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Energy Analysis of Standardized Shipping Containers for Housing

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Abstract: Shipping containers that remain in ports after exporting or importing products cause an environmental and logistical problem. Transporting them to the port of origin is costly; therefore, some of them are stored in the regions of destination. Recycling or reusing them in an efficient and sustainable way represents a clean alternative. The purpose of this article is to analyze the feasibility and impact of implementing different insulating configurations on the energy demands required by a house based on a construction with standardized shipping containers. More specifically, it assesses the impact of the different orientations in which the dwelling can be arranged, depending on the location and its meteorological data. To this aim, a construction model will be developed in which first, the geometrical parameters are defined, and second, the energy characteristics are identified. The results show that, in Southwest Europe, the western orientation generates a saving of 10% of the energy demand compared to the less favourable orientation, which is the southern one.

Keywords: shipping container home; reuse/redesign of technical artefacts; thermal efficiency

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1. Introduction

The invention of the shipping container in 1956 has been a catalyst for the globalization of the economy [1]. Its use led to a reduction in the average time to market for goods, even more so since the sea transport logistics chain was standardized by the "International Organisation for Standardisation" (ISO) in 1961 [2]. Moreover, by making the transport of production cheaper, offshoring spread, turning Asia into the world's factory [3].

Globally, between 1980 and 2000, container port growth rates (the rate at which the volume of container traffic handled by ports) ranged from 5% to 10% [4], decreasing at the beginning of the 21st century as world trade matured. While the total number of TEUs (twenty-foot equivalent units) handled globally has increased, the growth rate of container ports may have decreased due to factors such as market saturation, improved port efficiency, global economic fluctuations, and shifts in trade patterns. Consequently, global container throughput is also reflected in the data recorded for 1980 (36 million TEUs), 2000 (237 million TEUs), 2010 (545 million TEUs), and 2017 (740 million TEUs) [5]. Although the shutdown of part of the world trade due to the COVID-19 pandemic led to negative growth in the throughput of world container ports, in 2021 the sector recovered to reach 851 million TEUs [6]. This is based on the restoration of pre-pandemic conditions and the boost in shipping from China, Singapore, and the Republic of Korea. Indeed, through heavy investments, major commercial ports in Northwest Asia upgraded their infrastructures to increase cargo handling capacity and attract new shipping lines [7]. In addition, noteworthy is the digitization process, that is underway in major Southeast Asian ports, improves the responsiveness, agility, costs, and asset management of the ports [8].

Increasingly, the transport of empty containers is becoming more relevant. Compared to 2019, this practise has increased by 20% by 2023 [9]. The increase in transporting empty containers is mainly due to global trade imbalances, where certain regions import more goods than they export, leading to an excess of empty containers. Additionally, logistical challenges, such as mismatches in container availability and demand across different ports, further contribute to this rise. The profitability of transporting empty containers to the port of origin is low, making recycling an option in the face of increased space occupation at the port of destination [6]. This factor is compounded by the fact that the average lifespan of a container is between seven and fourteen years, and in 2017, there were already 14 million sea containers (23.3 million TEUs) out of service [10].

In the search for sustainable and efficient solutions to the growing problem of housing and industrial waste management, the reuse of shipping containers in residential construction emerges as an innovative alternative [11]. This approach not only offers a creative response to the surplus of unused containers accumulated in ports around the world but it also fits into circular economy practises by giving them a second life in a sustainable manner [12]. Considering containers as basic building units, this method addresses the problem from multiple angles: it reduces the carbon footprint associated with producing new building materials, it offers a potential solution to the housing deficit, and it promotes innovation in architectural design [13].

Using containers for purposes other than transport dates back to the 1960s [14]. However, it was only in the publication of work such as Stewart Brand's in 1995 that its architectural potential began to be seriously contemplated [15]. Since then, container construction has evolved. Shipping containers are adopted for many applications (e.g., single-family dwellings, office complexes, and temporary accommodations). Thus, adopting shipping containers for housing construction stands as proof for the versatility and adaptability of these elements and represents a field for research in energy efficiency and sustainability [16]. Implementing appropriate insulation strategies and considering housing orientation can make significant differences in energy consumption, turning these buildings into outstanding samples of efficiency and environmental responsibility. Because shipping containers are not designed to comply with construction requirements, using them as buildings can be challenging. In this regard, it should be noted that most urban plans are against the development of shipping containers for houses because they conflict with technical building code regulations.

