construction. In this case, a wider range of transportation was preferred while also maintaining limited vicinity to the region's main capital, Popayan, with the goal of keeping the same weather conditions from the data location used in the study, point which will be elaborated when presenting the EDGE tool within the methodology. Over the year, El Bordo has a temperature range of 19°C to 31°C, having a hot season of two months from July to September, and a cool season from October to January.

While the mornings can be within a range of 18°C to 24°C which is defined as comfortable by most standards such as the ASHRAE, later hours present warmer temperatures during the day, also granting the usage of cooling strategies to guarantee a temperature target with the aim of providing comfort for the user.

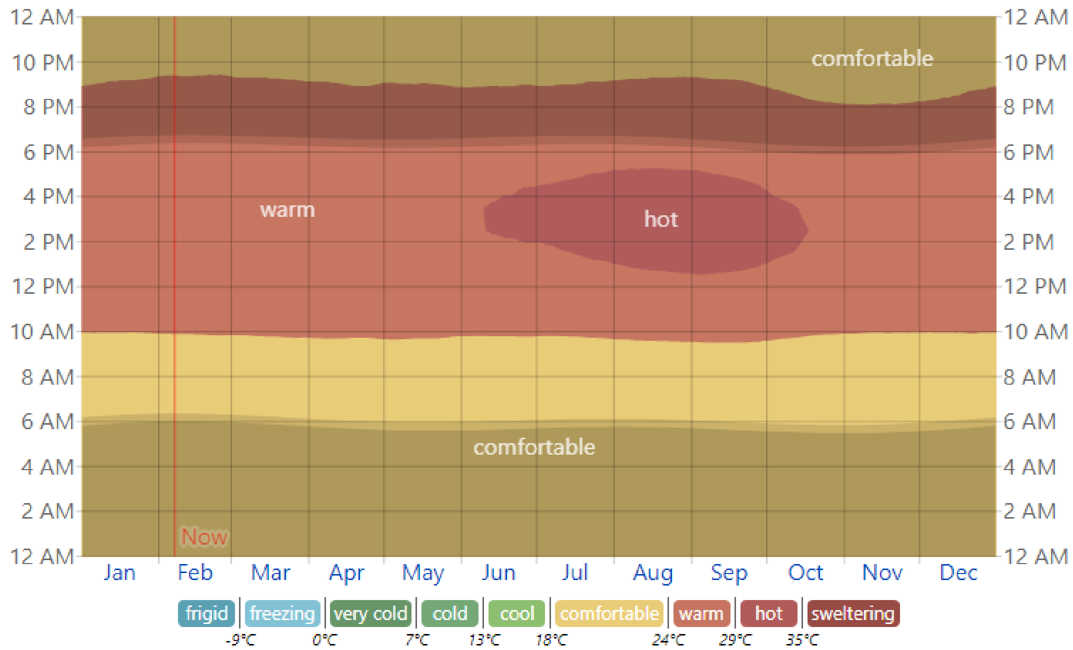

Figure 8: Average Hourly Temperature in El Bordo, taken from: https://weatherspark.com/y/21488/Average-Weather-in-El-Bordo-Colombia-Year-Round

VSRU - Aracataca, Magdalena

For the present case, a transversal corridor is placed connecting two wings of the house, making it a particular typology within the existing prototypes. Presents several walls with no windows, since more exterior boundary is revealed by the design but the number of windows is consistent across prototypes. Located in Aracataca, magdalena, an "Aw" Tropical Savanna climate in the Koppen classification, within the Large Marsh of Saint Martha.

Areas

Bedroom	23.8 m²
Toilet	3.2 m²
Kitchen	4.2 m²
Living	6.8 m²
Corridor	5.4 m²
Laundry	1.4 m²
Tool room	2.5 m²

Total utilized area: 54.9 m²

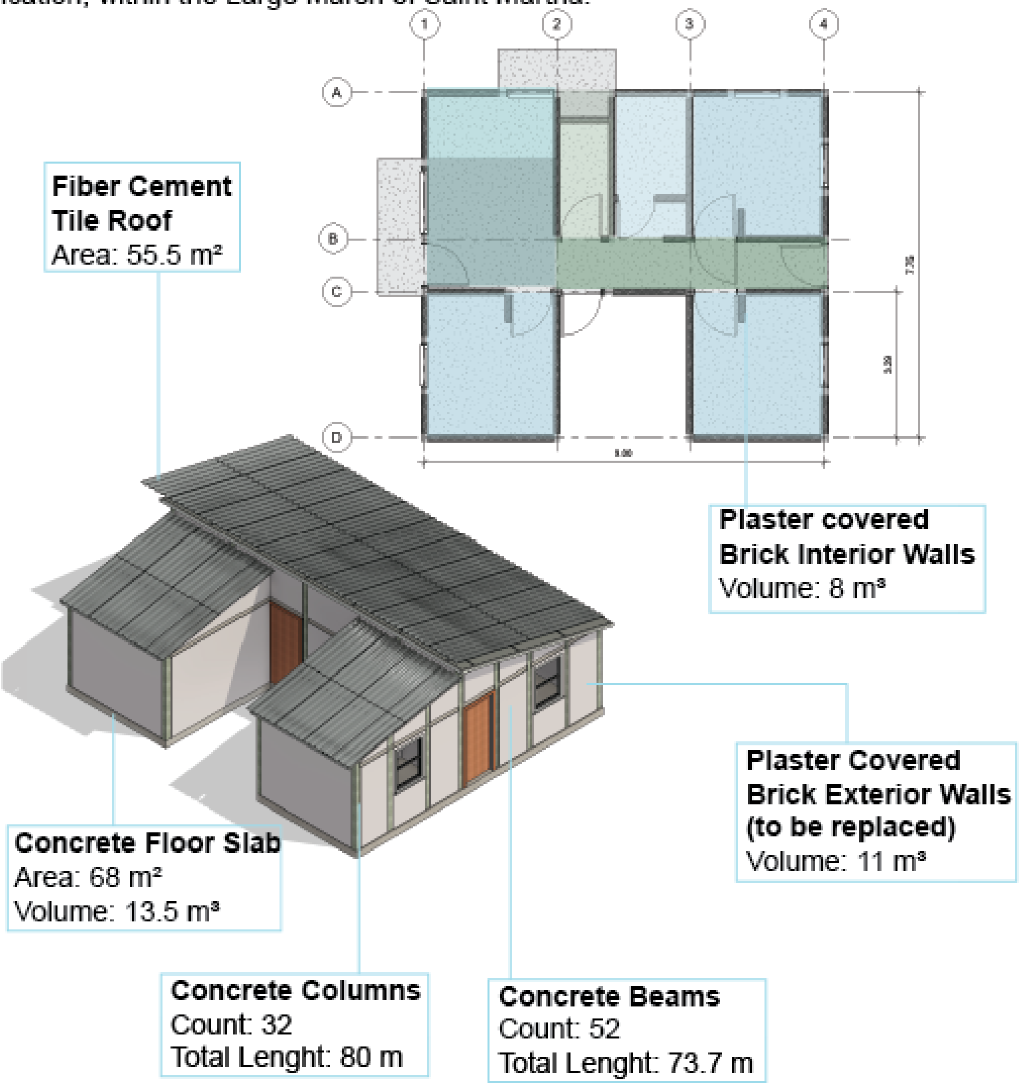

Figure 9:VSRU Prototype information sheet.

As for the VSRU prototype, its location is also taken from the previous participative process. In this case, being the region of Magdalena, the only region choosing this construction. Within this study, the municipality chosen for its location is Aracataca, Magdalena, again, keeping a relation with the original weather data location, in this case Santa Marta, while also being 80 km away from the closest production plant and material distributor. The municipality has a range of 24°C to 36°C temperature yearly, and hot season of 3 months from February to April and a cooler season from September to November.

In this case, there are no comfort hours outside, making the use of cooling strategies a necessity.

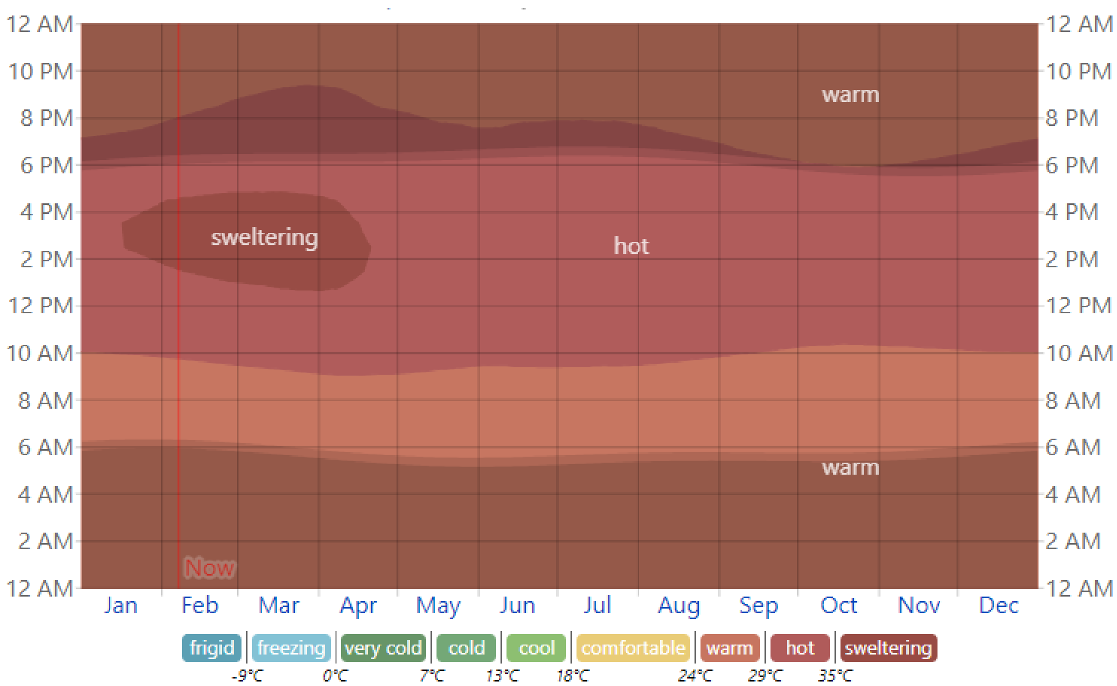

Figure 10: Average Hourly Temperature in Aracataca, taken from: https://weatherspark.com/y/23454/Average-Weather-in-Aracataca-Colombia-Year-Round

VSRT - Cereté, Córdoba

Located in Cereté, Córdoba, this prototype presents ample terraces on each of its entrances, as well as a defined division between bedrooms and the rest of the program in the other side of the house. The climate of the zone is an “Aw” Tropical Savanna in the Koppen classification, and is within the middle valley of the Sinu river.

Areas

Bedroom	24.9 m²
Toilet	1.7 m²
Kitchen	4 m²
Living	5.2 m²
Corridor	5.6 m²
Laundry	0.7 m²
Tool room	2.6 m²

Total utilized area: 55.2 m²

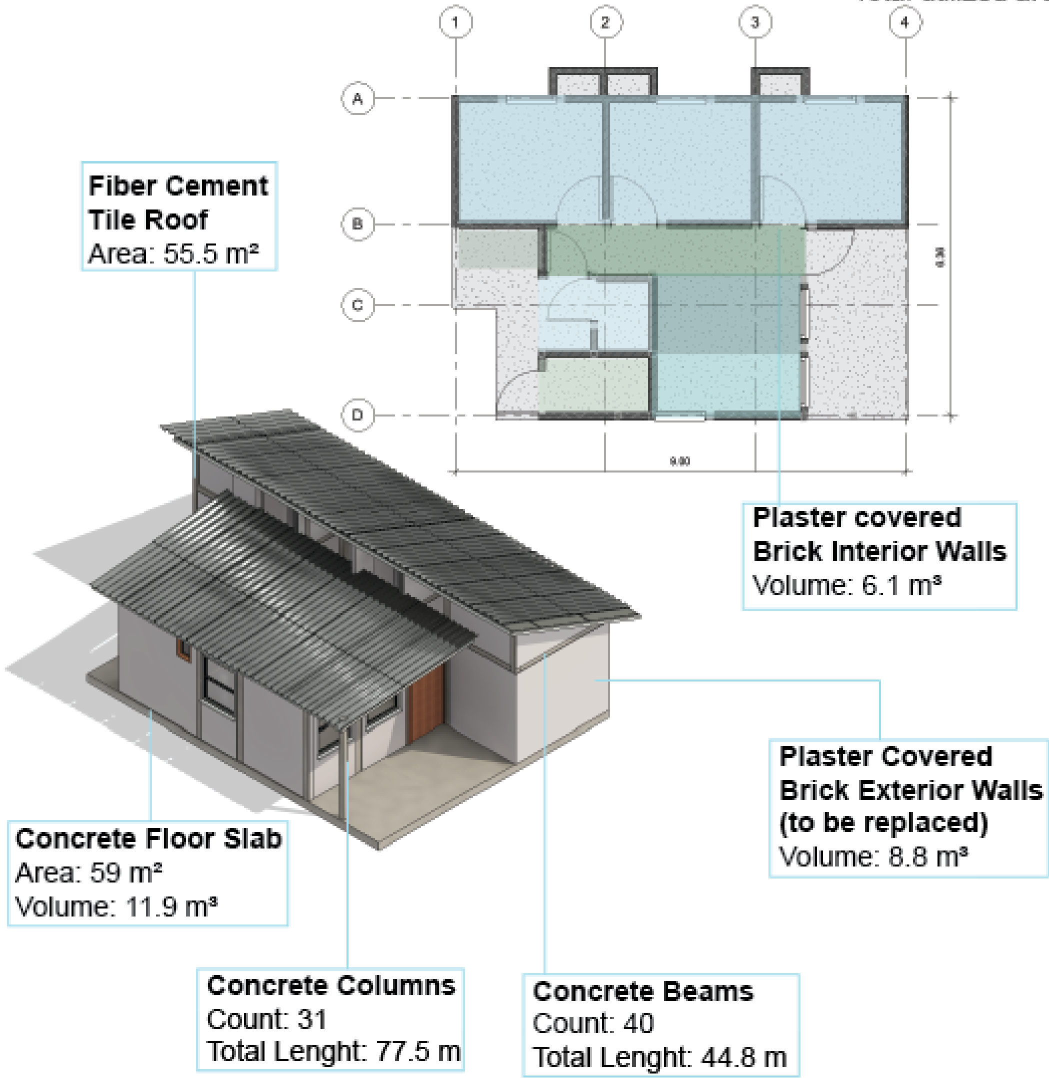

Figure 11: VSRU Prototype information sheet.

The VSRT prototype was located considering the results of the participative workshops conducted by the government, in which the region of Córdoba chose the VSRT construction. The municipality of Cereté was chosen within this study, taking into consideration previously mentioned points regarding weather data collection, while in this case, the distance between the prototype location and production plants of construction materials is 40 km. The municipality has a yearly temperature range of 24°C to 36°C, with a hot season from February to April, and a cooler season from August to December.

The number of comfortable hours outside is minimal in this case, having a considerable amount of warm and even sweltering hours outside, granting the need for cooling strategies.

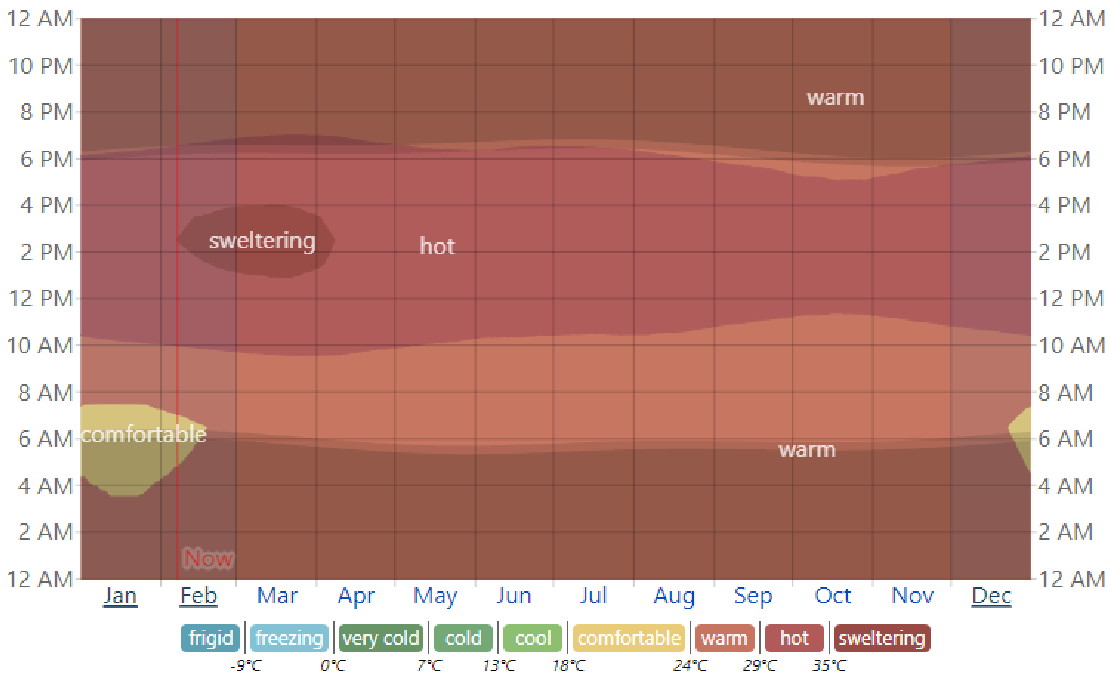

Figure 12: Average Hourly Temperature in Cereté, taken from: https://weatherspark.com/y/22561/Average-Weather-in-Ceret%C3%A9-Colombia-Year-Round

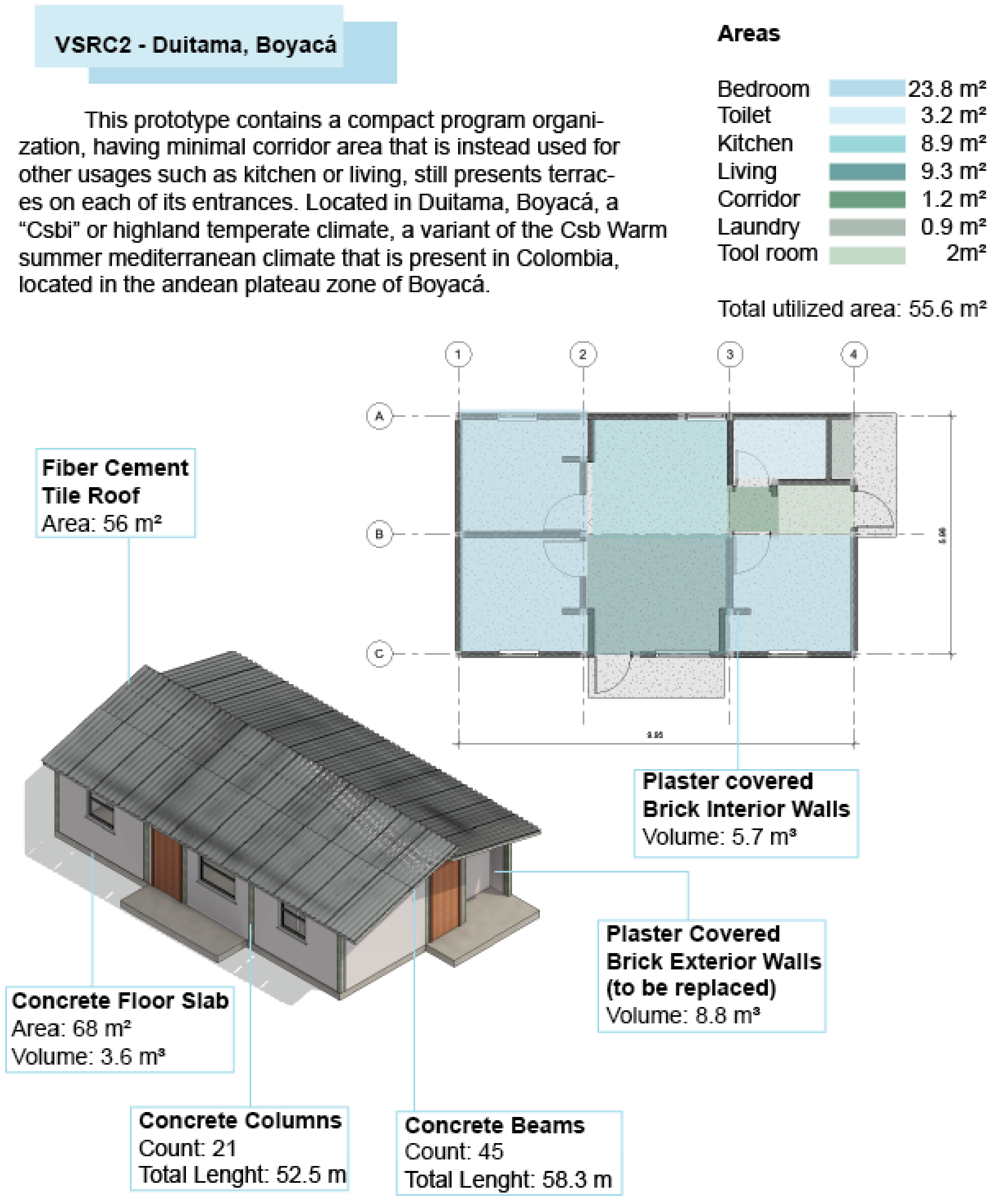

Figure 13: VSRC2 Prototype information sheet.