This approach also aligns with global efforts to mitigate the effects of climate change and move towards a more sustainable future [17]. Integrating these practises into the building environment contributes directly to sustainable development goals, promoting a shift in the traditional building paradigm towards one that values reuse, reduced environmental impact, and energy efficiency [18]. This movement towards sustainable and prefabricated construction challenges our traditional conceptions of a living space [19]. It paves the way for a new era of architectural design, where innovation and sustainability go hand in hand.

A limited number of research studies have examined passive techniques for energy efficiency in shipping containers [20,21]. In order to improve interior air quality and energy use, Kristiansen et al. compared different envelope U-values, door widths, ventilation strategies, and several glazing [22–24]. According to their research, 40% less energy can be used in well-insulated containers. Suo et al.'s recent evaluation assessed the effects of air infiltration rates and insulation types and thicknesses on cooling energy performance. They were able to cut their cooling energy usage by about 10% [23]. This makes it clear that a thorough study of energy assessment in container homes needs to be included.

The containerized housing design should be geared towards maximizing its operational sustainability. Thus, the design considers factors such as orientation to optimize passive solar gain, appropriate insulation systems to minimize energy demand, and the integration of natural ventilation solutions to improve indoor air quality and reduce the need for artificial air conditioning. The selection of materials, colours, and the window-to-wall ratio also plays a crucial role in the building's thermal performance and energy efficiency [25].

Despite the advantages, containerized construction faces challenges in regulation and public perception. The need for specific regulations and demonstrating compliance with habitability and safety standards can represent obstacles. However, the growing awareness of sustainability and innovation in the construction sector engenders significant opportunities to expand this methodology. Developing projects demonstrating the viability, comfort, and esthetics of containerized housing can contribute to greater acceptance and adoption of this practise.

2. Shipping Containers for Building

The shipping container construction methodology represents an innovative approach to designing and developing sustainable housing solutions, taking advantage of pre-existing structures to create efficient and adaptable living spaces. Initially designed for intermodal transport, these containers offer significant advantages in terms of strength, modularity, and reusability, contributing to the circular economy and reducing the construction's carbon footprint. According to research, reusing containers for construction leads to a notable reduction in embodied energy compared to traditional building methods [26]. In this regard, the life cycle analysis (LCA) of turning recycled containers into a modular home shows that over a 50-year lifespan, the life cycle impact differs by only 3% from traditional lightwood cases, and energy-efficient measures can maximize life cycle cost benefits [27]. Throughout its use, the container house has a lower global warming potential (GWP) than concrete and timber dwellings, which have GWPs of 22.3 and 38 CO_2 equivalents/m^2/year, respectively [28].

Several real-world implementations of container housing provide insights into the practical challenges and advantages associated with this construction method. One prominent example is Keetwonen in Amsterdam, the largest container housing project globally, which accommodates over 1000 students. The project encountered challenges such as ensuring adequate insulation, managing noise levels, and meeting local building regulations. However, it has been generally well received by residents due to its affordability and quick construction timeline, despite issues with temperature control during extreme weather conditions [29].

These cases illustrate common challenges in container housing, including regulatory compliance, insulation, and public perception. Addressing these concerns early in the design process is crucial; user feedback often highlights the importance of effective insulation, soundproofing, and ventilation to enhance comfort and reduce energy costs. For instance, different scholars demonstrated through dynamic simulations that different insulation types and thicknesses significantly impact energy efficiency, particularly in subtropical climates where cooling demand is high. They found that thinner insulation materials, such as mineral wool, may perform better in extreme temperatures, offering a promising solution for future container housing designs [23,30]. Similarly, specialists conducted a life cycle assessment and found that while container housing offers economic and environmental benefits compared to traditional housing, challenges related to insulation and regulatory standards remain [27,31]. Tofiluk (2023) also highlights the potential of prefabricated and modular construction, including container architecture, to address urban housing shortages efficiently while promoting sustainability [32]. Her study emphasizes the need to overcome regulatory and social challenges to fully realize the benefits of these innovative building methods. Moreover, Tralhão et al. (2010) underscore the importance of sustainable waste management, which is vital for the long-term viability of container housing by minimizing environmental impact through recycling and other sustainable practises [33].

The two primary shipping container standards established by the International Organization for Standardization (ISO) and the International Convention for Safe Containers (CSC), respectively, are complied with by almost all containers used worldwide [34]. ISO and CSC publications outline the standards, structural integrity, serviceability, applications, and structural limits of shipping containers [35–41].