For the VSRC2 Prototype the location choosing strategy worked differently, since by the annex report from the PNVISR it was noted that for the region of Boyacá there was a repeated prototype from other areas. Still, with the intention of evaluating a wide range of climates, the municipality of Duitama was chosen as a location, with the additional basis of being one of the few non-capital municipalities that have a weather point in the EDGE database, as well as the notorious presence of agricultural and livestock fields in its periphery and neighboring communities. Still, a distance leg of 30 km was input to the nearest production plants for construction materials. Yearly it has a temperature range of 7°C to 19°C, rarely below 4°C or above 21°C.

In this specific case, a particularity is that the temperature outside is mostly on the uncomfortable range, with minimal comfort hours and having mostly cool times during the day, and cold hours in the night, granting the usage of heating strategies.

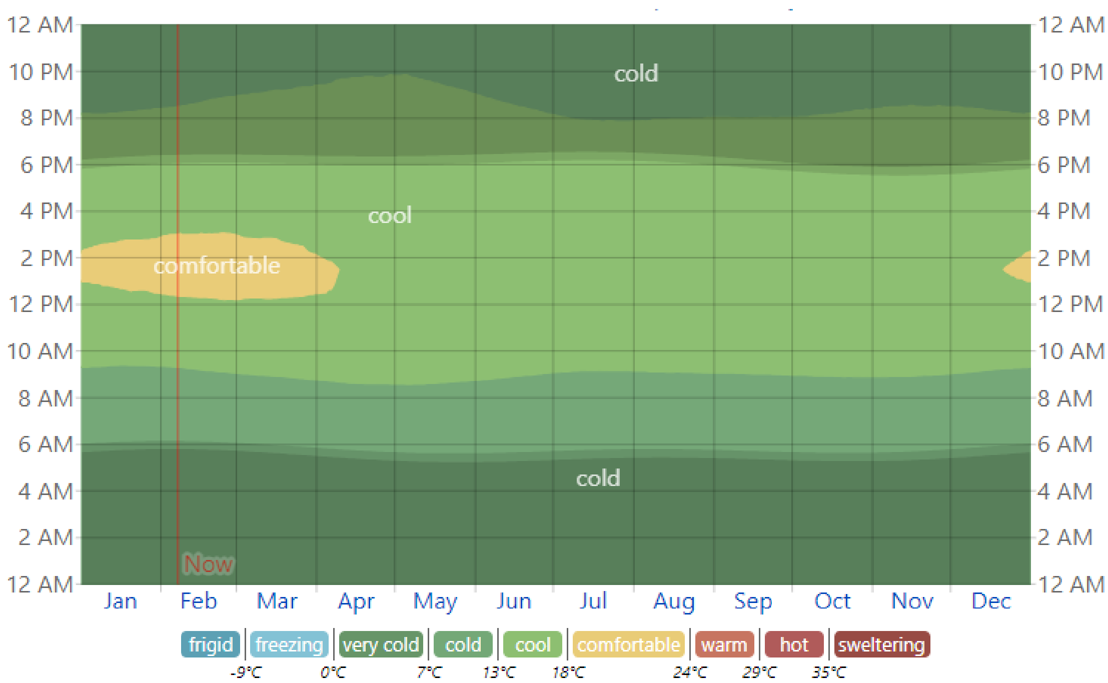

Figure 14: Average Hourly Temperature in Duitama, taken from: https://weatherspark.com/y/24351/Average-Weather-in-Duitama-Colombia-Year-Round

VSRC1 - Puerto Inírida, Guainía

This prototype presents a compact design, where the program is arranged in a rectangular manner with a central but not overtly long corridor. The living area is increased relatively with respect to other prototypes. Located in Puerto Inírida, Guainía, a remote zone accesible only by inland navigation and aerial transport, tropical rainforest “Af” climate in the Koppen classification, located in the Orinoco river valley in the Guiana Shield.

Areas

Bedroom	22.1 m²
Toilet	3.1 m²
Kitchen	5.2 m²
Living	9.1 m²
Corridor	4.3 m²
Laundry	1.2 m²
Tool room	2.2 m²

Total utilized area: 55.2 m²

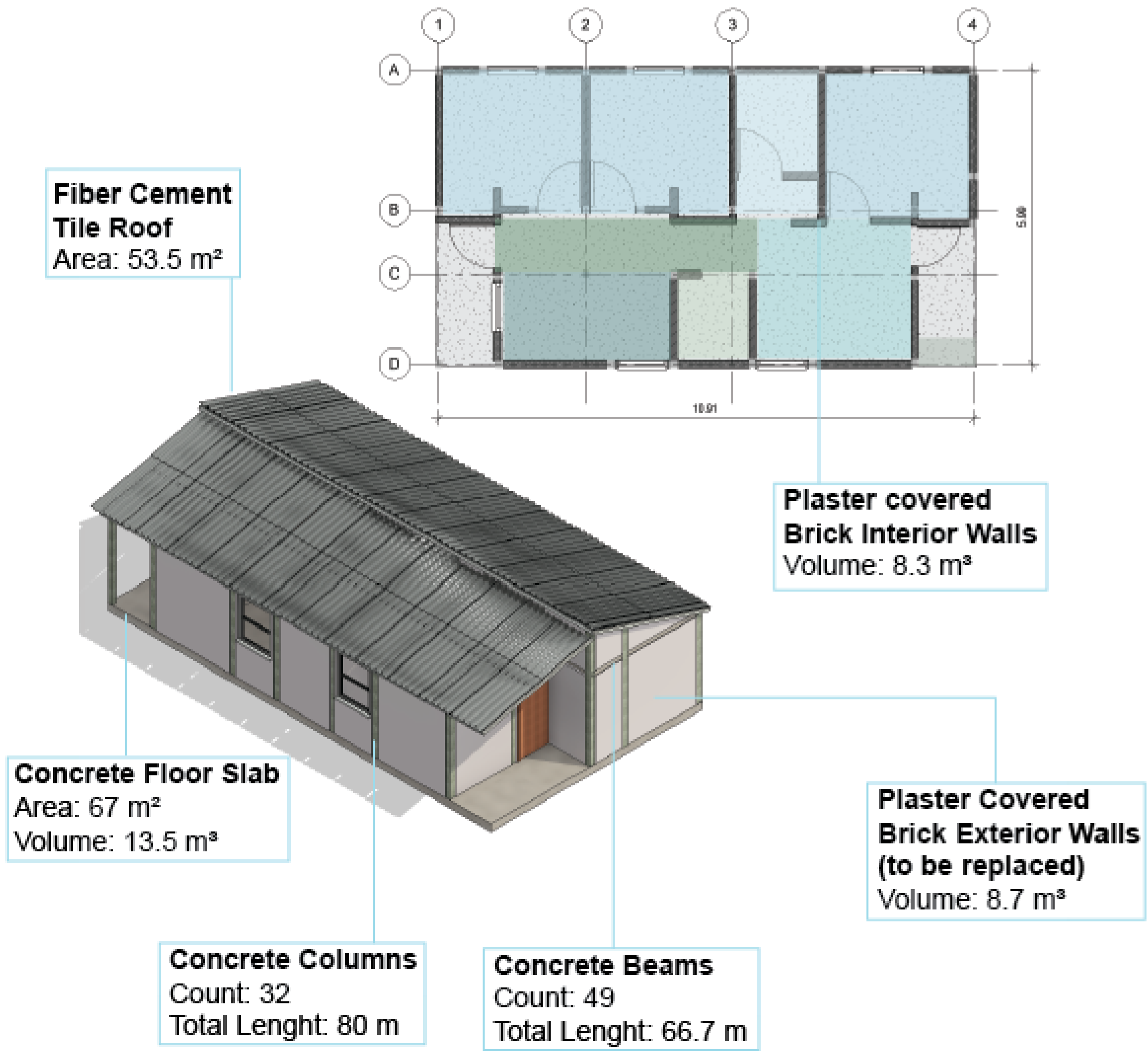

Figure 15: VSRC1 Prototype information sheet.

Finally, for the VSRC1 case the choosing strategy worked differently, since by the annex report from the PNVISR it was noted that there was no region that chose this prototype, still, with the interest of evaluating the six existing cases, the region of

Guainía was chosen, given its particularities regarding accessibility which will be elaborated in the document. The municipality chosen is Puerto Inírida given that it is also a weather data point in the EDGE database and its immediate rural context. It has a yearly temperature range that goes from 23°C to 30°C.

The comfort hours yearly are minimal only within a certain range in the mornings, being warm hours the ones with most coverage during the day and night, making it so that cooling strategies should be implemented to provide comfort for end users.

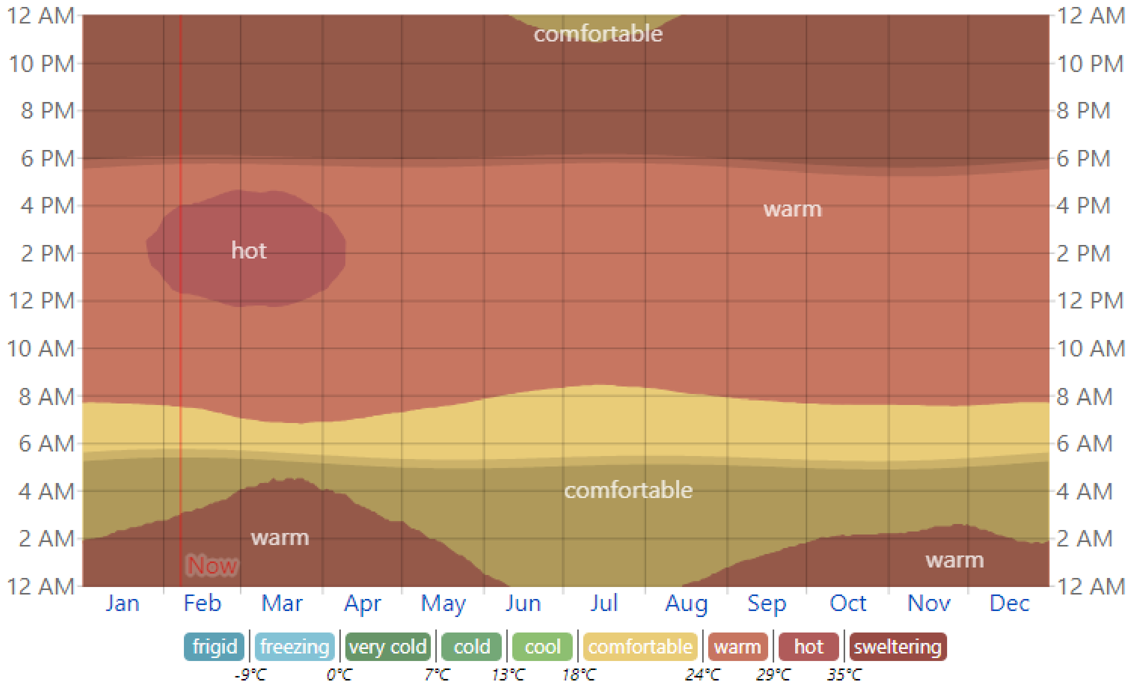

Figure 16: Average Hourly Temperature in Puerto Inírida, taken from: https://weatherspark.com/y/27532/Average-Weather-in-In%C3%ADrida-Colombia-Year-Round

The following graph depicts the geographic distribution of prototypes:

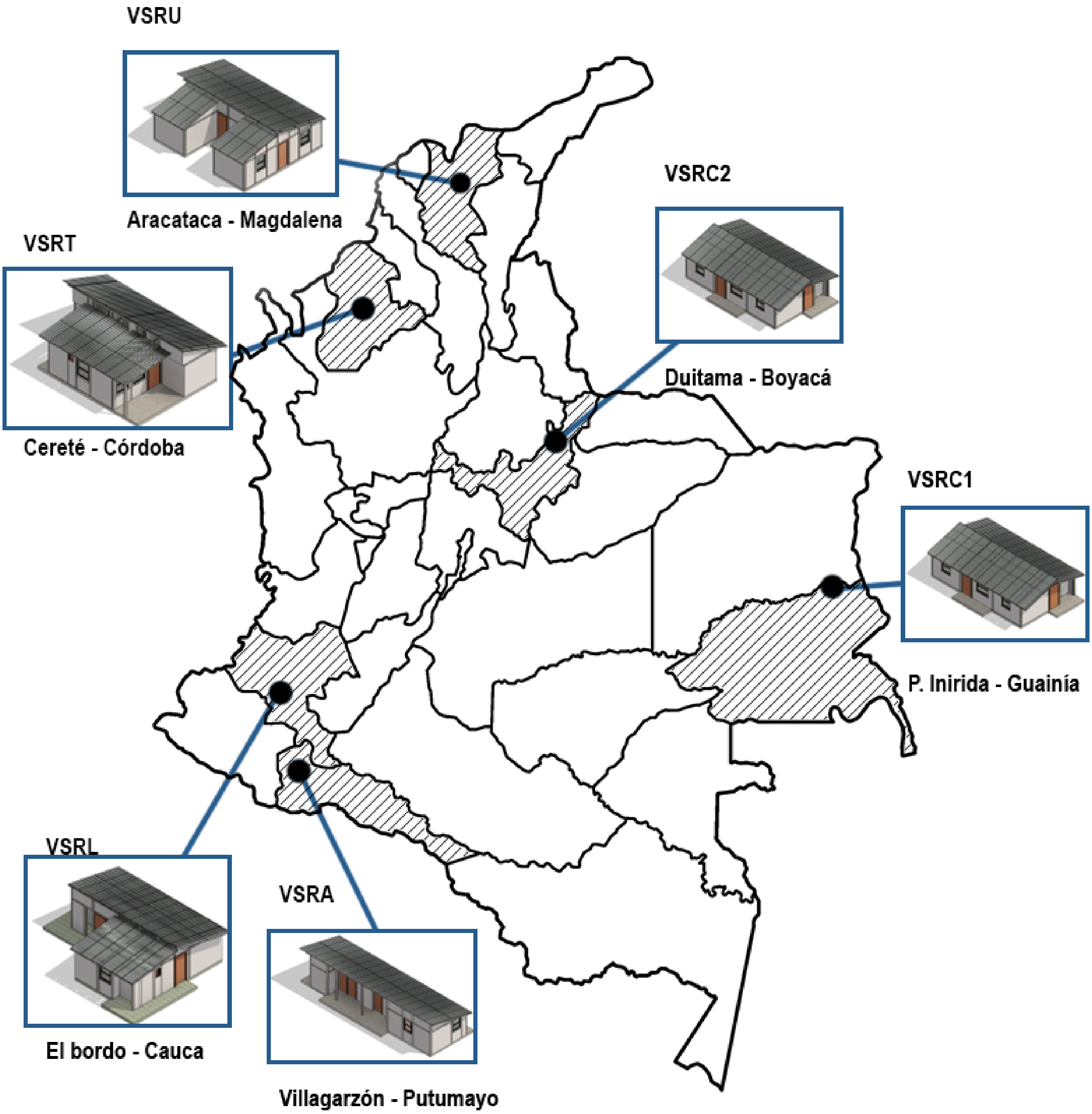

Figure 17: Colombia regional Map with each prototype after the localization process.

As it can be seen, the six prototypes are distributed in a wide range within the country's territory. The location of these points in relation to the Koppen climate types is represented in the following graph:

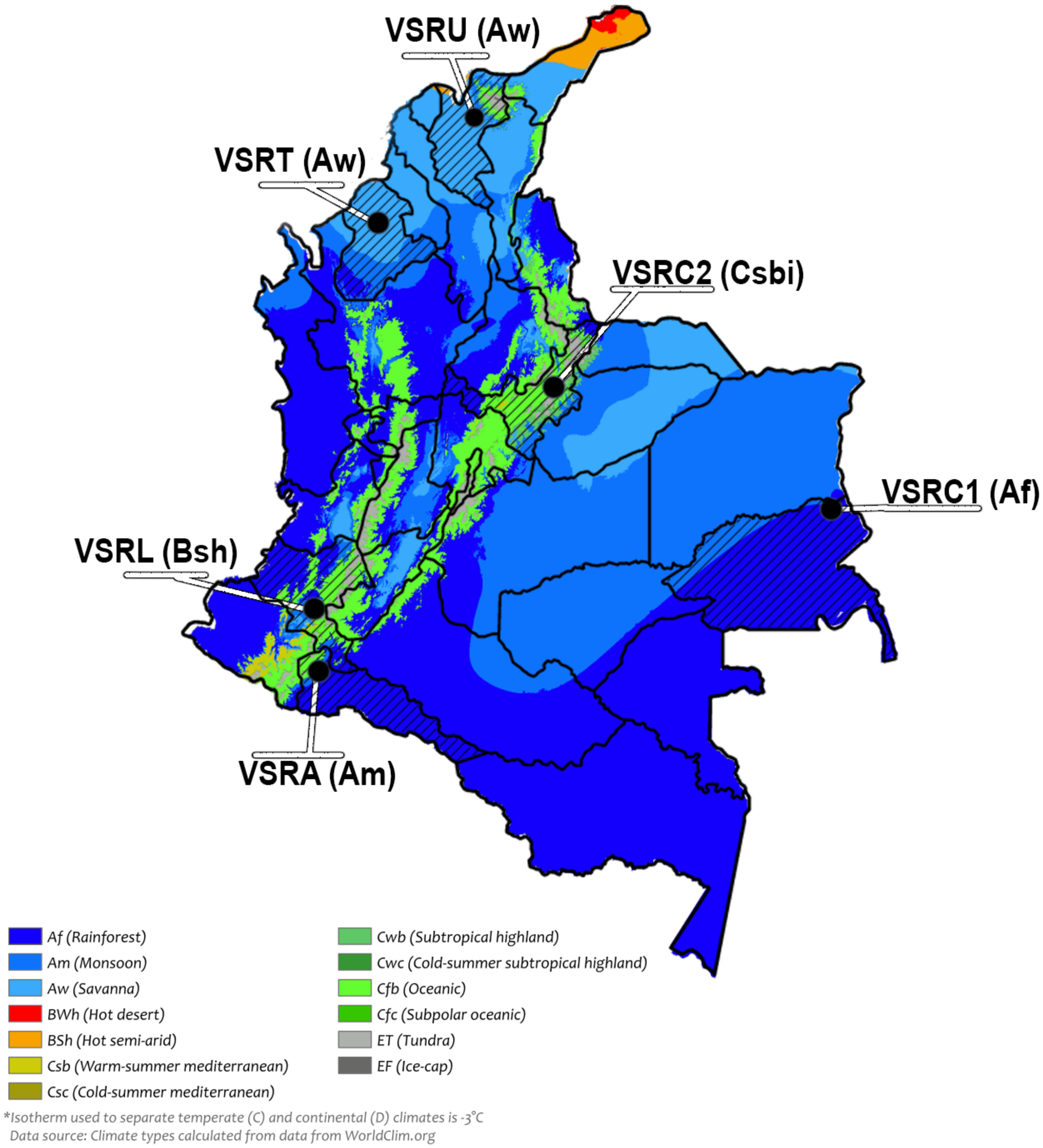

Figure 18: Prototype Locations in relation with the Koppen Climate type.

As evident, the main climate types present in Colombia are the tropical rainforest (Af) and Savana (Aw). Additionally, more types of climates like hot semi-arid (BSh) and highland temperate climate, (Csbi) are propitiated by the Andean Mountain system that traverses Colombia, where three of the six prototypes are located.

The transportation distance to and from production plants and distributors is identified geographically, meaning, the closest production plants and manufacturers for materials such as concrete and steel are looked for and their distance is calculated, in relation to routes instead of a merely linear calculation, process that is similar to the one conducted by Lárraga et al. (2014). It is worth adding that in most cases, production facilities and distributers are coincidental with each region's capital. Their distance for each prototype is represented in the following table:

Distance to manufacturers and production plants	km
VSRL	85
VSRC1	128+780
VSRC2	30
VSRT	40
VSRU	80
VSRA	80

Table 1: Distance from each prototype to regional distribution plants or distributors

With a particular case being VSRC1 consisting of two transportation legs, the first being in land roads and the second one using an inland navigation medium such as a ferry. This case is included in the study, and will be developed in the present document, as a means of accounting for the situation in a considerable part of rural Colombia, which is remote and a lot of times hardly accessible to resources as well as infrastructure, as is mentioned in the PEDTCTI or Strategic Regional Plan of Science, Technology, and innovation[7] made by the Amazonian studies institute in association with the Guainía Government, where the difficulty of accessibility is highlighted (2021). In this case, the construction material production facility or distributor is not located within the region, instead, the closest point for materials and resources was located as far as Yopal, which is a different region, hence, the long distance.

[7] Plan estratégico departamental de ciencia, tecnología e innovación

Additionally, on the EDGE platform developed by the International Finance Corporation IFC with the aim of assessing the sustainability and viability of certification for construction projects under their EDGE certification. On said platform, digital model is also created based on square meter quantities, envelope materials, façade areas, and implemented active and passive strategies. This platform contains climatic data for the main capitals of each department, which is why the projects were in rural contexts of that region that would resemble the capital, where climatic data is collected. Therefore, the location of the prototypes is as follows:

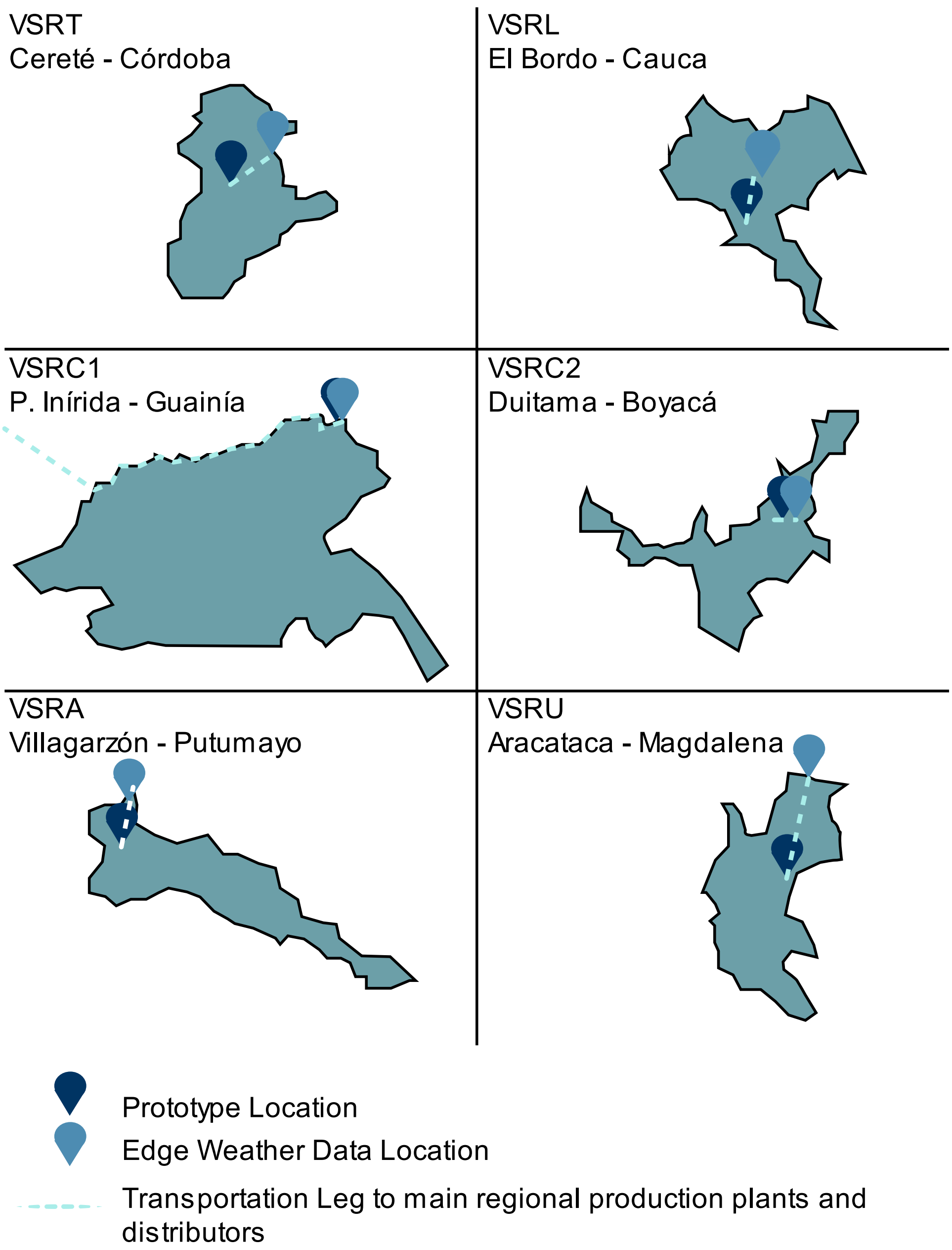

Figure 19: Prototype locations in relation to production plants and weather datapoints.

As a result, the EDGE platform provides information on the energy demand of each prototype associated with the type of user, situation (cooling or heating), and climatic data. Therefore, information about operation usage such as lighting, cooking and in general other uses of energy are not considered on this analysis, since the difference between prototypes on these aspects would be minimal, taking into account the similarities between areas across prototypes. Additionally, using this type of information as input would obscure the differences related to the key factor to take away from the energy demand, is the usage related to thermal comfort, making it the only energy demand parameter to be inserted, be it heating related or cooling related.

This material and energy demand data can then be included as inputs into LCA methodology software, in this case, the One Click LCA platform, which provides information from major existing EPD databases such as Ecoinvent, Q-Tech, and One Click LCA's own data. In this way, the development of a life cycle assessment for each prototype is conducted using both sources of information, with the added data coming from the localization of each prototype and its relationship with production centers.

Based on the definition in ISO 14040:2006, this LCA evaluation approach is divided into four main phases:

6.2 Goal and Scope definition:

Each dwelling is evaluated for 40 years of life span and for six inhabitants as defined by the house area and program. The main goal is to quantify environmental impacts associated with the house's construction and operational energy demand associated with comfort. The boundaries for the current system are defined by the start of the production phase of each material, their usage and implementation within the construction, their usage during the building’s life cycle and finally the end of life.

6.3 Life Cycle Inventory

- Material quantities from digital prototype models
- Material EPD's from manufacturers and databases
- Distance to each material production facility by region.
- Water usage from construction processes
- Annual thermal comfort-related energy demand from simulation and local weather data
- Recycling parameters from database

A minimal irrigation area of 40 m² is defined for all cases considering that there is no standard property size (DANE, 2022). This information is input into the EDGE model for each prototype and scenario.

6.4 Impact Assessment

A functional unit of CO_2 eq/m² and impact categories provided by the OneClick LCA Platform for each prototype evaluated:

- Global warming - kg CO_2 eq
- Biogenic carbon storage - kg CO_2 eq bio
- Ozone Depletion - kg CFC11eq
- Acidification - kg S O_2 eq
- Eutrophication - kg PO4eq
- Formation of ozone of lower atmosphere - kg ethane
- Abiotic depletion potential (ADP-elements) for non-fossil resources - kg Sbe
- Use of renewable primary energy resources as raw materials - MJ
- Total use of primary energy ex. raw materials - MJ
- Total use of renewable primary energy MJ
- Total use of non-renewable primary energy MJ
- Use of net freshwater m³

6.5 Interpretation

- Comparison between the different scenarios for each prototype.
- Dissection of the different impact categories
- Percentual difference between alternatives across significant impact categories
- Proportional differences between prototypes
- Comparison of energy demand
- Identification of key parameters that affect impact categories.

From firstly obtained results in the six baseline cases, generalized and transversal changes are proposed across all six prototypes. This is done with the objective of maintaining a degree of comparability between them and observing how some of their present particularities, such as the need for heating demand in the case of VSRC2 or being completely distant from production centers as observed in VSRC1, react to the proposed changes. These changes are processed through the EDGE platform, changing materials, and observing the given impacts in the energy demand. Additionally, the changes in material quantities and energy demand are introduced into the model through the One Click LCA platform.

6.6 Modifications and quantities

Changes Made to the Envelope of the Prototypes in a First Alternative "ALT":

Component	Current Envelope Conditions	Proposed Envelope Modifications for first phase "ALT"
Walls	Hollow Clay bricks with mortar on each side	Light construction: 100 mm panel: Plasterboard of 6 mm on each side and rockwool insulation in the center 37 mm. Supported by vertical steel studs.
Roof	Fibrocement roof sheets 9 mm.	Fibrocement roof sheets, pitched roof cellulose insulation 50 mm.
Recycling	No recycling plan	Steel elements introduced come from recycled material and are recycled at End of Life (EOL). Cellulose insulation recycled as material. Bricks from interior walls recycled as aggregates. Concrete recycled as aggregate.

Table 2: Table detailing first alternative scenario "ALT"

These proposed changes are inputs in an initial Life Cycle Assessment (LCA) and are analyzed in a first observational phase. In this phase, advantages, and disadvantages of the use of each material within each context and the energy demand generated in each case are assessed. Based on this analysis, decisions are made for application and changes in a second analysis phase "ALT 2," to which generalized modifications are added, with the noted exceptions. A different alternative “ALT 3” is also generated, applying yet a different material to the wall and providing a varied sample in the end, resulting in a total of three different alternatives besides the original case, their characteristics are shown in the following table:

Component	Proposed Envelope Modifications for first phase "ALT"	Proposed Envelope Modifications for second phase "ALT2"	Proposed Envelope Modifications for second phase "ALT3"
Walls	Light construction: 100 mm panel: Plasterboard of 6mm on each side and rockwool insulation in the center 37 mm. Supported by vertical steel studs.	Rammed earth wall. 300 mm thickness	Compressed Earth Block (CEB) 150 mm thickness
Roof	Fiber cement roof sheets, 50 mm pitched roof cellulose insulation	Fiber cement roof sheets, 50 mm* pitched roof cellulose insulation. *Reduced to minimal 5 mm insulation in the heating case (VSRC2)	Fiber cement roof sheets, 50 mm* pitched roof cellulose insulation. *Reduced to minimal 5 mm insulation in the heating case (VSRC2)
Recycling	Steel elements introduced come from recycled material and are recycled at End of Life (EOL). Cellulose insulation recycled as material. Bricks from interior walls recycled as aggregates. Concrete recycled as aggregate.	Cellulose insulation recycled as material. Bricks from interior walls recycled as aggregates. Concrete recycled as aggregate. Soil is recycled as landfill.	Cellulose insulation recycled as material. Bricks from interior walls recycled as aggregates. Concrete recycled as aggregate. Soil is recycled as landfill.

Table 3: Detail of subsequent scenarios ALT2 and ALT3

Consequently, the obtained modifications in the envelope can be summarized in the following table for each scenario:

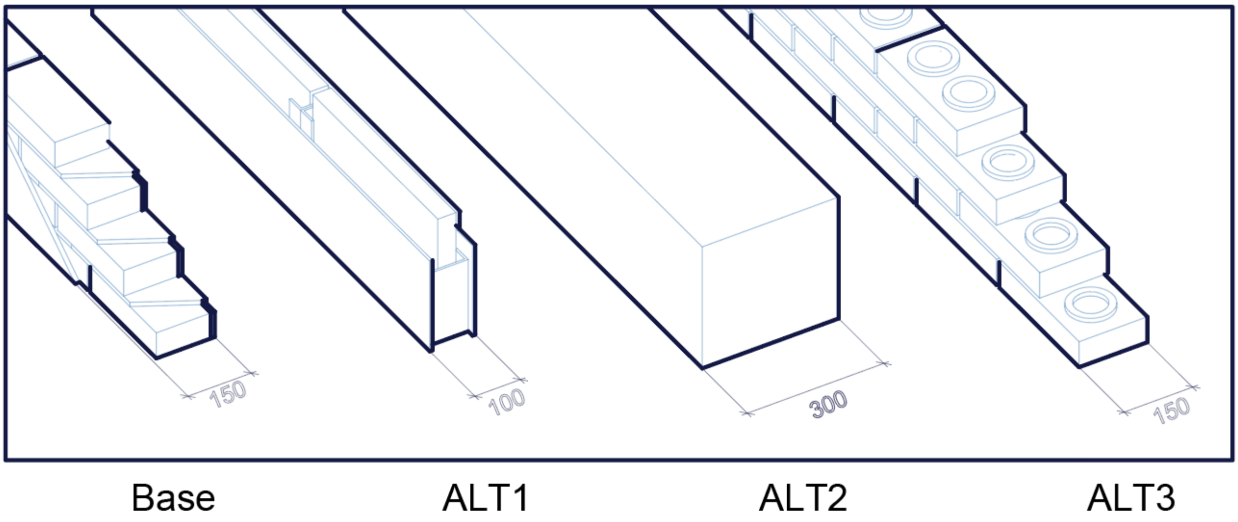

Figure 20: Detail of each scenario wall - Units in millimeters.

From this second phase, it is then possible to assess the differences between the four produced cases: the base case, ALT, ALT2 and ALT 3. The main elements responsible for each impact are assessed. Along with significant incidences of each life cycle phase defined in ISO 14040:2006 (A, B, C, D), and recognize advantages and disadvantages of implementing them. The rendered result is a transversal analysis that goes across all scenarios and models and can depict the relationship between the prototypes, and their behavior under the different modifications to be implemented.

Therefore, the changes and quantities in materials for each prototype are presented in the following way:

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRA	Foundations	Concrete Slabs (m^3)	14.65	Concrete Slabs (m^3)	14.65	Concrete Slabs (m^3)	14.65	Concrete Slabs (m^3)	14.65
	Facade	Terracotta brick with hollow chamber (m^3)	10	Gypsum Plasterboard 6 mm (m^2)	142	Rammed Earth wall 300 mm (m^3)	22	compressed earth block CEB wall 150mm (units)	2130
		Plaster Mortar (kg)	1211	Steel Studs (Kg)	554.2				
				Rockwool 37mm (m^2)	71				
	Internal walls	Terracotta brick with hollow chamber (m^3)	6	Terracotta brick with hollow chamber (m^3)	6	Terracotta brick with hollow chamber (m^3)	6	Terracotta brick with hollow chamber (m^3)	6
		Plaster Mortar (kg)	731	Plaster Mortar (kg)	731	Plaster Mortar (kg)	731	Plaster Mortar (kg)	731
	Roof	Fiber cement roof tiles 5mm (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55
		Structural hollow steel section (70x70)mm (kg)	538	Structural hollow steel section (kg)	538	Structural hollow steel section (kg)	538	Structural hollow steel section (kg)	538
				cellulose insulation 50 mm (m^2)	55	insulation 50 mm (m^2)	55	insulation 50 mm (m^2)	55
	Windows	PVC Frame single glazing (m^2)	6.25	PVC Frame single glazing (m^2)	6.25	single glazing (m^2)	6.25	PVC Frame single glazing (m^2)	6.25
	Doors	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6
	Structure	Concrete Column (m)	87.5	Concrete Column (m)	87.5	Concrete Column (m)	87.5	Concrete Column (m)	87.5
		Concrete Beam (m)	67	Concrete Beam (m)	67	Concrete Beam (m)	67	Concrete Beam (m)	67

Table 4: Materials across all scenarios for VSRA.

As can be observed, the previous table shows all materials introduced as inputs in the LCA model for the VSRA prototype. A detail to note is that a substructure of square steel sections that supports the roof tiles has been introduced in all prototypes, this, in accordance with illustrations and graphical works present in the PNVISR, which show this would be the structure used for that purpose. Said substructure is present in the BIM model as well, which allowed for a precise quantification of materials, which in this case, had to be input as kg. For this purpose, a reference was sought within national steel production industries, finding in the *Ternium* company catalogue, a tubular square profile which worked for this purpose, PTE CUA. 70 x 70 mm with a weight of 4.35 kg by linear meter.

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRL	Foundations	Concrete Slabs (m^3)	14.7	Concrete Slabs (m^3)	14.7	Concrete Slabs (m^3)	14.7	Concrete Slabs (m^3)	14.7
	Facade	Terracotta brick with hollow chamber (m^3)	8.1	Gypsum Plasterboard 6 mm (m^2)	106	Rammed Earth wall 300 mm (m^3)	17.9	Compressed earth block CEB wall 150mm (units)	1740
		Plaster Mortar (kg)	983	Steel Studs (Kg)	453.2				
				Rockwool 37mm (m^2)	58				
	Internal walls	Terracotta brick with hollow chamber (m^3)	8.2	Terracotta brick with hollow chamber (m^3)	8.2	Terracotta brick with hollow chamber (m^3)	8.2	Terracotta brick with hollow chamber (m^3)	8.2
		Plaster Mortar (kg)	950	Plaster Mortar (kg)	950	Plaster Mortar (kg)	950	Plaster Mortar (kg)	950
	Roof	Fiber cement roof tiles 5mm (m^2)	53	Fiber cement roof tiles (m^2)	53	Fiber cement roof tiles (m^2)	53	Fiber cement roof tiles (m^2)	53
		Structural hollow steel section (70x70)mm (kg)	541	Structural hollow steel section (kg)	541	Structural hollow steel section (kg)	541	Structural hollow steel section (kg)	541
				cellulose insulation 50 mm (m^2)	53	insulation 50 mm (m^2)	53	insulation 50 mm (m^2)	53
	Windows	PVC Frame single glazing (m^2)	6	PVC Frame single glazing (m^2)	6	single glazing (m^2)	6	PVC Frame single glazing (m^2)	6
	Doors	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6
	Structure	Concrete Column (m)	87.5	Concrete Column (m)	87.5	Concrete Column (m)	87.5	Concrete Column (m)	87.5
		Concrete Beam (m)	67	Concrete Beam (m)	67	Concrete Beam (m)	67	Concrete Beam (m)	67

Table 5: Materials across all scenarios for VSRL.

Additionally, a similar calculation was made for the steel studs that would be used in the gypsum plasterboard wall, where from the *Ternium* catalogue, a C profile was chosen in accordance with the construction technology. In this case, the PCN 8x2-5/8x1.5 and a weight by linear meter of 4.19 kg. For this case specifically, the number of studs was calculated dividing the length of the exterior façade by 0.64 m, which would be the distance between each stud.

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRC1	Foundations	Concrete Slabs (m^3)	13.48	Concrete Slabs (m^3)	13.48	Concrete Slabs (m^3)	13.48	Concrete Slabs (m^3)	13.48
	Facade	Terracotta brick with hollow chamber (m^3)	8.65	Gypsum Plasterboard 6 mm (m^2)	114	Rammed Earth wall 300 mm (m^3)	19.32	Compressed earth block CEB wall 150mm (units)	1860
		Plaster Mortar (kg)	1049	Steel Studs (Kg)	421.12				
				Rockwool 37mm (m^2)	62				
	Internal walls	Terracotta brick with hollow chamber (m^3)	8.3	Terracotta brick with hollow chamber (m^3)	8.3	Terracotta brick with hollow chamber (m^3)	8.3	Terracotta brick with hollow chamber (m^3)	8.3
		Plaster Mortar (kg)	1010	Plaster Mortar (kg)	1010	Plaster Mortar (kg)	1010	Plaster Mortar (kg)	1010
	Roof	Fiber cement roof tiles 5mm (m^2)	63	Fiber cement roof tiles (m^2)	63	Fiber cement roof tiles (m^2)	63	Fiber cement roof tiles (m^2)	63
		Structural hollow steel section (70x70)mm (kg)	642	Structural hollow steel section (kg)	642	Structural hollow steel section (kg)	642	Structural hollow steel section (kg)	642
				cellulose insulation 50 mm (m^2)	63	cellulose insulation 50 mm (m^2)	63	cellulose insulation 50 mm (m^2)	63
	Windows	PVC Frame single glazing (m^2)	7.2	PVC Frame single glazing (m^2)	7.2	single glazing (m^2)	7.2	PVC Frame single glazing (m^2)	7.2
	Doors	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6
	Structure	Concrete Column (m)	80	Concrete Column (m)	80	Concrete Column (m)	80	Concrete Column (m)	80
		Concrete Beam (m)	66.7	Concrete Beam (m)	66.7	Concrete Beam (m)	66.7	Concrete Beam (m)	66.7

Table 6: Materials across all scenarios for VSRC1.

Therefore, as is observed in the previous table, the quantity of materials for interior walls remains unaffected across all scenarios. This decision was made to maintain uniformity in the analysis, focusing solely on the envelope of the house for comparison and interpretation purposes. Moreover, the modifications in thickness of walls would change interior areas enough to impact interior spaces and their usage.