The construction process begins with carefully selecting the container, considering its history of use, structural condition, and potential contaminants. Fibreglass, stainless steel, aluminium, and steel comprise most container materials. The bulk of shipping containers have uniform measurements [42]. The foundations represent one of the most crucial steps on the construction site, being adapted to the soil's geography and specific characteristics. Concrete footing and raft-slab foundations are the two types of foundations that are frequently employed in container projects [43].

Window and door openings, as well as the incorporation of façades and roofs, are stages that demand detailed attention to design and esthetics. These elements define the ability to take advantage of local climatic conditions, optimizing natural lighting and ventilation [38].

2.1. Types of Sea Containers

The diversity of sea containers (Figure 1 and Table 1) on the market reflects the wide range of global transport and storage needs [3]. From the dry van containers, known for their widespread use in transporting dry goods and for being hermetically sealed, to the specialized open-top and open-side containers, designed for bulky or irregularly sized cargoes requiring top or side accessibility [44]. Flat-rack containers, on the other hand, stand out for their capacity to transport heavy or oversized loads, lacking side walls, or in some cases, also front and rear walls, which facilitate loading goods using cranes [45].

(**a**) Dry van container (**b**) Open-top/side container

(**c**) Flat rack container

Figure 1. Examples of types of sea containers.

Table 1. Sea container dimensions.

Container Type	Length (ft)	Width (ft)	Height (ft)	Interior Volume (m^3)
Standard Dry Container	20/40	8	8.5/9.5	33.1/67.7
Refrigerated Container	20/40	8	8.5/9.5	28.4/58.9
Open-Top Container	20/40	8	8.5/9.5	32.6/65.9
Flat-Rack Container	20/40	8	8.5	Variable
Tank Container	20	8	8.5	Approx. 26

Refrigerated containers offer an optimal solution for goods requiring temperature-controlled conditions, maintaining the interior at temperatures ranging from −25 °C to +25 °C, thanks to integrated refrigeration systems. This type of container is essential for transporting perishable goods, ensuring their preservation over long distances. Alternatively, ventilated containers provide constant air circulation through louvres, ideal for loads requiring ventilation to prevent moisture buildup and maintain a constant temperature.

As far as liquids or gasses are concerned, tank containers and flexi-tanks represent the preferable options. The former has a robust structure and an inner tank for safe liquid storage, whereas the latter uses a flexible tank inserted in standard dry van containers, providing a versatile and efficient solution for bulk liquid transportation.

The standardized dimensions and characteristics of the containers, in accordance with ISO standards, ensure their compatibility and efficiency in the global logistics system [46]. These specifications facilitate handling and storage, as well as intermodal transportation, contributing to the efficiency of international trade. Sea containers, in their diverse versions, are fundamental in the worldwide supply chain, responding to the distinctive needs of each type of cargo and playing a crucial role in the global economy.

2.2. Regulations

Contrary to popular belief, the construction of maritime containers in Spain is governed by a series of rules and regulations that do not differ significantly from those applicable to traditional construction [47].

Legalizing a containerized house involves several essential steps, starting with differentiating between movable and immovable property [48]. If the construction is considered movable property, as it is not permanently fixed to the ground, the applicable regulations are less stringent and may only require a location licence. On the other hand, if it is classified as immovable property because it is anchored to the ground, more complex procedures must be followed, similar to any other building, including obtaining location and building permits and complying with local zoning regulations.

Regulations to be considered include Law 38/1999 on building regulations, which establishes the frameworks for building quality, and the technical building code (CTE, its Spanish acronym), which is the regulatory framework for the basic quality requirements of buildings and their installations, ensuring the wellbeing of citizens and the protection of the environment. In addition, buildings must adhere to the specific habitability and accessibility standards of the corresponding autonomous community, such as Decree 29/2010 in Galicia, which establishes the habitability standards for dwellings in that community. This paper will be consistent with what is stated in the Autonomous Community of Galicia (Northwest Spain), as the simulation study will be developed in this region.

2.3. Economic Analysis

Container housing presents a cost-effective alternative to traditional construction methods, influenced by several factors such as initial setup costs, long-term maintenance, and energy efficiency. Initial costs for container homes are generally lower, often 30–50% less than conventional houses of a similar size, due to savings in labour, reduced materials, and quicker construction timelines [13,42,49]. This affordability is attributed to the modular nature of shipping containers, which allows for prefabrication and standardization, significantly reducing on-site work. Additionally, container homes can be installed on simpler foundations, further lowering the upfront expenditure.

However, long-term maintenance costs for container housing vary based on environmental exposure and the quality of materials used. For instance, in humid or coastal areas, containers are susceptible to corrosion and may require regular inspections, coatings, and insulation upgrades to maintain their integrity and energy efficiency [20,50]. Conversely, traditional homes might initially incur higher maintenance costs due to complex building materials and methods, but they often exhibit more predictable long-term upkeep, particularly if constructed with durable materials [51].

In terms of energy efficiency, container homes offer potential savings due to their compact size and adaptability for energy-efficient modifications. Dara and Hachem-Vermette (2019) found that container homes with appropriate insulation and energy-saving technologies, such as reflective roofing or passive solar design, can achieve up to 20% lower energy consumption than traditional homes, especially in moderate climates. Nonetheless, the extent of these savings is heavily influenced by climate, insulation quality, and the incorporation of renewable energy sources, like solar panels [27,31,49,52].

Overall, while container housing presents an economically viable solution, particularly in urban areas with high land costs or housing shortages, its benefits depend on careful planning and adaptation to local conditions. The lower initial costs and potential for energy savings make it an attractive alternative, but stakeholders must also consider potential maintenance challenges and the environmental impact of materials used. This context-dependent analysis highlights the need for comprehensive planning to maximize the benefits and minimize the drawbacks of container-based housing.

2.4. Design Criteria

In the design of housing made of shipping containers, it is critical to apply sustainable and energy-efficient design criteria in order to optimize the comfort, habitability, and sustainability of these spaces. These criteria range from the strategic choice of location and orientation of the project to specific details such as thermal mass, ventilation, choice of colours, window-to-wall ratio, insulation techniques, and the intelligent distribution of the primary living areas.

The building's location, as the starting point, determines the climatic conditions, topography, and environmental elements that will influence the design [53,54]. Moreover, the dwelling's orientation is crucial to the utmost use of passive solar radiation and natural air currents. Correct orientation can minimize the need for heating in winter and cooling in summer, taking advantage of the sun's path and prevailing winds to improve indoor thermal comfort. In the northern hemisphere, for example, orienting the busiest areas to the south maximizes solar gain during the cold months, while in the southern hemisphere, this orientation is reversed [55].

The window-to-wall ratio (WWR) directly influences the daylighting and thermal efficiency of the home. A balanced WWR maximizes natural daylight and views to the outside while controlling heat gain or loss through windows, using high-performance glazing and strategic shading to optimize the thermal balance [56].

2.5. Thermal Insulation

Thermal insulation plays a critical role in the construction of shipping containers, being fundamental to guaranteeing thermal comfort inside the dwelling and the project's energy efficiency [23,30]. As metallic structures, containers have low thermal inertia, which means that they can heat up and cool down quickly, directly affecting the interior living conditions [57,58].

Effective insulation solutions are essential to mitigate this behaviour and achieve a comfortable indoor environment. Insulation improves thermal performance, reduces air conditioning needs and thus energy consumption, and contributes to the project's sustainability [59]. It is vital to select suitable insulation materials that meet the thermal resistance requirements and match the specific characteristics of container construction. In the context of shipping container construction, insulation assumes a twofold significant role, addressing both thermal and acoustic needs [60]. Given the metallic nature of containers, they present inherent challenges in terms of thermal regulation and noise mitigation.

In this respect, some materials encompass thermal and acoustic properties, allowing both challenges to be addressed in an integrated manner [61]. Materials such as polyurethane foam, rock wool, or specific sandwich panels can provide an effective solution by combining thermal insulation with noise reduction, optimizing space, and installation efficiency.

Thermal simulation, in this context, becomes a valuable tool to predict the thermal performance of the building, allowing us to evaluate different insulation strategies and to optimize the design of the building envelope [62].

3. Methodology

3.1. Dwelling Description

A configuration consisting of six containers was established to conduct a thermal simulation: three 20′ dry van HC containers and three 40′ dry van HC containers (Figure 2). The construction encompasses a floor area of 132 m^2, with dimensions of 18.24 m in length, 7.29 m in depth, and 2.89 m in height.