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRC2	Foundations	Concrete Slabs (m^3)	13.6	Concrete Slabs (m^3)	13.6	Concrete Slabs (m^3)	13.6	Concrete Slabs (m^3)	13.6
	Facade	Terracotta brick with hollow chamber (m^3)	8.3	Gypsum Plasterboard 6 mm (m^2)	106	Rammed Earth wall 300 mm (m^3)	22.08	Compressed earth block CEB wall 150mm (units)	1890
		Plaster Mortar (kg)	1067	Steel Studs (Kg)	441.3				
				Rockwool 37mm (m^2)	53				
	Internal walls	Terracotta brick with hollow chamber (m^3)	6.8	Terracotta brick with hollow chamber (m^3)	6.8	Terracotta brick with hollow chamber (m^3)	6.8	Terracotta brick with hollow chamber (m^3)	6.8
		Plaster Mortar (kg)	696	Plaster Mortar (kg)	696	Plaster Mortar (kg)	696	Plaster Mortar (kg)	696
	Roof	Fiber cement roof tiles 5mm (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55
		Structural hollow steel section (70x70)mm (kg)	645	Structural hollow steel section (kg)	645	Structural hollow steel section (kg)	645	Structural hollow steel section (kg)	645
				cellulose insulation 50 mm (m^2)	55	cellulose insulation 5 mm (m^2)	55	cellulose insulation 5 mm (m^2)	55
	Windows	PVC Frame single glazing (m^2)	6.45	PVC Frame single glazing (m^2)	6.45	single glazing (m^2)	6.45	PVC Frame single glazing (m^2)	6.45
	Doors	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6	Wooden 2x1 door (unit)	6
	Structure	Concrete Column (m)	52.5	Concrete Column (m)	52.5	Concrete Column (m)	52.5	Concrete Column (m)	52.5
		Concrete Beam (m)	58.2	Concrete Beam (m)	58.2	Concrete Beam (m)	58.2	Concrete Beam (m)	58.2

Table 7: Materials across all scenarios for VSRC2.

Regarding the structure, it remains unaffected keeping accordance with the projects main scope and goals. The foundations component is input as the base slab of the house, which is calculated in cubic meters. As for the columns and beams, their total length is calculated which is the input parameter for said component in the LCA model. Moreover, in the previous table specifically, it can be seen how cellulose insulation thickness was changed from the ALT scenario to the subsequent scenarios ALT2 and ALT3. The rebar quantities are calculated implicitly within the One Click LCA tool.

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRU	Foundations	Concrete Slabs (m^3)	13.65	Concrete Slabs (m^3)	13.65	Concrete Slabs (m^3)	13.65	Concrete Slabs (m^3)	13.65
	Facade	Terracotta brick with hollow chamber (m^3)	10.98	Gypsum Plasterboard 6 mm (m^2)	158	Rammed Earth wall 300 mm (m^3)	26.04	Compressed earth block CEB wall 150mm (units)	2370
		Plaster Mortar (kg)	1332.1	Steel Studs (Kg)	605.8				
				Rockwool 37mm (m^2)	79				
	Internal walls	Terracotta brick with hollow chamber (m^3)	8.08	Terracotta brick with hollow chamber (m^3)	8.08	Terracotta brick with hollow chamber (m^3)	8.08	Terracotta brick with hollow chamber (m^3)	8.08
		Plaster Mortar (kg)	980.1	Plaster Mortar (kg)	980.1	Plaster Mortar (kg)	980.1	Plaster Mortar (kg)	980.1
	Roof	Fiber cement roof tiles 5mm (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55	Fiber cement roof tiles (m^2)	55
		Structural hollow steel section (70x70)mm (kg)	618	Structural hollow steel section (kg)	618	Structural hollow steel section (kg)	618	Structural hollow steel section (kg)	618
				cellulose insulation 50 mm (m^2)	55	insulation 50 mm (m^2)	55	insulation 50 mm (m^2)	55
	Windows	PVC Frame single glazing (m^2)	6.94	PVC Frame single glazing (m^2)	6.94	PVC Frame single glazing (m^2)	6.94	PVC Frame single glazing (m^2)	6.94
	Doors	Wooden 2x1 door (unit)	9	Wooden 2x1 door (unit)	9	Wooden 2x1 door (unit)	9	Wooden 2x1 door (unit)	9
	Structure	Concrete Column (m)	52.5	Concrete Column (m)	52.5	Concrete Column (m)	52.5	Concrete Column (m)	52.5
		Concrete Beam (m)	73	Concrete Beam (m)	73	Concrete Beam (m)	73	Concrete Beam (m)	73

Table 8: Materials across all scenarios for VSRU.

Clearly, a characteristic across prototypes is the fact that the areas and numbers of doors remained practically equal, with the exception of the VSRU case as can be seen in the previous table. This decision goes in accordance with the intention of keeping a low cost across all projects, which can be inferred that an area around 6 m^2 for windows and six units of doors approximately is the minimum for a functional house unit for the established number of users that also remains constant in all prototypes.

Prototype	Building Component	Materials Base	Qty.	Materials Alt	Qty.	Materials Alt2	Qty.	Materials Alt3	Qty.
VSRT	Foundations	(m^3)	13.5	(m^3)	13.5	(m^3)	13.5	(m^3)	13.5
	Facade	Terracotta brick with hollow chamber (m^3)	8.66	Gypsum Plasterboard 6 mm (m^2)	116	Rammed Earth wall 300 mm (m^3)	18.7	Compressed earth block CEB wall 150mm (units)	1890
		Plaster Mortar (kg)	1050	Steel Studs (Kg)	416.5				
				Rockwool 37mm (m^2)	63				
	Internal walls	Terracotta brick with hollow chamber (m^3)	5.96	Terracotta brick with hollow chamber (m^3)	5.96	Terracotta brick with hollow chamber (m^3)	5.96	Terracotta brick with hollow chamber (m^3)	5.96
		Plaster Mortar (kg)	722	Plaster Mortar (kg)	722	Plaster Mortar (kg)	722	Plaster Mortar (kg)	722
	Roof	Fiber cement roof tiles 5mm (m^2)	54	Fiber cement roof tiles (m^2)	54	Fiber cement roof tiles (m^2)	54	Fiber cement roof tiles (m^2)	54
		Structural hollow steel section (70x70)mm (kg)	509	Structural hollow steel section (kg)	509	Structural hollow steel section (kg)	509	Structural hollow steel section (kg)	509
				cellulose insulation 50 mm (m^2)	54	insulation 50 mm (m^2)	54	insulation 50 mm (m^2)	54
	Windows	PVC Frame single glazing (m^2)	6	PVC Frame single glazing (m^2)	6	single glazing (m^2)	6	PVC Frame single glazing (m^2)	6
	Doors	Wooden 2x1 door (unit)	8	Wooden 2x1 door (unit)	8	Wooden 2x1 door (unit)	8	Wooden 2x1 door (unit)	8
	Structure	Concrete Column (m)	77.5	Concrete Column (m)	77.5	Concrete Column (m)	77.5	Concrete Column (m)	77.5
		Concrete Beam (m)	44.8	Concrete Beam (m)	44.8	Concrete Beam (m)	44.8	Concrete Beam (m)	44.8

Table 9: Materials across all scenarios for VSRT.

As evident from the previous tables, exterior wall area and length heavily affects the actual quantities of materials needed for each prototype, this case being more evident when looking at the differences between the quantities of CEB blocks or the cubic meters of soil necessary to construct a rammed earth wall across the different cases. This opens a question regarding the relation of the length of the exterior wall and the performance of each prototype which will be explored in subsequent sections of this study.

The following scheme depicts the current methodology execution:

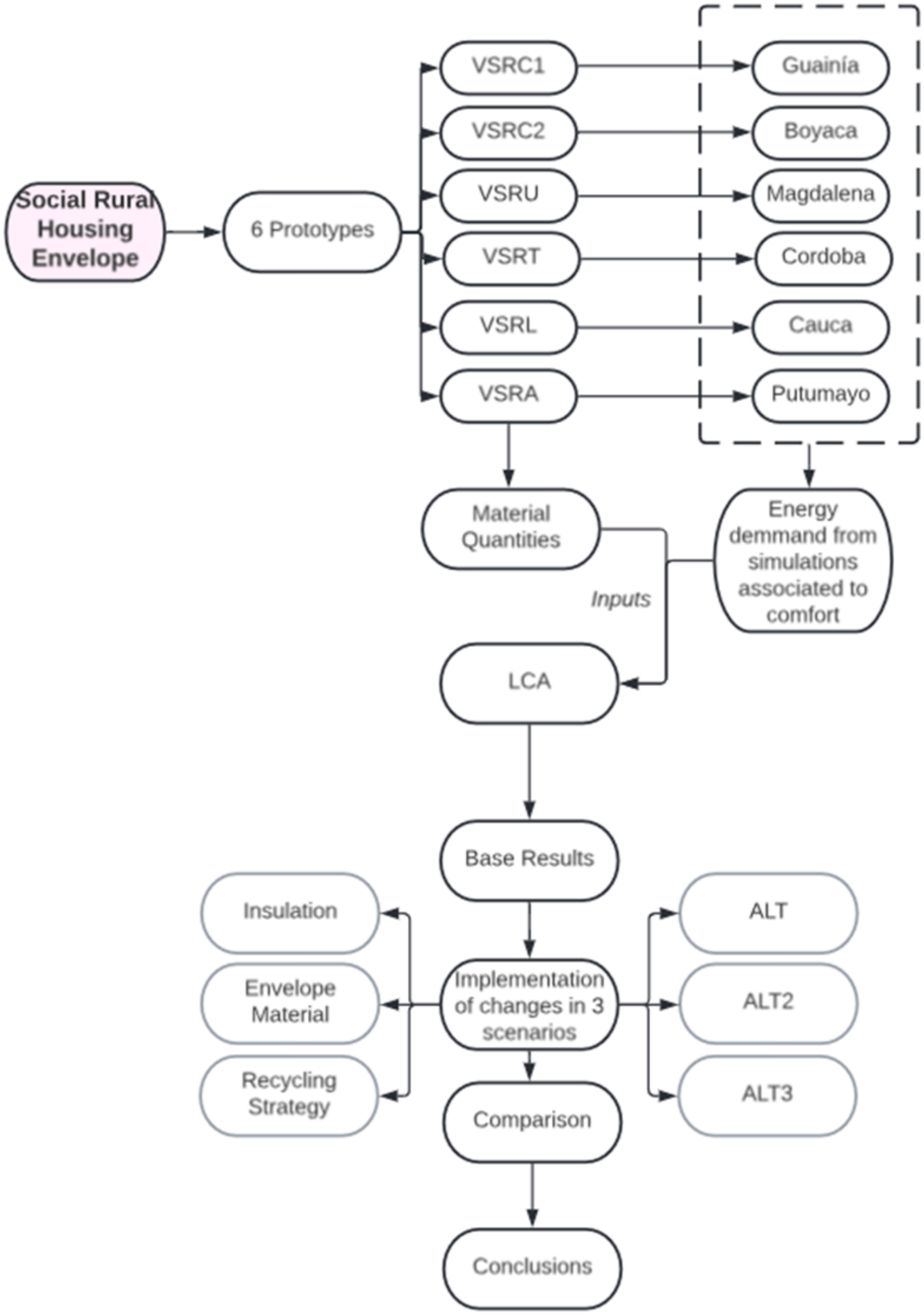

Figure 21: Methodology Flowchart

7. Results

7.1 Introduction to results

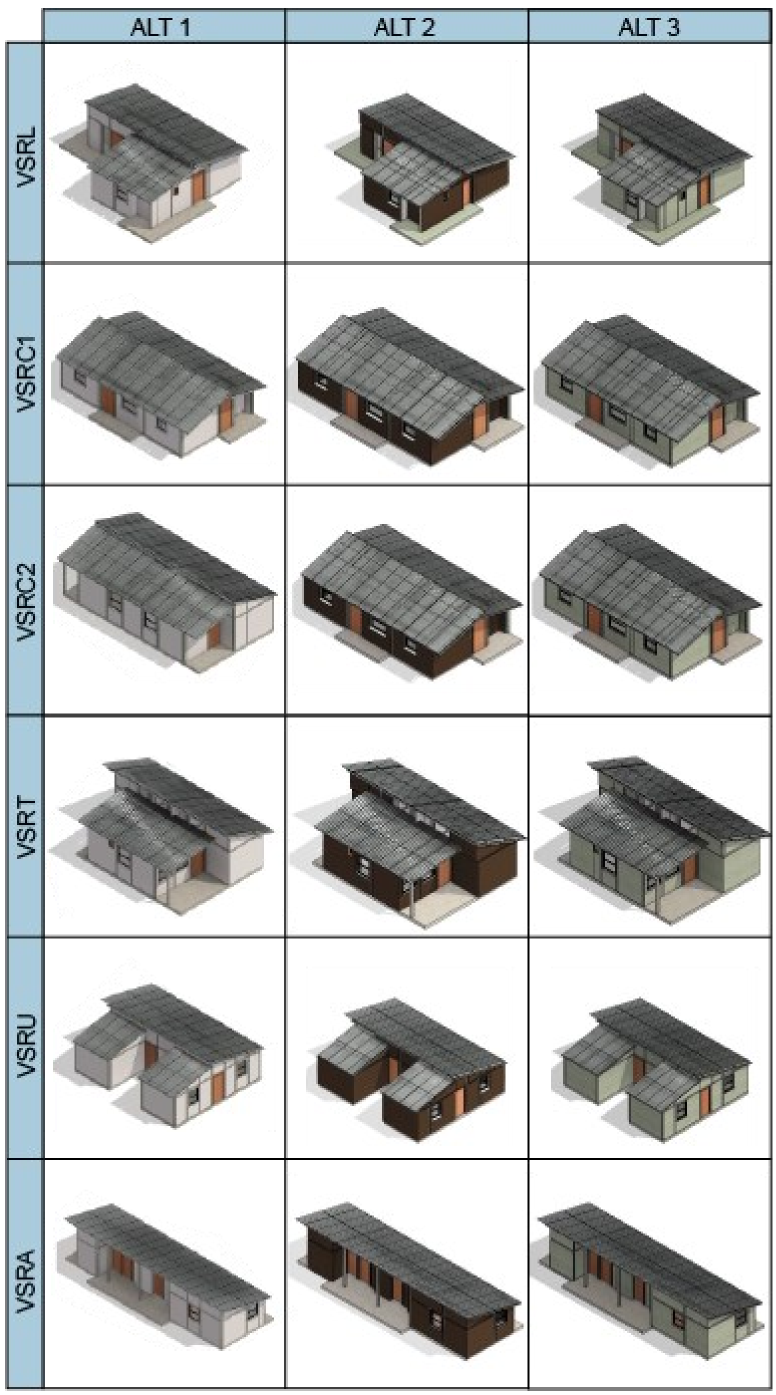

Figure 22: Materiality impacts by scenario.

As indicated in the preceding table, there are minimal disparities in terms of spatiality among the prototypes. This is primarily attributed to the fact that alterations are confined to the envelope, resulting in negligible impacts on the dwelling's dimensions. Notably, in the case of ALT 3, the wall thickness remains consistent with the original design, thereby avoiding any consequential changes. Conversely, in the ALT 2 scenario, an increase in wall thickness to 300 mm is observed. However, this augmentation is outward-facing, carefully planned to preserve the interior functionality of the home. Meanwhile, the ALT scenario features a reduced thickness of 100 mm, yet it does not compromise the shape or functionality of the dwelling.

These changes in materiality signify a difference in the thermal transmittance values of the envelopes for each scenario, it exclusively affects each prototype’s performance regarding the energy demand metric. It is depicted as follows:

COMPONENT	EXISTING	ALT	ALT2	ALT3
EXTERIOR WALLS U ($W/m^2·K$)	2.25	1.58	0.47	0.51
ROOF U ($W/m^2·K$)	7.1	0.77	0.77	0.77

Table 10: Thermal transmittance (U value) by component and scenario ($W/m^2·K$). Values from the EDGE platform used as inputs throughout the model.

From the previously described methodology, a total of 24 LCA models where produced, four for each prototype, a base scenario, ALT, ALT2 and ALT3. Rendering the following results:

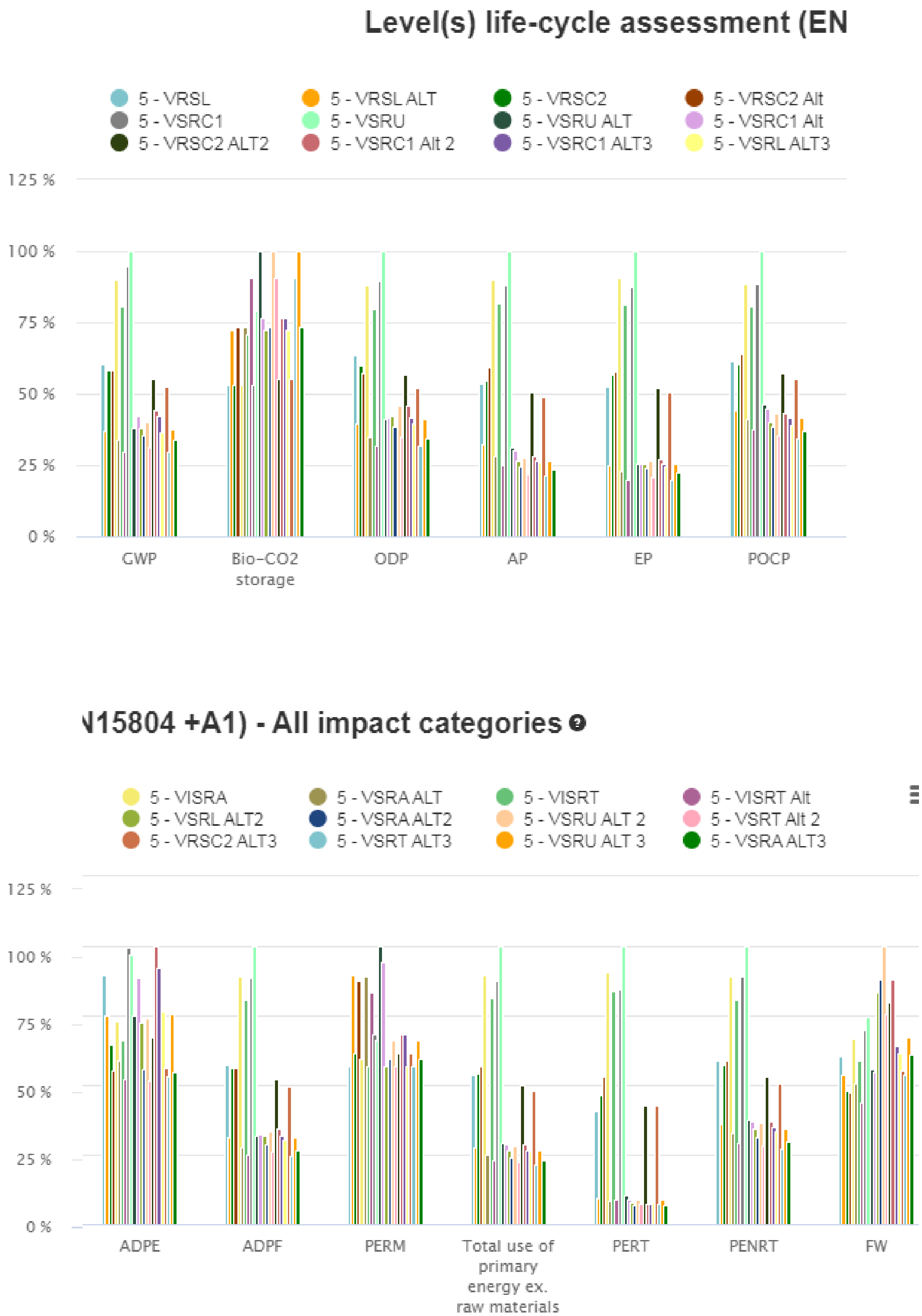

Figure 23: Overall Impact category results for all models. Produced with the One Click LCA Tool

Certainly, this information requires further analysis and comprehension. However, a notable observation from this graph is the emergence of 13 distinct impact categories generated by the model, spanning across 24 unique cases, resulting in a total of 312 individual outcomes available for analysis by category, scenario, or prototype. The present document endeavors to explore several of these potential avenues.