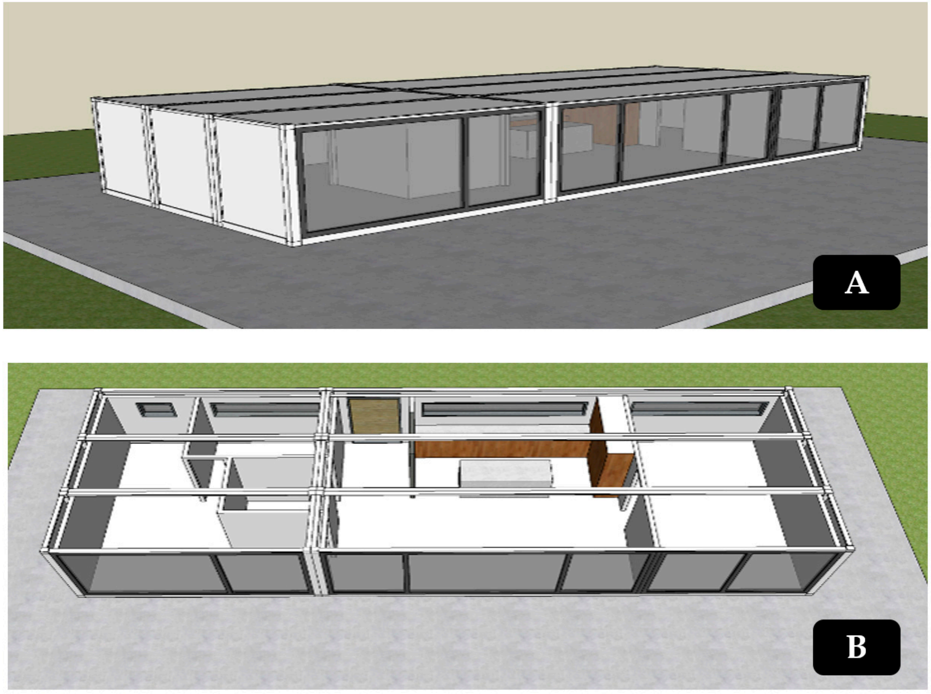

Figure 2. Configuration of the analyzed dwelling. (**A**): Back façade view. (**B**): Plan view of the interior layout.

In the proposed dwelling design, as shown in Figure 2, the window areas for each orientation were designed for both natural lighting and thermal efficiency. The WWR was calculated to ensure sufficient daylight while minimizing excessive solar gain. Specifically, the north façade features a WWR of 16%, which helps reduce heat loss during winter without significant summer overheating. Summer overheating from the north facade can occur due to diffuse solar radiation, which impacts all orientations, especially when ambient temperatures are high, and there is limited shading or ventilation. While direct sunlight is minimal on the north side, diffuse radiation can still raise indoor temperatures. The south façade features a WWR of 89%, taking advantage of passive solar gain during winter, i.e., for the south facade, with a high window-to-wall ratio (WWR), the larger glass surface area increases heat gain from direct sunlight, particularly in summer. To mitigate these effects, strategies such as shading devices, high-performance glazing, and natural or mechanical ventilation can help regulate indoor temperatures effectively. The U-values for the standardized shipping container envelope without insulation components are as follows: walls at 2.89 W/m^2K, roof at 2.89 W/m^2K, and floor at 2.56 W/m^2K. The U-value for a coated double glazing window was estimated at 1.2 W/m^2K [63]. Sensible heating demands were evaluated, assuming the dwelling had unlimited thermal resources, i.e., the HVAC system is theoretically considered to have an infinite capacity to meet the building's thermal demands, ensuring that any energy required is always available to maintain comfort. Northwest Spain's climate, characterized by mild, wet winters and cool, comfortable summers, with average temperatures ranging from 8 °C in winter to 25 °C in summer, influences the building's thermal and moisture management strategies [64].

Utilizing the OpenStudio plugin, this analysis began with defining the 3D design in SketchUp (2020, Trimble, Sunnyvale, CA, USA). Materials and unique building qualities were provided for the design via OpenStudio (3.0.0, Alliance for Sustainable Energy, Lakewood, CO, USA). Once the model was developed in SketchUp 2023.0, it was exported to EnergyPlus for thermal simulation, based on known dwelling envelope characteristics (Table 2).

Table 2. Construction materials details.

Category	**Materials**			
	Element	**Conductivity [W/m·K]**	**Specific Heat [J/kg·K]**	**Layer Thickness [mm]**
External wall	Corten steel	17	460	5
	Polyurethane (PUR)	0.022	1400	250
	Corten steel	17	460	5
	Glass wool	0.04	7955	63.5
	Plasteboard	0.25	1000	100
	SIP	0.023	1880	220
Ground	Extruded polystyrene	0.034	1540	300
Roof	Corten steel	17	460	5
	Glass wool	0.04	7955	63.5
	Plaster (ceiling)	0.25	1000	150

In order to determine the effect of insulation on thermal demand, three different configurations were contrasted: first, a base configuration without insulation; second, a configuration with traditional insulation; and third, a configuration in which a structural insulation panel (SIP) was added to the conventional insulation (Figure 3). There are various manufacturers of structural insulation panels, offering a wide range of panels with diverse finishes, dimensions, and thicknesses available in the market. For this study, we selected an SIP comprising a 200 mm extruded polystyrene insulation covered with two layers of 10 mm thick plywood. The construction details of the container are shown in Table 2. Transmittance values are in accordance with ISO 6946:2018 and ISO 10456:2007 [65,66].