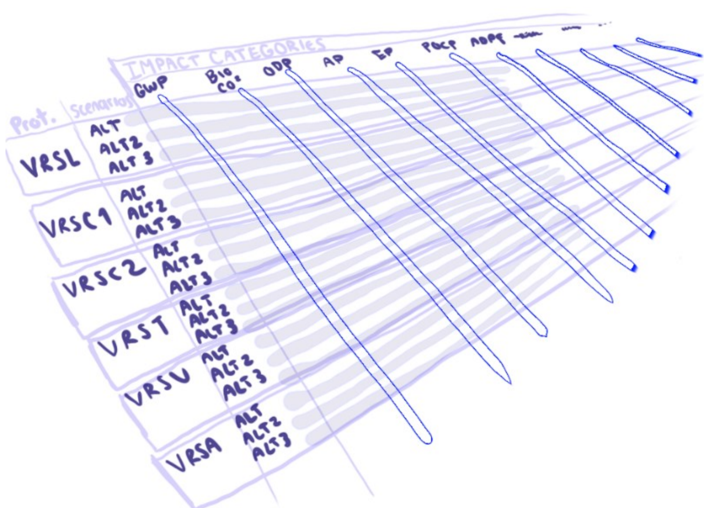

Figure 24: Information Distribution Illustration

7.2 General Analysis

Firstly, a functional unit in the present model is the embodied carbon benchmark which is measured by kg CO_2eq/m^2 and can give a glimpse into the characteristics for each case while also keeping the comparability amongst them. it is represented as follows:

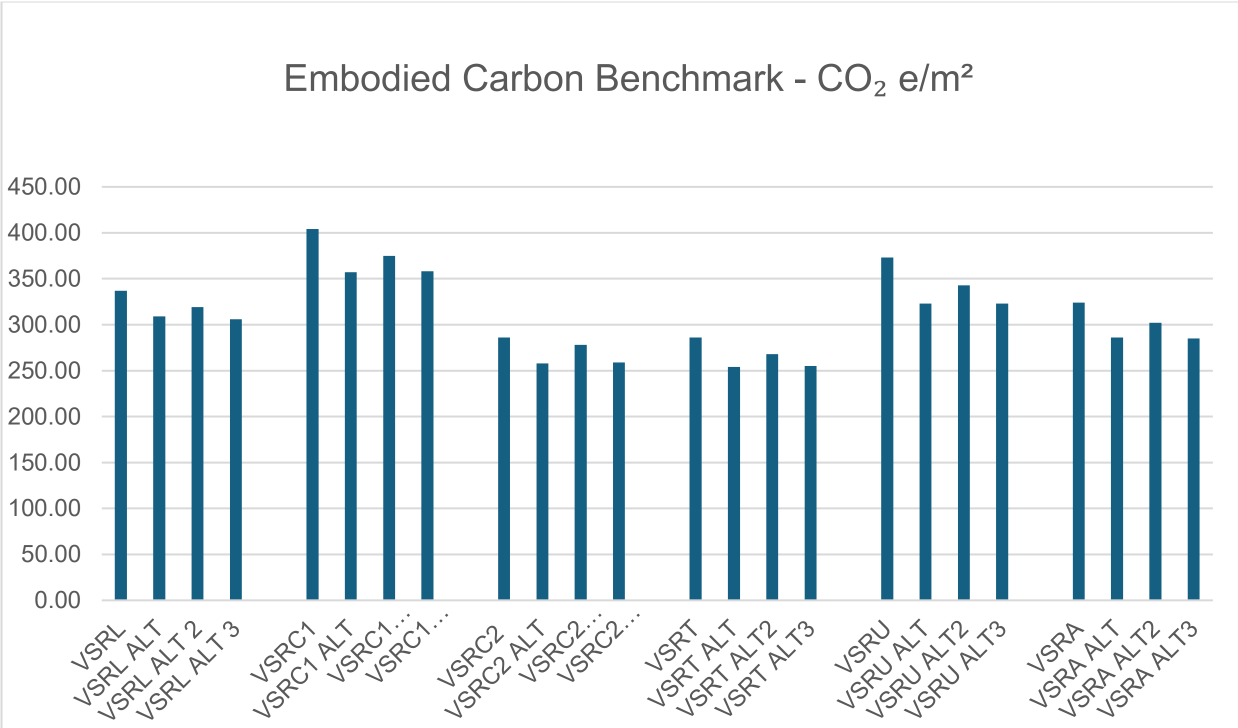

Figure 25: Embodied Carbon Benchmark for all cases.

These results provide a chance to have a look into the behavior of each case comparatively. It is important to highlight the overall higher embodied carbon that the original cases present with respect to the rest of the scenarios. Still, impact categories are analyzed, since it is important to consider the different types of influence the projects might have on its immediate context and on the environment, which will be presented.

The weight of the distinct stages in all scenarios regarding kg CO_2 can be appreciated in the following graph:

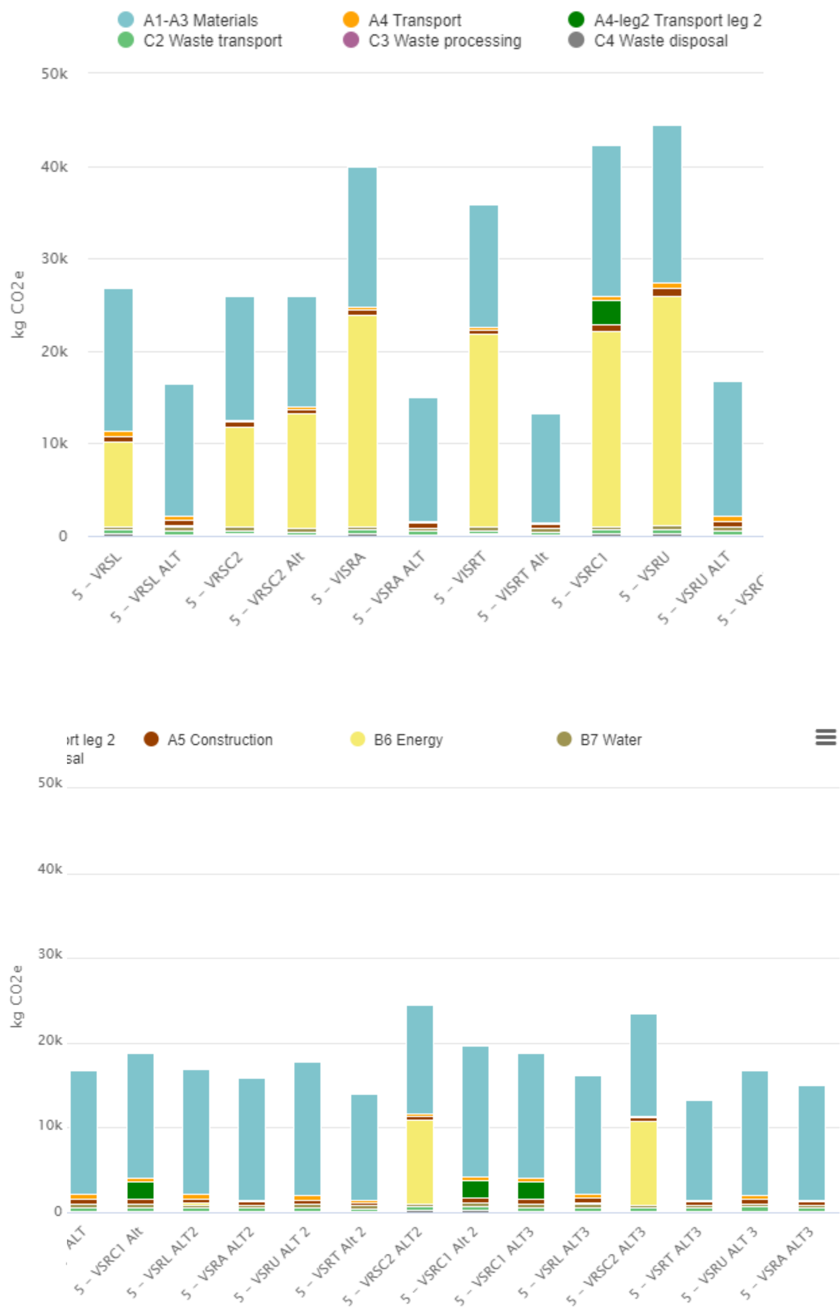

Figure 26: kg CO_2 by life cycle stage for all cases and scenarios. Produced with One Click LCA.

The analysis reveals that the B6 energy phase and production phase of materials have the most significant influence on the kg CO_2eq metric. It's also notable that transport impact is negligible, except for the VSRC1 case, which, as previously mentioned, is remote from the production site and requires extensive transportation efforts. Interestingly, the recycling phase (C3 waste processing) and waste disposal (C4) do not significantly impact the analyzed metric. This suggests that the recycling phase may only delay the release of captured carbon within materials, as implementing recycling strategies in the model actually resulted in a 0.5% increase in total kg CO_2e.

Therefore, the obtained results for impact categories can be observed in the following table, which contains the original case and 3 existing alternatives for each prototype:

Prototype	Global warming kg CO_2eq	Biogenic carbon storage kg CO_2eq bio	Ozone Depletion kg CFC11eq	Acidification kg SO_2eq	Eutrophication kg PO_4eq	Formation of ozone of lower atmosphere kg Ethane	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Use of renewable primary energy resources as raw materials MJ	Total use of primary energy ex. raw materials MJ	Total use of renewable primary energy MJ	Total use of non renewable primary energy MJ	Use of net fresh water m³	Energy demand from thermal comfort (Heating or Cooling) kWh Year
VSRL	26883.29	517.00	0.00	110.43	22.38	6.16	5.51	299132.35	481.20	417956.99	91297.93	328790.27	177.88	600.02
VSRL ALT	16430.16	706.97	0.00	66.88	10.68	4.44	4.62	162955.69	754.77	216009.50	20765.65	199814.15	158.52	0.00
VSRL ALT 2	16883.22	706.97	0.00	54.57	10.74	4.04	4.45	165570.26	481.20	208177.03	17936.62	192371.60	246.63	0.00
VSRL ALT 3	16251.75	706.97	0.00	53.37	10.40	3.92	4.73	158793.69	481.20	200844.87	17796.93	185179.14	182.33	0.00
VSRC1	42213.07	517.00	0.00	181.41	37.15	8.92	6.12	463133.69	577.44	681227.27	189438.81	494345.90	206.17	1387.00
VSRC1 ALT	18807.76	747.15	0.00	62.56	10.84	4.52	5.46	168766.82	796.20	221473.25	19423.14	207141.19	161.26	0.00
VSRC1 ALT2	19711.04	747.15	0.00	57.81	11.48	4.34	6.16	178661.00	577.44	220950.59	16750.55	206757.48	259.44	0.00
VSRC1 ALT3	18818.22	747.15	0.00	55.31	10.85	4.19	5.67	166795.12	577.44	208452.13	16571.87	194437.70	189.18	0.00
VSRC2	25975.30	517.00	0.00	112.65	23.94	6.08	3.99	295354.77	517.29	421715.65	104413.58	319593.10	141.76	715.90
VSRC2 ALT	25977.90	717.93	0.00	122.17	24.45	6.42	3.39	295555.02	740.36	442601.26	119468.24	328226.42	139.47	818.60
VSRC2 ALT2	24440.56	537.09	0.00	104.13	22.15	5.74	4.15	273395.20	517.29	388512.44	96127.04	294676.43	236.04	654.00
VSRC2 ALT3	23421.83	537.09	0.00	101.06	21.40	5.57	3.46	259553.27	517.29	373519.30	9441.70	280368.64	162.79	650.00
VSRT	35828.43	689.33	0.00	169.04	34.44	8.14	4.08	421950.47	481.20	633327.89	187625.51	447833.58	173.87	1372.00
VSRT ALT	13224.32	886.61	0.00	51.58	8.40	3.78	3.22	129938.67	703.61	177939.66	19548.96	163096.53	129.32	0.00
VSRT ALT2	13923.76	886.61	0.00	45.46	8.76	3.57	3.19	135162.71	481.20	172548.70	16796.26	157883.64	223.87	0.00
VSRT ALT3	13259.41	886.61	0.00	44.15	8.40	3.46	3.29	127484.50	481.20	164299.93	16658.33	149772.80	157.89	0.00
VSRU	44442.15	775.50	0.00	206.43	42.35	10.05	5.97	523251.30	556.59	778150.27	224197.75	556417.61	219.51	1637.20
VSRU ALT	16790.66	976.43	0.00	64.77	10.83	4.66	4.63	167340.91	844.37	226535.75	23400.30	208837.93	164.10	0.00
VSRU ALT2	17765.21	976.43	0.00	56.46	11.34	4.37	4.57	174649.01	556.59	220290.16	19915.80	202839.44	295.52	0.00
VSRU ALT3	16740.03	976.43	0.00	54.33	10.75	4.19	4.66	163024.36	556.59	207832.82	19685.71	190612.19	198.26	0.00
VSRA	39967.80	517.00	0.00	186.37	38.27	8.90	4.50	466387.81	501.25	695472.62	202641.48	495051.14	197.05	1501.00
VSRA ALT	15076.42	717.93	0.00	57.82	9.69	4.14	3.61	144992.25	752.14	195425.76	18678.73	181868.84	149.08	14.70
VSRA ALT2	15848.94	717.93	0.00	50.73	10.08	3.88	3.44	150160.75	501.25	188367.32	15537.63	175049.69	259.74	0.00
VSRA ALT3	14970.37	717.93	0.00	48.72	9.55	3.72	3.37	139620.25	501.25	177127.00	15352.01	163994.99	179.67	0.00

Table 11: Overall results across all impact categories, all scenarios, and all prototypes.

7.3 Analysis by category

As a starter, the global warming potential for each prototype is mapped as it follows:

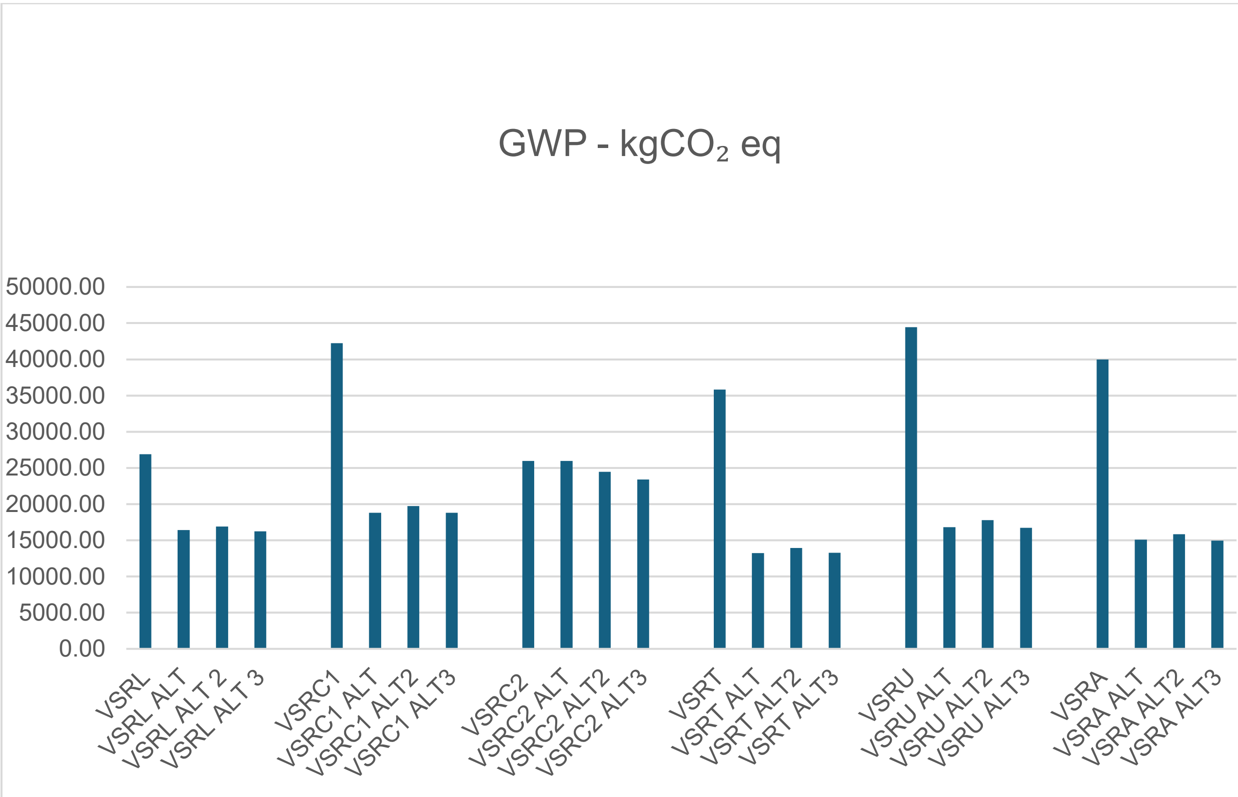

Figure 27: Global Warming Potential Comparative

This metric differs from the embodied carbon benchmark since it is not weighted by area, instead, it evaluates the complete amount of carbon and equivalent gases measured by kgCO_2 eq in each prototype. The first behavior to note is that the results from all prototypes apart from VSRC2 is similar, this is mainly because they are in similar climate zones, hence, the main drivers for differences among them should be differences in quantities of materials. Nonetheless, they keep homogeneous proportions between each alternative. Being the base prototype the one that produces more CO_2, then interestingly there is ALT2 followed by ALT. This signifies that at least in these cases, the first phase of changes is more effective for the goal to reduce GWP when compared to the implementation of rammed earth wall or CEB.

On the other hand, for prototype VSRC2 ALT2 option becomes a better solution, since it has the particularity that is a heating scenario, energy demand comes from the usage of active heating systems and as it was noted previously, the roof isolation is set to minimal, this, because during the impact assessment phase of the LCA it was observed that heat gains through the roof greatly diminish the heating demand of the space, contrary to all the rest of cooling cases which would return greater energy demand when this change is applied.

Another key category to evaluate is the biogenic carbon storage, which corresponds to carbon that is not released to the atmosphere or environment, instead, is kept within organic materials or materials from organic origin (Dincer & Bicer, 2018). Such materials are used in the project in the case of wooden doors, and cellulose panel insulation. Across the different prototypes can be represented by the following graph:

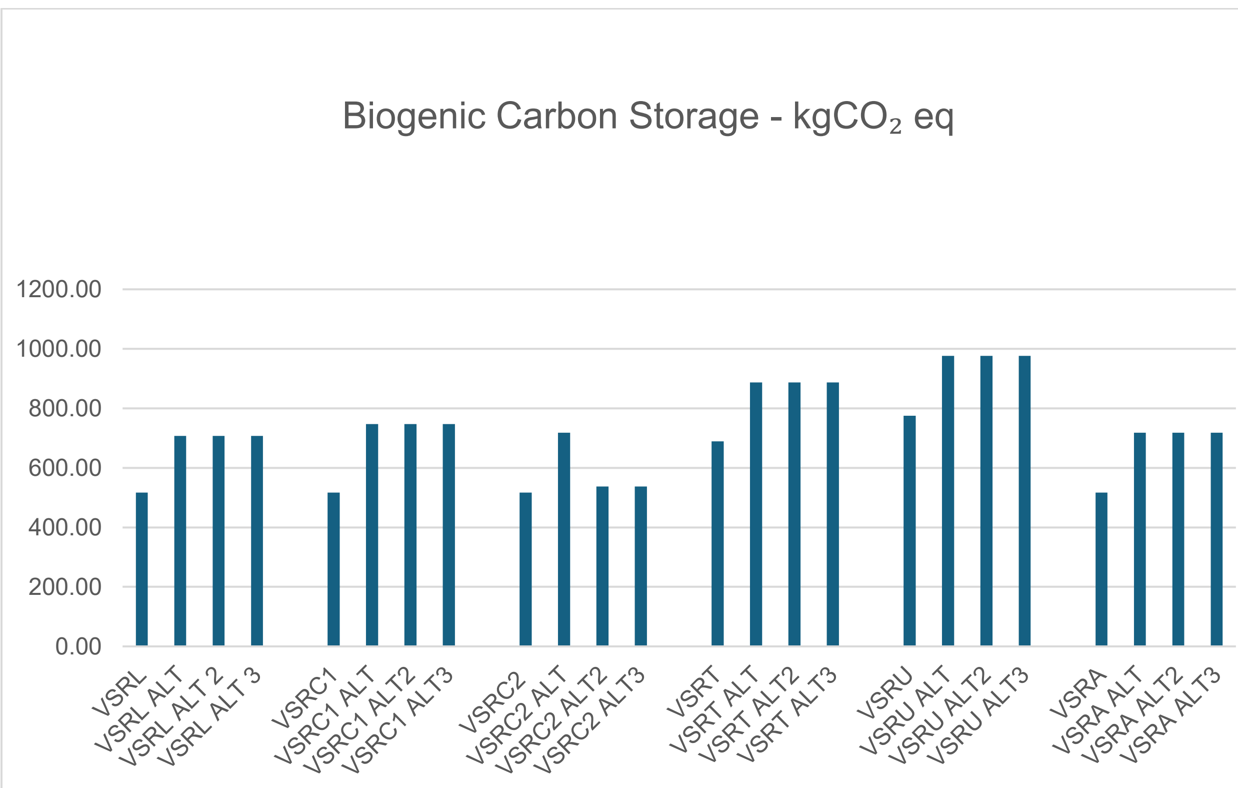

Figure 28: Biogenic Carbon Storage Comparative

As evident, the carbon storage parameter overall stays equal between the ALT, ALT2 and ALT3 options, this is due to the cellulose insulation and doors not changing throughout the alternatives. Of course, this changes in the VSRC2 prototype given that the amount of cellulose insulation is decreased to allow for more heat gains and obtain a better standing result regarding energy demand in the last two alternatives. Nonetheless, it is remarkable that the increase in carbon storage is constant along prototypes and can be beneficial regarding the environmental impact of each case.