The exterior wall insulation configuration, as presented in Table 2, achieves a low U-value, indicating a high level of thermal efficiency. Even though this characteristic is advantageous during the colder periods of the year, it causes overheating in summer. To address this challenge, ventilation strategies and solar control technologies can be integrated into the container design. The overheating analysis reveals how different design configurations and orientations affect indoor temperatures during the summer months. Façades with high window-to-wall ratios (WWR), particularly those facing south, experience significant heat gains due to direct solar radiation, which can lead to overheating.

Additionally, north-facing façades may also contribute to overheating due to diffuse solar radiation and high ambient temperatures. In addition, the use of phase change materials for more dynamic interior temperature regulation could be explored, as demonstrated in previous research [48]. The U-value of the third configuration (0.043 W/m^{2}K) complies with the basic document on energy saving, which is part of the technical building code established by the Spanish government [67].

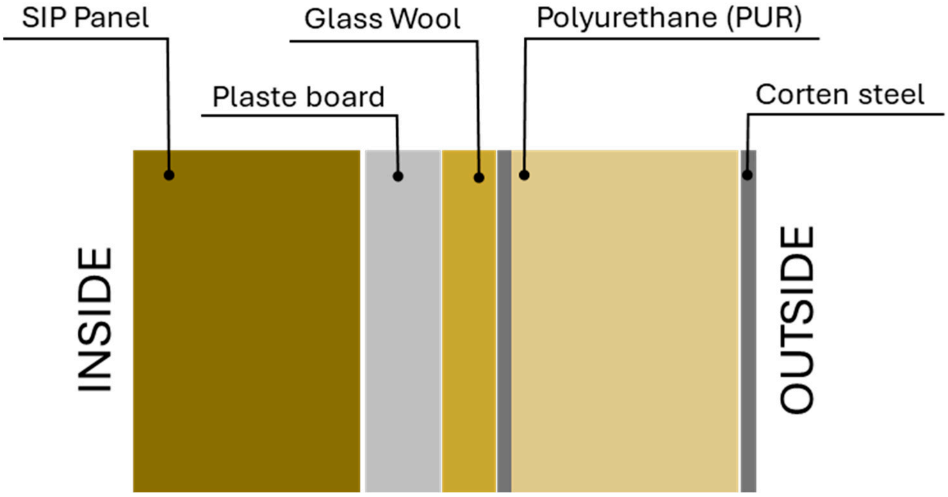

Figure 3. Enclose model for simulation.

3.2. Thermal Model Definition

Internal gains and infiltration loads were included since the purpose of this research is to forecast the advantages of using various insulations in the building enclosure. The dwelling was considered a single thermal area. Thus, a single temperature zone and a dual set point thermostat was used. The temperature set point for living spaces was 25 °C for cooling and 21 °C for heating, according ASHRAE guidelines [68].

As a result, it was decided to use the facility continuously during HVAC operating hours. Lighting was anticipated to need 54 W of electricity, and the rate of infiltration was estimated to be 0.63 air changes per hour. The ventilation system was natural. The internal gains were set at the equivalent of three occupants every day, and the occupancy schedule was constant over the year. The following schedule was assumed: from 21:00 to 06:59, the occupants are sleeping (72 W/person); from 07:00 to 07:59, the occupants are having breakfast (100 W/person); from 08:00 to 13:59, the dwelling is empty; from 14:00 to 14:59, the occupants are having lunch (100 W/person); from 15:00 to 16:00, the occupants are sitting (108 W/person); from 16:00 to 18:59, the dwelling is empty; from 19:00 to 19:59, the occupants are sitting; and from 20:00 to 20:59, the occupants are having dinner (108 W/person). These assumptions rely on ASHRAE 90.2-2010. These values for heat gains due to occupancy were obtained from the EnergyPlus documentation [69]. To calculate the internal gains derived from lighting, a standard configuration for housing with different spaces was defined: 51.75 m^2 for the kitchen and living room, 51.13 m^2 for bedrooms, and 15.23 m^2 for bathrooms.