A different category to note is the acidification potential, or AP "is connected to acid deposition of acidifying contaminants on soil, groundwater, surface waters, biological organisms, ecosystems, and substances." (Dincer & Bicer, 2018, p. 1048). Across the different prototypes, it presents the following results:

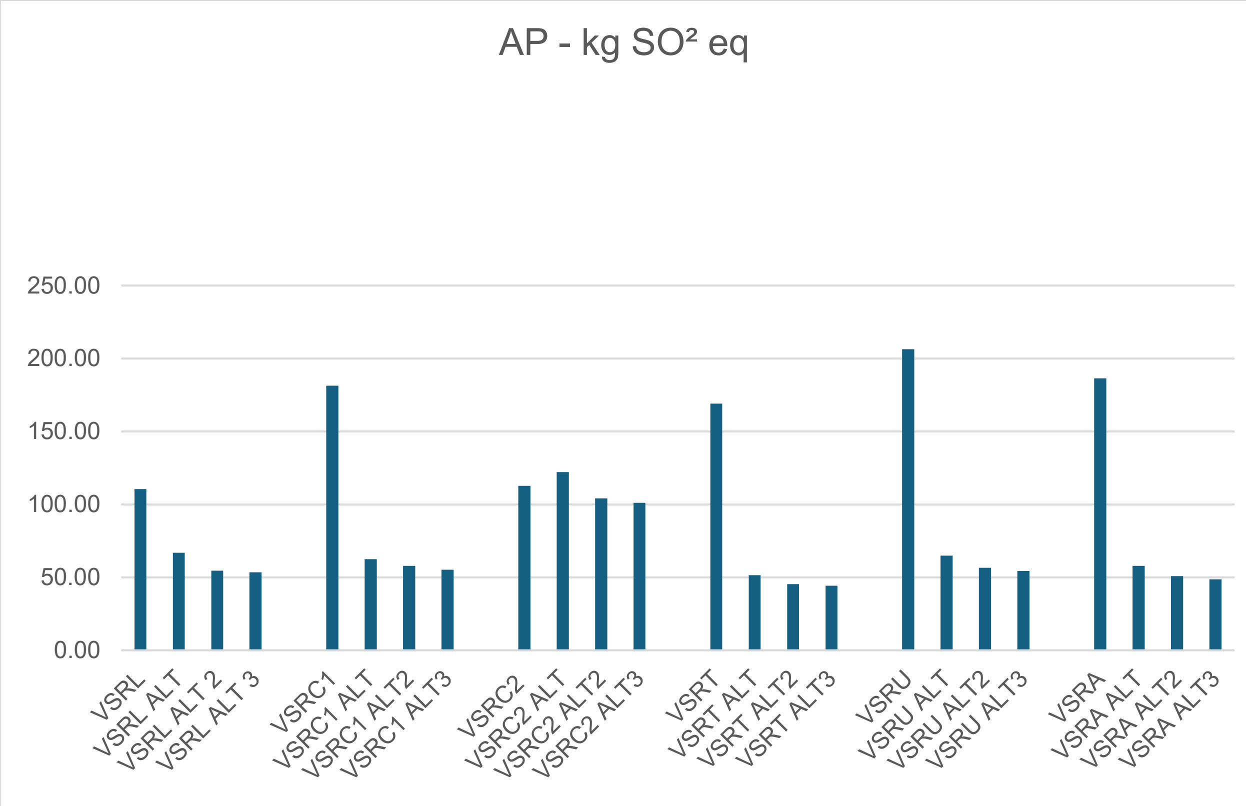

Figure 29: Acidification Comparative

Acidification potential (AP) decreases across all prototypes in the presented alternatives, apart from VSRC2, which is due to the project not being relatively far from production plants, having less transportation kilometers when compared with other cases which heavily impact this category. AP is reduced subsequently in each alternative, meaning the implementation of rammed earth wall influences and improves this category, as does the implementation of compressed earth blocks (CEB). It can also be noted that instead, the usage of masonry walls of brick and plaster covering as well as the increment in energy demand and the transportation of materials are related to the increase of this specific impact, as can be noted in the following extract from results of the VSRL base case prototype:

Life-Cycle Assessment for Level(s) in compliancy with EN 15978

	Result category	*Global warming kg CO2e*	*Biogenic carbon storage kg CO2e bio*	*Ozone Depletion kg CFC11e*	*Acidification kg SO2e*
A1-A3	Construction Materials	15 528,01 I +11 %	517 I −27 %	0 I +18 %	48,76 I +12 %
A4	Transportation to site	503,57 I +6,3 %		0 I +7 %	1,22 I +13 %
A5	Construction/installation process	659,52 I +27 %		0 I +37 %	2,1 I +28 %
B1	Use phase				
B3	Repair				
B4-B5	Material replacement and refurbishment				
B6	Energy consumption	9 116,28 I +4000 %		0 I +4000 %	51,86 I +4000 %
B7	Water use	368,07 I 0 %		0 I 0 %	2,52 I 0 %
C1-C4	End of life	705,44 I +13 %		0 I +13 %	3,95 I +16 %
D	External impacts (not included in totals)	−3 345,49 I 0,8 %		−0 I −5,8 %	−10,2 I −2,2 %
	Total	***26 880,88***	***517***	***0***	***110,42***
	Comparing total results with: 5 - VSRL ALT3				
	5 - VSRL ALT3 Total	16 251,75	706,97	0	53,37
	5 - VRSL compared with 5 - VSRL ALT3	+65 %	−27 %	+61 %	+110 %

Figure 30: Extract from VSRL Results compared with VSRL ALT 3

Where we can also observe that construction materials contribute to a 12% difference in acidification when compared to a lower case like the ALT3 scenario, as well as transportation of materials which indicate a 13% increase. Additionally, there is a representative +4000% specific increase related to energy usage. Of course, this percentage would actually be infinite since the parameter for energy usage in the ALT3 scenario is 0. Nonetheless, all of these differences accumulate, summing up to an overall total of a 110% difference when comparing both cases specifically for the AP parameter.

A different aspect to evaluate is the energy demand related to thermal comfort generated by each scenario, the results are the following:

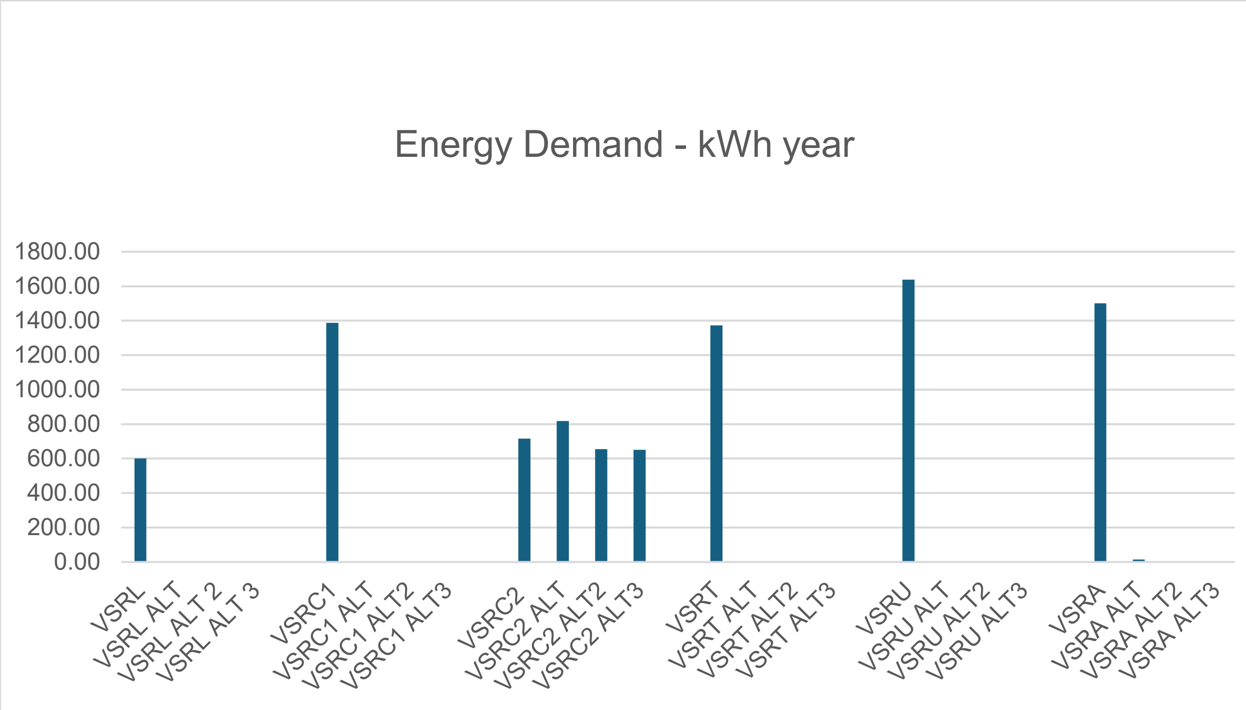

Figure 31: Energy Demand Comparative

A first aspect to highlight is the fact that in most cases, energy demand associated with thermal comfort is reduced to zero. This occurs in all cases where the demand is for cooling. It can be said that the implementation of insulation strategies, as well as attention to reducing heat gains through the roof with a 50 mm cellulose insulation as implemented, is the driving factor behind this reduction.

Additionally, it is observed that in the case of VSRC2, which requires heating, the demand momentarily increases in the ALT1 scenario, due to the implementation of 50 mm insulation, which is reduced in subsequent scenarios. Finally, there is a minimal difference in energy demand between the ALT2 and ALT3 scenarios for VSRC2, which will be elaborated when discussing the thicknesses of the wall.

7.4 Analysis by scenario

A comparative analysis between all alternatives can be conducted, by evaluating the average percentual difference between each scenario and the original case across all prototypes allowing for a comparative review of results:

Impact Category	ALT average difference from base case	ALT2 average difference from base case	ALT3 average difference from base case
Global warming kg CO_2e	-47%	-46%	-49%
Biogenic carbon storage kg CO_2e bio	36%	30%	30%
Acidification kg SO_2e	-51%	-57%	-59%
Eutrophication kg PO_4e	-58%	-58%	-60%
Formation of ozone of lower atmosphere kg Ethane	-39%	-43%	-45%
Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	-18%	-14%	-17%
Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	-53%	-53%	-55%
Use of renewable primary energy resources as raw materials MJ	48%	0%	0%
Total use of primary energy ex. raw materials MJ	-54%	-57%	-59%

Total use of renewable primary energy MJ	**-70%**	**-76%**	**-90%**
Total use of non-renewable primary energy MJ	**-47%**	**-50%**	**-53%**
Use of net freshwater m³	**-18%**	**38%**	**-3%**
Total standard deviation by scenario	**0.355825973**	**0.353459576**	**0.321528179**

Table 12: Average percentual differences by impact category and scenario.

The previous table shows several percentages, some of them positive or negative, highlighting the actual difference the scenarios had with the original cases. Some values of interest can be the total use of fresh water which displays positive and negative values, as well as the use of renewable primary energy sources as raw materials. Or other items that show entirely positive percentages as is the Biogenic carbon storage, these differences can also be visualized in the following way:

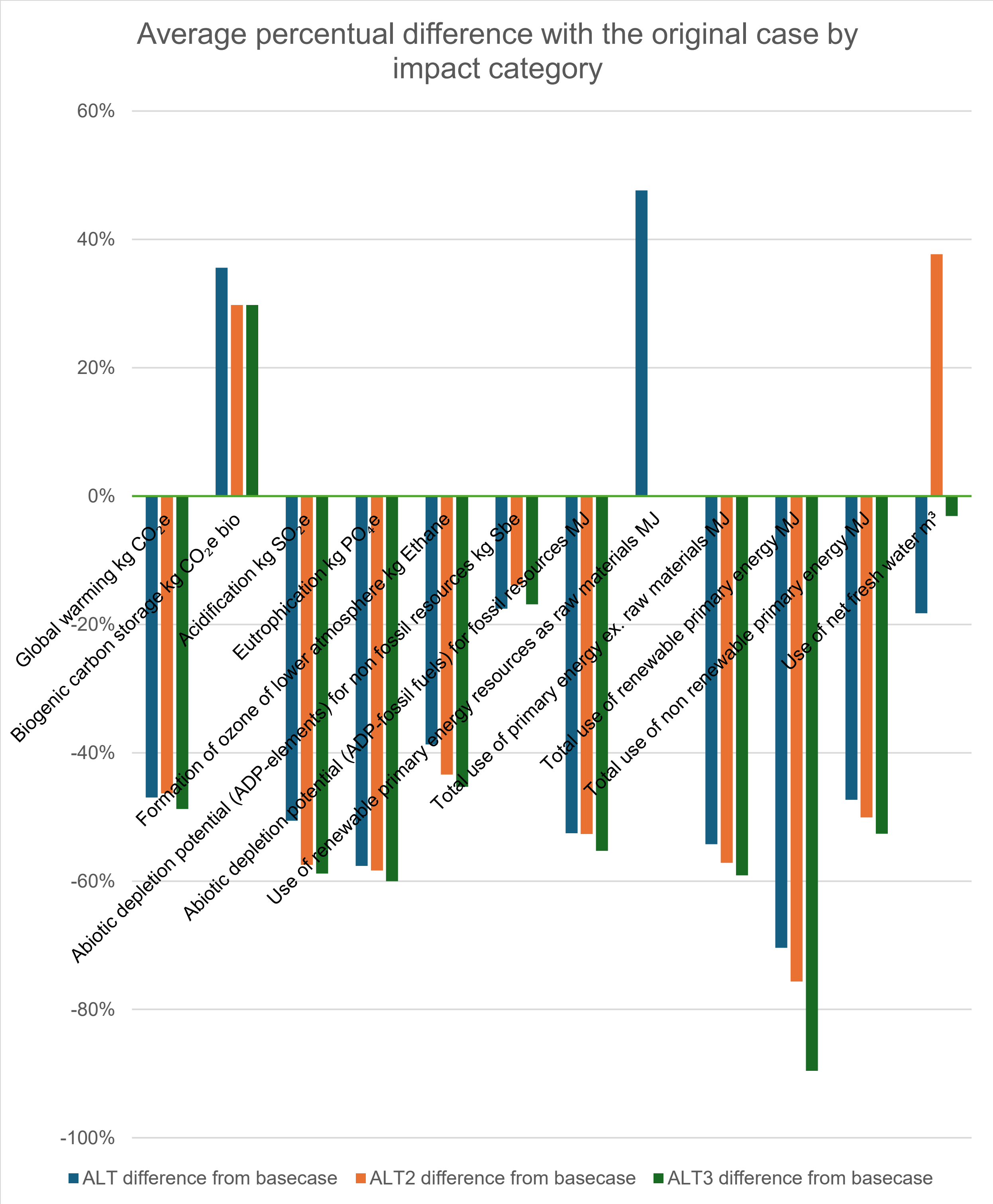

Figure 32: Grouped Bar graph from average percentual differences by impact category and scenario.

As a first observation, between ALT and the original case, all differences are negative, apart from use of renewable primary energy resources as raw materials

(PERRM) and biogenic carbon storage. When looking into the specific data for these cases, it becomes clear that the PERRM increase in the ALT scenario is due to the usage of rock wool insulation as well as the gypsum boards used for the envelope, which ponderously affects this specific impact category as can be observed in the following extract from the results of the VSRL ALT case:

Social Rural Housing Colombia: VRSL ALT

Level(s) life-cycle assessment (EN15804 +A1): Construction Materials

Construction	*Resource*	*User input*	*Use of renewable primary energy resources as raw materials MJ*	*Total use of primary energy ex. raw materials MJ*	*Total use of r… prima…*
› Building materials > Foundations and substructure > Foundation, sub-surface, basement and retaining walls					
		Section share		8,88 %	
⌄ Building materials > Vertical structures and facade > External walls and facade					
	Rock wool insulation panels, foil reinforcement and scrim kr... ?	58 m2	48,19 %	21,92 %	
	Gypsum plaster board, regular, 90% recycled gypsum, 6.5-25 m... ?	106 m2	51,81 %	28,13 %	
	Structural steel profiles, generic, 90% recycled content (ty... ?	453,2 kg		49,95 %	
		Section share	34,01 %	7,17 %	
› Building materials > Vertical structures and facade > Columns and load-bearing vertical structures					
		Section share		21,16 %	
› Building materials > Vertical structures and facade > Internal walls and non-bearing structures					
		Section share		18,35 %	
› Building materials > Horizontal structures: beams, floors and roofs > Floor slabs, ceilings, roofing decks, beams …					
		Section share		19,26 %	
› Building materials > Other structures and materials > Other structures and materials					
		Section share		13,54 %	
› Building materials > Other structures and materials > Windows and doors					
		Section share	65,99 %	11,65 %	

Figure 33: Extract from VSRL ALT Results, Detail on URPERRM parameter

As it can be noted, just on the usage of those two materials, they constitute a 34% of the overall PERRM, which is then conformed by doors and windows, a parameter that remains mostly unaffected across the original case and scenarios and can explain the 0% difference showcased in the average percentual difference from the baseline.

A different point to highlight is the fact that the use of fresh net water increases for the ALT2 scenario, as it is related to construction with rammed earth. However, in the rest of the impact categories, the ALT2 scenario shows improvements compared to the ALT1 scenario. Likewise, it is observed that the ALT3 scenario is favorable in terms of this fresh net water category, indicating that a smaller amount of water is used in the implementation of compressed earth blocks (CEB). This makes sense considering the manufacturing process of CEB, which can be done on site mechanically with machines like the CINVA-RAM (Vargas-Rubiano et, al., 2007), which do not use the same amount of water compared to the process of compressing soil within a wall in the case of rammed earth.

One final observation to make regarding the average difference chart is the fact that the last scenario ALT3 is favorable in most impact categories, which makes it attractive and positions it as the most optimal option under environmental impact analysis, often being better than scenario ALT2 by two or even three percentage points. This is also considering its favorability in terms of comfort for the heating case, which decreases from 654 kWh per year to 650 kWh per year in the case of the VSRC2 prototype. The difference may not be significant, but it is indicative of an approach to an optimal wall thickness aimed at preserving the interior temperature of the spaces.

7.5 Analysis by prototype

On a separate matter, the ongoing analysis conducted thus far highlights significant disparities between scenarios and their correlation with the original case for each prototype. However, it is pertinent to dive into the inherent relationship that each prototype may have with its performance and development. With this objective in mind, an initial process was undertaken to assess a score for each prototype, gauging its capacity to diverge and progress from the original scenario. To achieve this, the absolute value of all percentage differences with respect to the original scenarios was aggregated for each impact category, followed by computing the average of these sums for each prototype. The application of this process is exemplified in the table below, using the case of VSRL as a reference point.

VSRL SCENARIOS	Global warming kg CO_2e	Biogenic carbon storage kg CO_2e bio	Acidification kg SO_2e	Eutrophication kg PO_4e	Formation of ozone of lower atmosphere kg Ethane	Abiotic depletion potential (ADP-elements) for non fossil resources kg Sbe	Abiotic depletion potential (ADP-fossil fuels) for fossil resources MJ	Use of renewable primary energy resources as raw materials MJ	Total use of primary energy ex. raw materials MJ	Total use of renewable primary energy MJ	Total use of non renewable primary energy MJ	Use of net fresh water m^3	Average (Variance score)
VSRL ALT	-39%	37%	-39%	-52%	-28%	-16%	-46%	57%	-48%	-77%	-39%	-11%	
VSRL ALT 2	-37%	37%	-51%	-52%	-34%	-19%	-45%	0%	-50%	-80%	-41%	39%	
VSRL ALT 3	-40%	37%	-52%	-54%	-36%	-14%	-47%	0%	-52%	-81%	-44%	3%	
	1.16	1.10	1.42	1.58	0.99	0.50	1.37	0.57	1.50	2.38	1.24	0.52	1.193804

Table 13: Process of obtaining the Variance Score for prototype VSRL.

The average value of all the sums is denominated *Variance score*, this, in reference to the fact that is a representative value that will serve to compare with other prototypes and assign them a score based on their capacity to differ from the original scenario, since those are evaluated under the same impact categories. However, it is understood that this value is not representative of a real property in any capacity, since the impact categories themselves are values that exist in several different units and magnitudes. Consequently, the same process is repeated for each prototype, rendering the following results:

Prototype	Variance score
VSRL	1.19
VSRC1	1.52
VSRC2	0.45
VSRT	1.62
VSRU	1.62
VSRA	1.66

Table 14: Variance score by prototype.

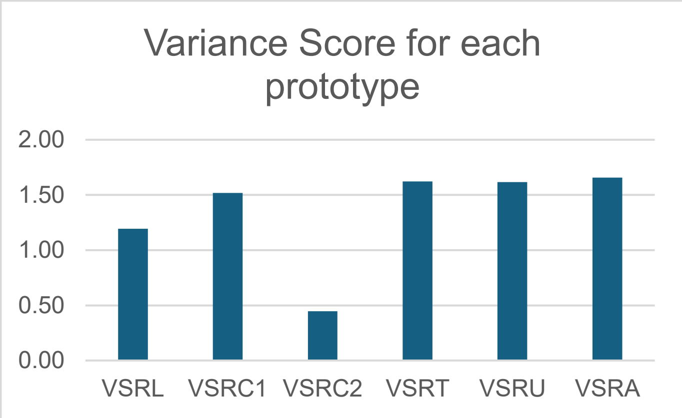

Figure 34: Bar graph of variance score by prototype.