Luminaires of the 12 W Circular SuperSlim Cut Ø 155 mm LED Plate type were taken as a reference with an estimated consumption of 12 W and 960 lumens (OSRAM brand). The values stipulated by the Spanish Energy Diversification and Savings Institute were used for the recommended luminosity levels in each space according to its use [70].

An empirical technique based on prior research [71–73] and outlined by ASHRAE [58] was employed to compute the building infiltration. Equation (1) provides the number of air changes per hour (*ACH*).

$$ACH = K1 + K2 \cdot (T_z - T_a) + K3 \cdot W_s \quad (1)$$

where T_a is the outside temperature, W_s is the wind speed, and T_z is the zone temperature.

The following K coefficients—$K1$—0.1, $K2$—0.017, and $K3$—0.049—were established utilizing ASHRAE standards for a building built with traditional construction methods [68]. The Kusuda and Archenbach model [74] was utilized to define the ground temperature. Relative humidity, pressure, and wind speed were used to compute infiltrations (K1 K2 K3 ASHRAE coefficients). The timestep was set to one hour. An entire year was simulated (8760 records). The weather files were downloaded from the EnergyPlus webpage for a location in Galicia (Northwest Spain) [69]. More precisely, the location of the meteorological files corresponded to the coordinates N 43°22′, W 8°25′.

The materials employed for the windows and doors remained consistent across all simulations. As for the entrance door, a model manufactured from 0.8 mm thick stainless steel on both sides, featuring a 71.4 mm extruded polystyrene core, served as the reference.

As regards the windows, the reference standard was set by those integrated in the EnergyPlus software itself. Therefore, in this case, the ASHRAE 189.1-2009 ExtWindow ClimateZone 3 configuration was selected according to the climate zone defined by ASHRAE for the pre-established location.

4. Results

Table 3 displays the total energy consumed for heating and cooling during a year for the three proposed envelopes along with the four orientations under study. As expected, the configuration without insulation requires a higher energy demand for air conditioning than those with insulation. For the selected location, the western orientation is more beneficial for the insulated options regarding energy consumption. In the case of the configuration without insulation, the least demanding orientation is the eastern orientation. However, the demand is more significant than any orientation we give to any constructive configurations with insulation. The most unfavourable option, the configuration without insulation, has an energy demand that is 24% higher than the most favourable option, the configuration with SIPs facing west. As for the configurations based on rock wool insulation and SIPs, they provide similar values in both energy demand and orientation. Although insulation results in more significant savings, its effect is reduced when the orientation is modified, i.e., a study of three different insulation configurations across four building orientations (north, east, south, and west) to understand their impact on energy performance and thermal comfort was conducted.

Table 3. Yearly energy demand under different insulating conditions.

Energy Required	**Heating [kWh]**			**Cooling [kWh]**		
Orientation of the Main Façade	**Base**	**Insulation**	**Insulation + SIP**	**Base**	**Insulation**	**Insulation + SIP**
North	2438.63	1832.16	1823.06	971.42	871.89	870.39
South	2405.62	1976.19	1975.64	956.84	891.16	862.67
East	2398.05	1899.75	1860.27	960.91	782.37	781.60
West	2449.29	1834.71	1806.25	966.66	737.45	727.52

The highest energy demand (heating + cooling) occurs in the autumn period (Figure 4). This is consistent with the location under study. On the other hand, it is essential to highlight that peak demand does not have to be shown in the month when HVAC consumption is highest [57]. Based on the results, the western orientation is to be selected for this construction configuration, in terms of energy demand for air conditioning, resulting in a 10% reduction in demand over the less favourable southern orientation. This may be justified because the western orientation has a high potential to effectively balance heating and cooling energy demands across seasons. This orientation takes advantage of the sun’s position in the late afternoon, which is particularly beneficial in climates with temperature variations between day and night. Taking into account the data obtained for the heating of the building, we observe that the lowest value energy demand occurs when we place the construction in a western orientation. This orientation reduces the annual energy consumption used for heating by 9% compared to the least favourable orientation, the southern orientation. We also verified that in monthly terms, the highest demands occur in the winter cold months, reaching 200 kWh. It is important to note that the main façade has small windows, while the rear façade has large windows. It was determined that the main façade of the house was where the access door was located. The consumption results based on orientation for the location studied are justified in terms of this construction configuration. As can be seen from the results, containers allow the implementation of innovative and efficient isolation systems. By covering the containers internally and externally with high-quality insulating materials, energy losses are minimized in winter months, and gains are reduced in summer months, optimizing energy use for air conditioning. The recorded energy consumption estimation is equivalent to or even lower than a house of similar dimensions that is traditionally built.