Upon initial examination, it becomes evident that the VSRC2 prototype stands out as an outlier compared to other cases, demonstrating the least propensity for alterations relative to the original scenario. Given that the energy demand category exhibits the highest resistance to change by scenario in this instance, a correlation coefficient was computed between the variance score and the total percentage difference in energy demand achieved by each prototype from its original iteration. This analysis aimed to ascertain whether energy demand might influence a prototype's capacity for improvement across the evaluated impact categories.

Prototype	Variance score	Total energy demand difference to ALT, ALT1 and ALT2 from the original scenario
VSRL	1.19	300%
VSRC1	1.52	300%
VSRC2	0.45	43%
VSRT	1.62	300%
VSRU	1.62	300%
VSRA	1.66	298%
	Correlation Coefficient:	0.930449931

Table 15: Correlation Coefficient between variance score and energy demand.

Therefore, a strong relationship can be observed between both variables, with the correlation coefficient arriving at a 0.93 value, where a value of 1 would mean a perfectly linear relationship and a value of 0 would indicate no existing relationship. A scatter graph representing this relationship can also be visualized:

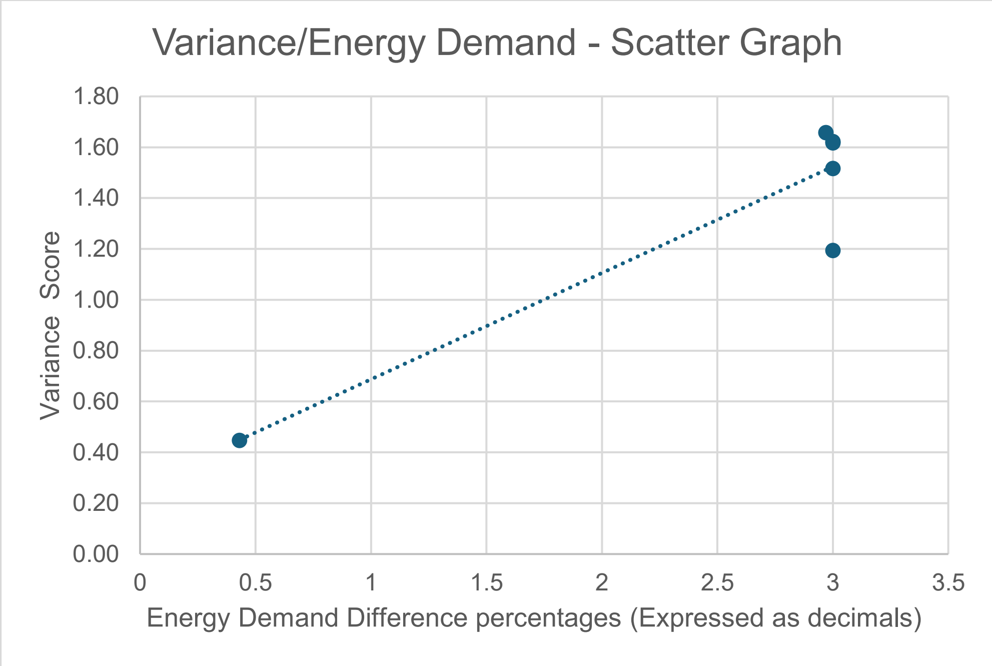

Figure 35: Scatter graph for Variance Score/Energy Demand

This can be explained by the impact the energy demand has on the overall LCA model, keeping into account that the energy demand input is then accounted for each year in the building life cycle, having a total of forty. This can exemplify why it constitutes most of the resources that contribute to the global warming potential GWP as can be seen on the following extract from the prototype VSRA results:

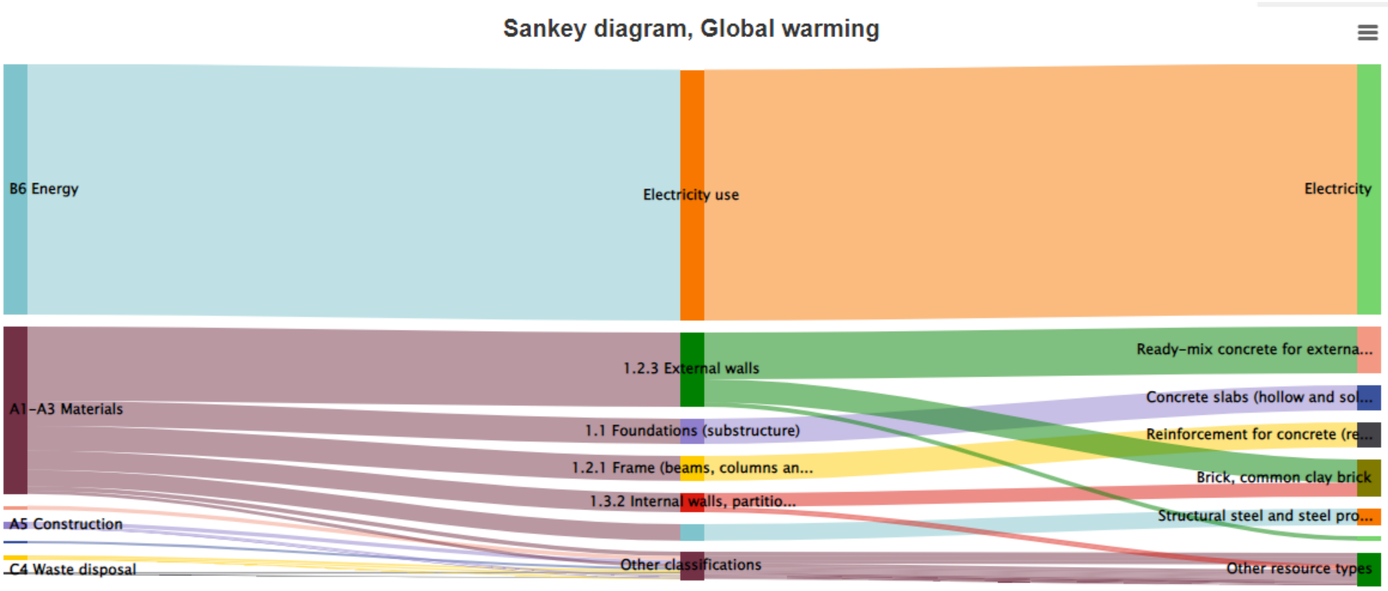

Figure 36: Sankey diagram of GWP resource types. VSRA Prototype - Produced with the One Click LCA platform.

Comparatively, the following is the Sankey diagram for GWP of the VSRA Alt scenario, where it is apparent that the electricity value disappears, and it is the materials providing most of the GWP value:

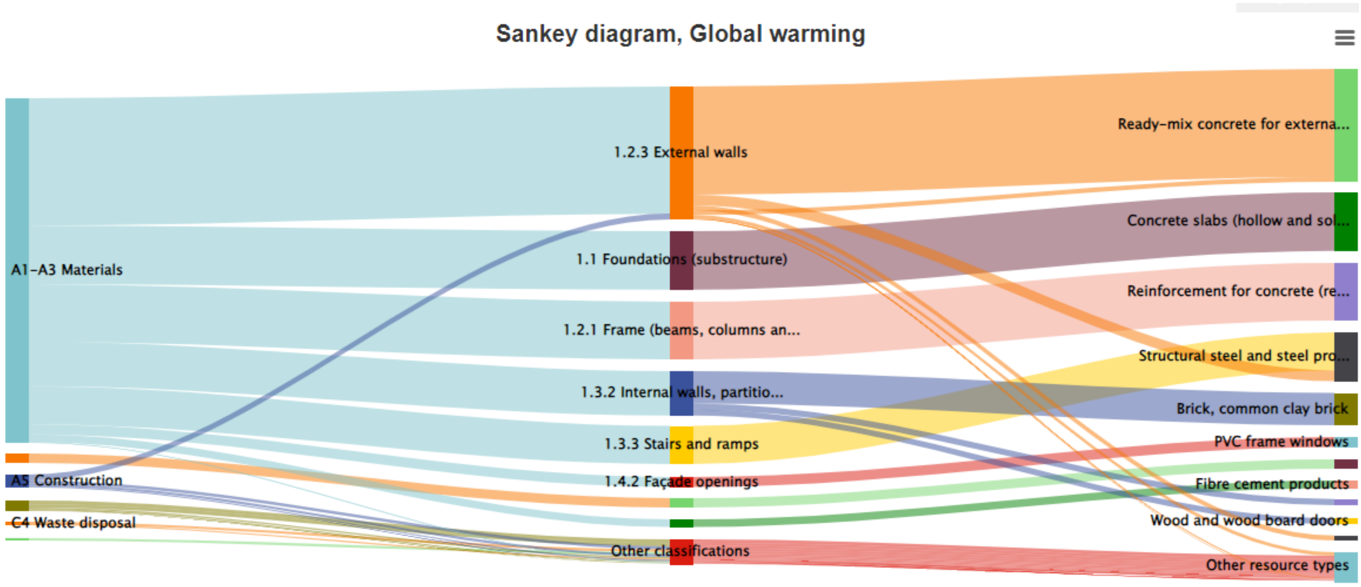

Figure 37: Sankey diagram of GWP resource types. VSRA Alt Scenario - Produced with the One Click LCA platform.

Furthermore, to explore additional factors that could influence a prototype's potential for improvement, a separate correlation coefficient was assessed. Specifically, this analysis examined the relationship between a prototype's physical attributes, such as the total façade area, and its variance score. The findings of this analysis are outlined below:

Prototype	Total Facade Area	Variance score
VSRL	58	1.19
VSRC1	62	1.52
VSRC2	53	0.45
VSRT	63	1.62
VSRU	79	1.62
VSRA	71	1.66
	Correlation Coefficient:	0.75

Table 16: Correlation Coefficient between variance score and total facade area.

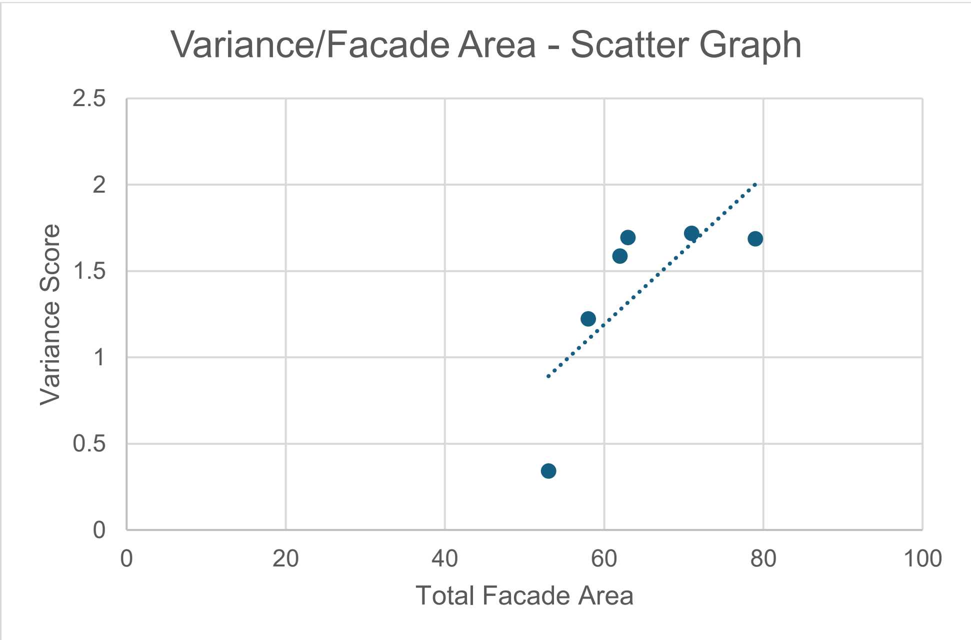

Figure 38: Scatter graph between Variance Score and Facade Area

In this scenario, utilizing the total façade area as the independent variable still reveals a notably strong correlation with the variance score parameter. Although the correlation coefficient in this case is smaller compared to the previous one at 0.75, the data points on the graph exhibit less dispersion. This aligns with the methodology employed in this study, as most material alterations occur within the façade. However, this observation prompts further consideration regarding whether a building designed for future evolution stands to gain from a greater proportion of replaceable surface area that can accommodate improvements.

With the objective of evaluating what other possible effects can be correlated with the façade area, a different correlation coefficient is evaluated, in this case, with the total percentual difference gotten for GWP on each prototype, the results are presented in this manner:

Prototype	Total Facade Area	Total GWP difference to ALT, ALT1 and ALT2 from the original scenario
VSRL	58	115.63%
VSRC1	62	164.17%
VSRC2	53	15.75%
VSRT	63	187.22%
VSRU	79	184.58%
VSRA	71	185.17%
	Correlation Coefficient:	0.76

Table 17: Correlation Coefficient between total GWP difference across scenarios and total facade area.

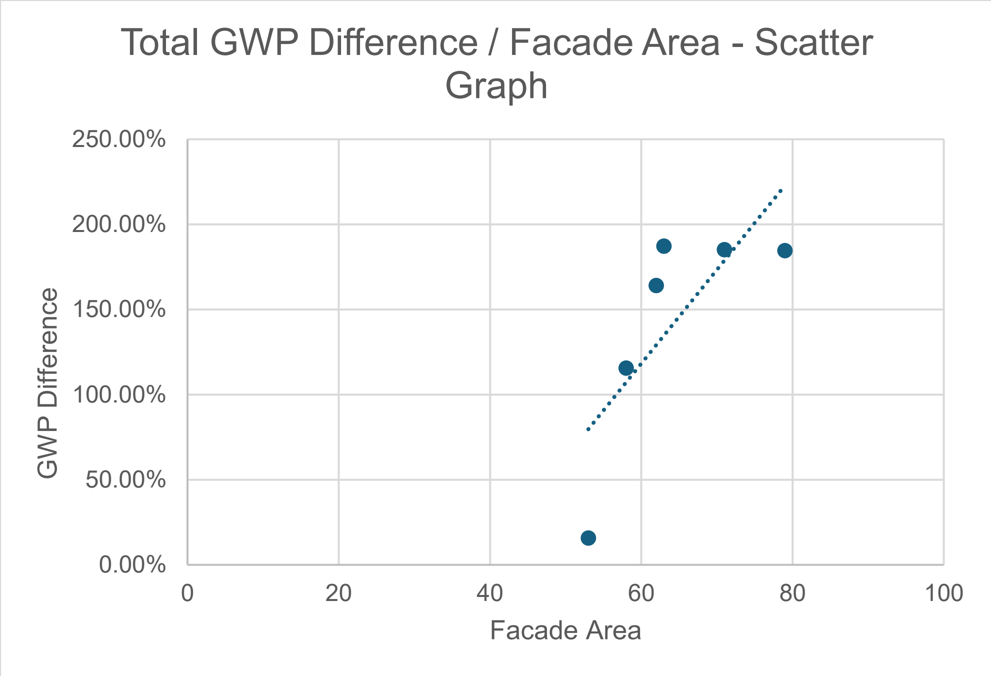

Figure 39: Scatter graph between Total GWP difference and façade area.

The graph exhibits a comparable pattern to the previous one, suggesting that the façade area similarly influences the GWP difference across all scenarios relative to the variance score.

8. Discussion

While it is true that there is room for discrepancies on the EPD's submitted by manufacturers, (Cruz & Finnegan, 2021, p.3) it is still important to encourage the sector to apply this life cycle methods specially in a context of a country in development like Colombia. Since it can pressure more companies in the industry to also apply for eco-labels and certifications, making the process more precise and dependable eventually.

It is also important to question the processes behind the submission of such prototypes and ponder their relevance and feasibility of application within the sector. While it is something of value to have an intention of adaptability for each prototype, the reality is that in all cases not a clear path for adaptation was drawn, hence, leaving that responsibility for later stakeholders in the process to take. Some of these stakeholders potentially being private construction companies whose interest might be moved by market dynamics and not the well-being of the home's final users (Ceballos, 2006).

The presented LCA cases show the potential that exists in the application of such analysis in a rural context where several distinct factors might come into play, like astonishingly long distances to production centers the case being the VSRC1 prototype in Guainía or humid and hot condition in Aracataca, Magdalena where the prototype VSRA was located. All the diverse sources of information in the LCA inventory being able to be contrasted and read in a seamless way through the impact categories provide a picture of the impact an architectural project might have on the environment and its users.

In this case, the comfort parameter was input through the energy demand information obtained from a simulation platform such as EDGE. Nonetheless, this approach can evolve, being able to incorporate more precise and complete tools for energy demand information, which can evaluate architectural gestures that can range from overhangs, shading systems, and an increment in different strategies that could be incorporated in the betterment of base cases and proposal of new projects, giving more insight into different architectural technologies and the impact they can produce in the built environment, natural environment and its users.

One of the most recurrent aspects in the literature review was the criticism from various authors regarding the emergence of architectural bodies detached from the landscape, or as many of them term it, "decontextualized architectures". Nonetheless, in the present investigation, the topic of prototypes was still approached as an alternative for rural social housing. The main intention behind this is precisely to contribute to and enrich the existing prototype design processes, aiming to foster architectural bodies that are less detached and more connected and mindful of their immediate environment and the end-user who will occupy them. The impacts on the immediate environment being one of the key factors to improve in the current context.

A notable aspect is the fact that cost considerations are not present in this analysis. While, indeed, in some instances, alternatives exhibit proximity concerning their environmental impact categories, a crucial factor for a more comprehensive evaluation of the optimal choice is cost. Yet, at the moment of writing, the integration of a life cycle costing analysis (LCC) with an LCA remains a subject under exploration in the field. Encompassing such an analysis would introduce additional variables that go beyond the current research scope. However, this leaves an open question and an invitation for future investigations to explore this realm.

An area for potential exploration in future research is the orientation of the house. In this study, the orientation of each prototype was input as indicated on the plan to ensure consistency for analysis and comparability. However, there is potential for further investigation using a developed platform capable of evaluating the impacts of rotating the architectural body in real time. Such an analysis could provide valuable insights into how orientation influences energy demand, thereby enhancing the decision-making process in housing planning and construction.

One noteworthy result is the complete elimination of energy demand related to cooling in all scenarios. This highlights the effectiveness of passive strategies in the Colombian context, where although the climate is varied, the absence of extreme seasonal fluctuations renders active strategies like cooling devices unnecessary in most cases. This, coupled with the negative carbon impact stemming from biogenic carbon storage, as well as the evaluation of a different type of strategies such as cross ventilation and architectural and spatial strategies could suggest a pathway toward achieving a carbon-neutral status for rural housing projects, an area ripe for further exploration within the Colombian context.

On another note, an aspect to consider is the organization of the program within each prototype, as it has been shown in the methodology section, it can differ from each case, finding more optimized solutions where the square meters dedicated to circulation are reduced with respect to other prototypes, the space is then used for specifical activities which can be productive or as Acevedo & Hurtado (2022) note, be turned into encounter spaces for leisure and community building which are specially beneficial in this context.

The relevance of putting various prototypes to a vote among different regions in a participatory process led by the government is questioned, particularly when the differences between the prototypes primarily concern program distribution, with similar square meters and construction materials and techniques across the board. This prompts consideration of the significance of these differences for each region. Was there a clear purpose behind these participative workshops, or was the government-driven process more focused on showcasing outcomes that may not translate into substantial improvements for users and their respective communities?

9. Conclusions

9.1 On LCA as a tool

Impact categories from the LCA approach are representative of the sustainability impact for each prototype. Nonetheless, these impacts are related mostly to the production phase of the materials. Information about the immediate environmental impact for each construction in the operational phase is limited and can be improved with more information added to the EPD of each product. Thermal comfort is implicit within the energy demand parameters, making this approach a holistic alternative to the analysis and evaluation of rural housing projects, a type of approach provides an effective insight regarding the different aspects and parameters present in said context as the work of Gianetti et al, (2018) suggests.

Specifically, the available information is mostly related to techniques that use soil for construction, overlooking specialized techniques that can be used in specific cases, such as the construction of walls and surfaces woven with plant fiber or so-called "esterilla", or even the traditional bahareque more commonly known in the global north as wattle and daub, which is representative and existing in the region but not included within the currently analyzable techniques. Hence, there is a need to update, parameterize, and inventory such technologies for subsequent evaluation and comparison of their viability in different contexts.

Figure 40: Photography - Presence of "Esterilla" ceiling in traditional rural construction - Nobsa, Boyacá, 2022.

Nonetheless, the LCA impact in the prototypal approach to rural social housing has been shown to be potentially positive. Since it is able to evaluate a model in different conditions and decision making being informed by said analysis, one of the most sheer cases of this being the VSRC2 model, in which the decision to decrease roof insulation was made, resulting in a reduced energy demand parameter allowing heat gains from the exterior and an improved environmental impact associated with reducing the amount of cellulose material used in that specific case, exemplifying how the implementation of such methodology can enrich and benefit decision making behind the design of projects.

Another notable aspect of LCA analysis is its capacity for expansion with newly generated information and cases. Throughout the course of this investigation, the number of scenarios increased, affording the opportunity to integrate varied materials into previously parameterized prototypes. This highlights the potential for adaptability and scalability inherent in LCA analysis, as it can be continually updated with recent information and findings. Such flexibility is crucial when assessing the feasibility of its implementation in a sector that increasingly demands updates and innovation, as noted by Acevedo (2012).

9.2 On the housing envelope

Regarding the ALT scenario, it is evident that industrialized processes such as dry construction with gypsum panels and the addition of thermal insulation can benefit housing prototypes, resulting in mostly improvements of up to 40% in impact categories and mostly total reductions in energy demand. It is worth noting that these panel modifications can be applied progressively, considering the frame construction system in the actual prototypes and even in accordance with progressive adaptation ideas introduced by Fathy (1986) and Acevedo & Hurtado (2022). Their hybrid implementation alongside the other two scenarios; ALT2 and ALT3 respectively can even be considered. The idea of adding technologically advanced techniques to low-cost rural housing construction in relation with the industrially used “wet” construction with masonry walls covered by plaster is undoubtedly an option to evaluate based on the results obtained.

While in most of the presented results, the ALT cases that implement lightweight construction are superior to the ALT2 scenario, that uses rammed earth, a solid case can be made for both of them improving the overall conditions of the base cases for each prototype. While it is most likely that the rammed earth alternatives return in average 2% more impact on global warming potential when compared with ALT, this is heavily affected by the stabilization cement within the material and the overall thickness of the wall, 300 mm, hence, signifying an increase in the total mass of the wall when compared to a hollow clay brick wall with overall 150 mm thickness. Still, the fact that they are within that range means that rammed earth environmental impacts can still be improved with tuning and adjusting the material properties, implementing strategies like lime stabilization instead of cement which was tested returning a 2.7% improvement on the global warming category, or implementing strategies to reduce its thickness, potentially returning an even better result in a next iteration.

As for the ALT3 scenario, it is evident that it presents improvements in the majority of impact categories and has the potential to be widely used in most regions. It is important to clarify that the use of CEB blocks facilitates these findings and conclusions. Considering that it does not require extensive transportation distances, with soil being the main material to be used, and even considering the implementation of cement for stabilization, it yields favorable results compared to the other scenarios.

A key factor to highlight is that for the ALT2 and ALT3 scenarios, unskilled labor is an option, and the involvement of users in the housing construction process is an added value that can be incorporated into these options. As demonstrated in the work of Arroyave et al. (2021), the involvement of communities in the construction of housing is not only beneficial for cost reduction but also contributes to the concept of collaboration and building relationships, which has historically been present in the development of vernacular constructions and has gradually diminished over time, as indicated by Saldarriaga & Fonseca (1980) and Anzellini & Garcia-Reyes (2019).

Consequently, improving impact categories is feasible since the burning of fossil fuels in the production of region-specific materials like earth or plant fibers is nonexistent. Since most of them implement organic materials or components from organic origins, they can provide the added value of carbon storage. Similarly, transport distances decrease, although, as reflected in the models, the carbon cost of transportation is minimal when compared with the carbon cost of material production. This point being reflected in the most remote prototype, VSRC1 which is still proportionally distributed across scenarios in an equivalent manner to the rest of the models.

Furthermore, studies similar to this one may potentially offer an additional benefit by potentially enhancing the living conditions for users. Thermal comfort, recognized as one of the primary considerations, has been subject to evaluation, it is worth noting that this is not always the case and that the health and well-being of users are often sacrificed as exposed in the literature review. For this reason, the need to evaluate this impact on well-being is highlighted, and furthermore, to demonstrate that often the well-being of the user and the economic and feasibility improvement of a project can align and not conflict with each other. As observed, the reduction in energy demand for thermal comfort is beneficial for generating fewer environmental impacts, lower energy costs, and users who often come from vulnerable environments (Ceballos, 2006) finding themselves in a space that can provide them with well-being and optimal conditions for the development of living and productive activities.

9.3 On the approach by the government with public policy

Emphasizing the urgency for a paradigm shift in public policy regarding the construction of rural social housing in Colombia is paramount. Incorporating concepts such as energy efficiency and understanding the building life cycle, akin to practices in Europe, holds significant promise. This transformative process can foster a deeper appreciation for each region's unique context and the needs of its inhabitants.

The critique offered by Guardiola & Velandia (2018), highlighting the disconnect between government-led design teams and the realities of local regions and cultures, remains pertinent today, as evidenced by recent prototype models. Only through a conscientious approach to addressing these issues can we lay the groundwork for the successful implementation of LCA analyses as the one outlined in this document, while also leading to tangible improvements in the lives of beneficiaries. It is striking that in the document produced by the housing ministry or MVCT (2021), a clear intention to localize the approach is stated “Structuring the projects based on regional scale and operability (supply) along with the typological, functional, and cultural parameters of the housing solutions specific to the region (demand)” (p.43). In the same document, even after citing Guardiola & Velandia’s 2018 work, said intention was only manifested in words but not clear design solutions or guidelines to localize the later proposed prototypes.

Hence, this study demonstrates the potential for various alternatives to undergo assessment, possibly leading to improvements that not only could enhance the project's economic viability but also contribute to the overall quality of life for its end users. This aspect holds particular significance for developing countries, as underscored by Giraldo (1992): “There cannot be economic development if we do not pay attention to housing, which is where the worker lives, eats and rests." (p.14). However, further research is warranted to ascertain the broader implications of these findings and to explore additional avenues for enhancing the effectiveness and sustainability of rural social housing initiatives in Colombia.

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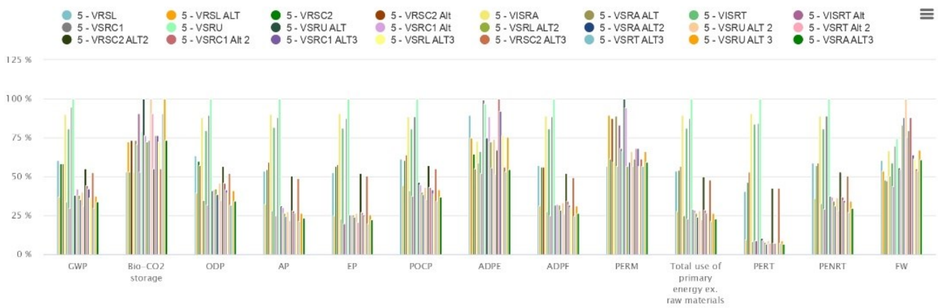
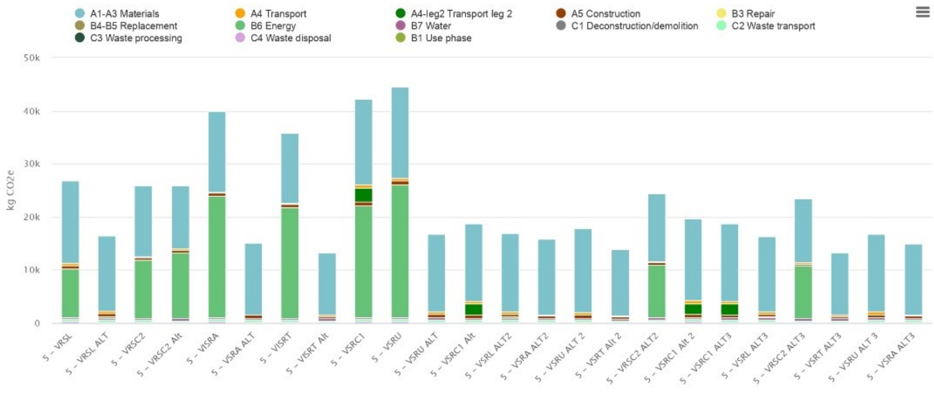
11. Appendix

11.1 Report from *One Click LCA*

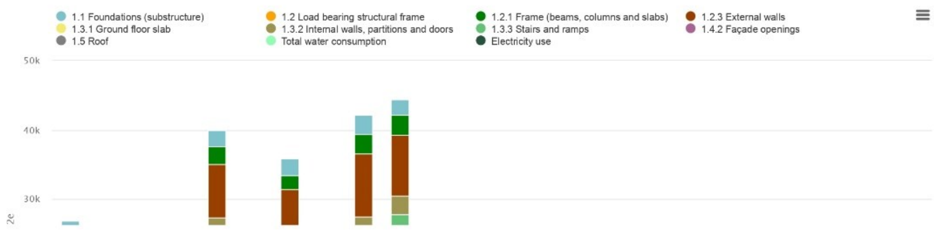
Level(s) life-cycle assessment (EN15804 +A1) - All impact categories

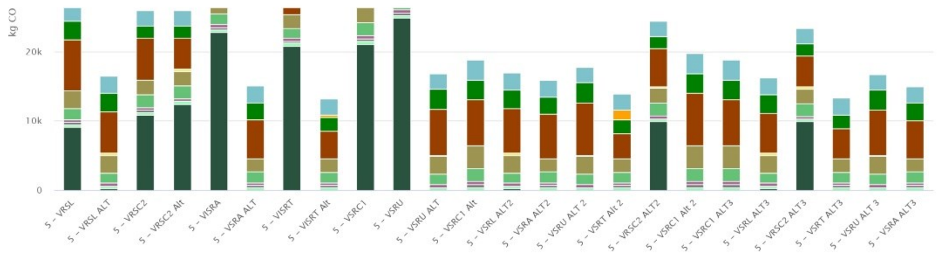


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Life-cycle stages

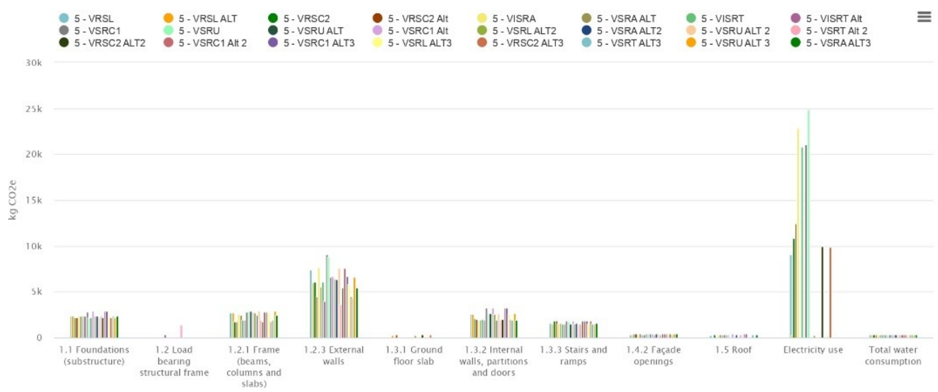


Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements

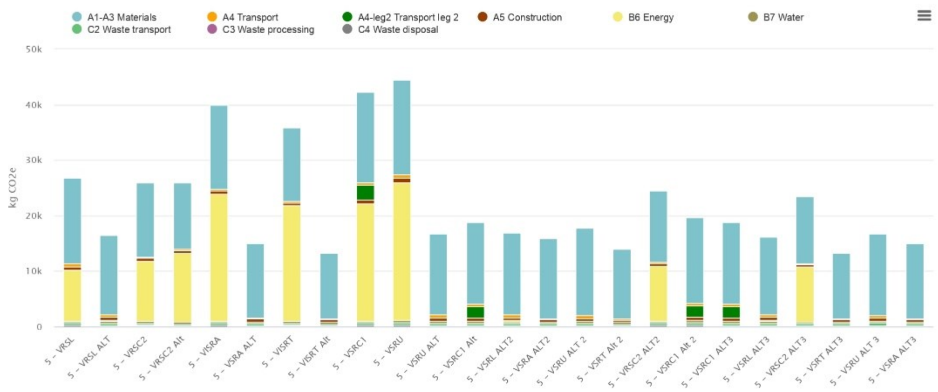




Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Compare elements



Level(s) life-cycle assessment (EN15804 +A1) - Global warming, kg CO_2e - Elements and life-cycle stages



11.2 Report from *EDGE APP*

Subproject Name	Project Name	Project Status	Auditor Name	Certifier	Building Type	Country	Version Number	File Number
VRSL	VRSL	Self-Review			Homes	Colombia	v3.0.0	24010810182487
VRSL Alt	VRSL1 Alt	Self-Review			Homes	Colombia	v3.0.0	24010910182532
VRSL Alt2	VRSL Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183633
VRSL Alt3	VRSL Alt3	Self-Review			Homes	Colombia	v3.0.0	24012510183634
VSRC1	VSRC1	Self-Review			Homes	Colombia	v3.0.0	24012310183466
VSRC1 Alt	VSRC1 Alt	Self-Review			Homes	Colombia	v3.0.0	24012310183471
VSRC1 Alt2	VSRC1 Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183637
VSRC1 Alt3	VSRC1 Alt3	Self-Review			Homes	Colombia	v3.0.0	24020510185478
VRSC2	VRSC2	Self-Review			Homes	Colombia	v3.0.0	23121010180765
VRSC2 Alt	VRSC2 Alt	Self-Review			Homes	Colombia	v3.0.0	24010710182443
VRSC2 Alt2	VRSC2 Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183636
VRSC2 Alt3	VRSC2 Alt3	Self-Review			Homes	Colombia	v3.0.0	24020510185486
VSRT	VISRT	Self-Review			Homes	Colombia	v3.0.0	24011610183067
VSRT Alt	VISRT Alt	Self-Review			Homes	Colombia	v3.0.0	24011610183070
VSRT Alt2	VISRT Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183634
VSRT Alt3	VISRT Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183635
VSRU	VSRU	Self-Review			Homes	Colombia	v3.0.0	24012310183464
VSRU Alt	VSRU Alt	Self-Review			Homes	Colombia	v3.0.0	24012310183465
VSRU Alt2	VSRU Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183632
VSRU Alt3	VSRU Alt3	Self-Review			Homes	Colombia	v3.0.0	24012510183633
VISRA1	VISRA1	Self-Review			Homes	Colombia	v3.0.0	24011510182971
VISRA Alt	VISRA Alt	Self-Review			Homes	Colombia	v3.0.0	24011510182978
VISRA Alt2	VISRA Alt2	Self-Review			Homes	Colombia	v3.0.0	24012510183630
VISRA Alt3	VISRA Alt3	Self-Review			Homes	Colombia	v3.0.0	24012510183631

Project Number	Share with Bank(s)	Energy	Water	Material	Energy Savings(MWh/Year)	Water Savings(m³/Year)
1001433151	Yes	-2.09%	0.00%	23.00%	-0.17	0
1001433544	Yes	2.49%	0.00%	24.00%	0.2	0
1001442978	Yes	2.49%	0.00%	24.00%	0.2	0
1001442979	Yes	2.49%	0.00%	24.00%	0.2	0
1001441402	Yes	-7.39%	0.00%	20.00%	-0.44	0
1001441457	Yes	15.14%	0.00%	23.00%	0.92	0
1001443013	Yes	15.14%	0.00%	23.00%	0.92	0
1001450629	No	15.14%	0.00%	23.00%	0.92	0
1001417459	Yes	-4.57%	0.00%	21.00%	-0.4	0
1001432661	Yes	-4.55%	0.00%	24.00%	-0.4	0
1001443006	No	-2.47%	0.00%	23.00%	-0.22	0
1001450705	Yes	-2.43%	0.00%	23.00%	-0.21	0
1001437935	Yes	-7.95%	0.00%	20.00%	-0.5	0
1001437966	Yes	15.06%	0.00%	23.00%	0.94	0
1001442985	No	15.06%	0.00%	23.00%	0.94	0
1001442986	No	15.06%	0.00%	23.00%	0.94	0
1001441388	Yes	-7.57%	0.00%	21.00%	-0.47	0
1001441395	Yes	15.31%	0.00%	24.00%	0.95	0
1001442961	No	15.31%	0.00%	25.00%	0.95	0
1001442962	No	15.31%	0.00%	25.00%	0.95	0
1001437173	Yes	-7.31%	0.00%	19.00%	-0.44	0
1001437235	Yes	15.94%	0.00%	23.00%	0.96	0
1001442947	Yes	15.94%	0.00%	23.00%	0.96	0
1001442948	Yes	15.94%	0.00%	23.00%	0.96	0

Embodied Energy in Material Savings(GJ)	Embodied Carbon in Material Savings(tCO_2e)	CO2 Savings(tCO_2/Year)	Total Project Floor Area(m^2)
	5.12	0	42.07
	6.09	0.04	48.86
	6.08	0.04	48.86
	6.08	0.04	48.86
	5.32	0	52.12
	6.27	0.19	52.12
	6.08	0.19	52.12
	6.08	0.19	52.12
	5.41	0	50.06
	6.38	0	50.06
	6.05	0	50.06
	6.04	0	50.06
	5.12	0	49.55
	5.75	0.2	49.55
	5.73	0.2	49.55
	5.73	0.2	49.55
	5.19	0	46.93
	6	0.2	46.93
	6.11	0.2	46.93
	6.11	0.2	46.93
	5.38	0	54.04
	6.51	0.2	54.04
	6.48	0.2	54.04
	6.48	0.2	54.04

Total Subroject Floor Area(m^2)	Total Building Construction Cost	Total Building Construction Cost Unit	Incremental Cost	Incremental Cost Unit
42.07	27.8	Million COP/House	1.16	Million COP/House
48.86	32.3	Million COP/House	-1.31	Million COP/House
48.86	32.3	Million COP/House	-1.39	Million COP/House
48.86	32.3	Million COP/House	-1.39	Million COP/House
52.12	36.4	Million COP/House	0.59	Million COP/House
52.12	36.4	Million COP/House	-0.49	Million COP/House
52.12	36.4	Million COP/House	-0.66	Million COP/House
52.12	36.4	Million COP/House	-0.66	Million COP/House
50.06	33.1	Million COP/House	0.6	Million COP/House
50.06	33.1	Million COP/House	-0.77	Million COP/House
50.06	33.1	Million COP/House	-0.33	Million COP/House
50.06	33.1	Million COP/House	-0.36	Million COP/House
49.55	34.6	Million COP/House	0.88	Million COP/House
49.55	34.6	Million COP/House	0.15	Million COP/House
49.55	34.6	Million COP/House	-1.17	Million COP/House
49.55	34.6	Million COP/House	-1.17	Million COP/House
46.93	32.8	Million COP/House	1.14	Million COP/House
46.93	32.8	Million COP/House	0.19	Million COP/House
46.93	32.8	Million COP/House	-1.79	Million COP/House
46.93	32.8	Million COP/House	-1.79	Million COP/House
54.04	37.8	Million COP/House	0.94	Million COP/House
54.04	37.8	Million COP/House	-1.52	Million COP/House
54.04	37.8	Million COP/House	-1.49	Million COP/House
54.04	37.8	Million COP/House	-1.49	Million COP/House

Local Currency Unit	Increase In Cost (%)	Payback In Years	Preliminary Created Date	Post Construction Created Date	Last Activity
COP	4.19%		2024-01-08 14:22		1/24/2024 14:57
COP	0.00%		2024-01-09 07:40		1/24/2024 15:16
COP	0.00%		2024-01-25 05:34		1/25/2024 5:34
COP	0.00%		2024-01-25 05:34		1/25/2024 5:34
COP	1.61%		2024-01-23 15:58		1/23/2024 16:27
COP	0.00%		2024-01-23 16:28		1/24/2024 15:56
COP	0.00%		2024-01-25 06:03		2/5/2024 15:47
COP	0.00%		2024-02-05 15:49		2/5/2024 15:49
COP	1.82%		2023-12-10 09:57		1/24/2024 15:48
COP	0.00%	1900-01-09 00:00	2024-01-07 11:50		1/24/2024 15:46
COP	0.00%	1900-01-07 02:24	2024-01-25 05:44		1/25/2024 6:00
COP	0.00%	1900-01-08 00:00	2024-02-05 18:52		2/5/2024 18:52
COP	2.54%		2024-01-16 14:21		1/24/2024 15:32
COP	0.43%	1900-01-00 16:48	2024-01-16 15:25		7/8/2024 4:07
COP	0.00%		2024-01-25 05:40		1/25/2024 5:40
COP	0.00%		2024-01-25 05:40		1/25/2024 5:40
COP	3.48%		2024-01-23 15:45		1/23/2024 15:50
COP	0.57%	1900-01-00 21:36	2024-01-23 15:47		7/7/2024 11:52
COP	0.00%		2024-01-25 05:27		1/25/2024 5:29
COP	0.00%		2024-01-25 05:27		1/25/2024 5:29
COP	2.49%		2024-01-15 11:34		1/24/2024 15:09
COP	0.00%		2024-01-15 13:14		1/24/2024 15:06
COP	0.00%		2024-01-25 05:17		1/25/2024 5:20
COP	0.00%		2024-01-25 05:17		1/25/2024 5:20