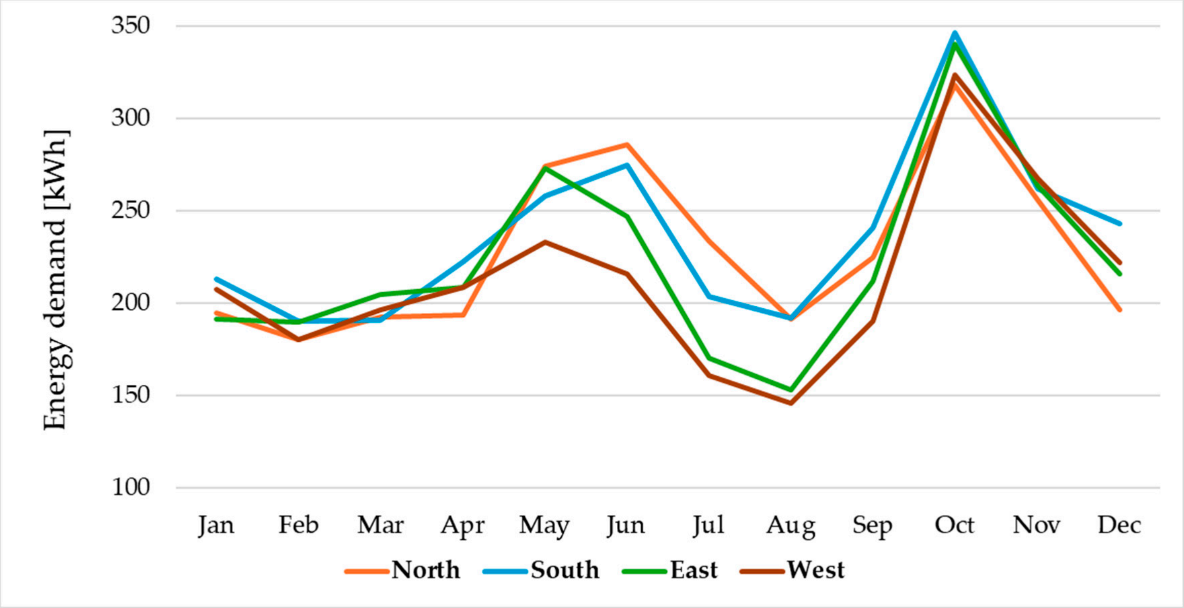

Figure 4. Monthly energy demand for heating and cooling (total) for every orientation for insulation plus SIP condition.

Although the energy demand for heating and cooling in the third configuration is similar to that of other less insulation-intensive configurations, the long-term benefits, sustainability, comfort, and operational efficiency justify its choice [75]. SIPs significantly reduce the presence of thermal bridges, which are standard in more traditional construction methods [76]. This reduction is vital as it improves the efficiency of the installed insulation, preventing heat losses in winter and heat gains in summer, which may not be immediately evident in energy consumption figures but is evident in comfort and long-term energy performance [77]. In addition, the structural integrity and airtightness provided by SIPs contribute to better indoor air quality and reduce air infiltration, thus minimizing unwanted load on heating and cooling systems and providing more efficient indoor climate control.

The addition of internal insulation layers must be considered and has a direct impact on the usable interior living space of the building. Each insulation configuration results in a different reduction in space, which needs to be balanced against energy efficiency gains. For example, configuration insulation reduces the interior space by approximately 4%, configuration insulation + SIP by 7%. These changes are due to the varying thicknesses of insulation materials applied to the walls.

Hourly heating demand was analyzed throughout the year. The statistical distribution of the hourly heating demands data for a January day using a violin plot is shown in Figure 5. A box plot and a symmetric kernel density plot are combined to create the violin plot. This allows for comparing many distributions by providing precise data on the distribution's spread, outliers, asymmetry, and central values [78]. The shape in Figure 6 represents the data density determined using the kernel approach. More data are connected to a given value when the shape is wider. The width of the violins indicates the variability in heating demand, with wider violins suggesting more significant variability. The thin line represents the lower and upper percentiles, while the thick line segment displays the 25th to 75th percentile. The median of the distribution, represented by a white equis, takes higher values for the early morning hours (around 6 a.m.) and the evening (around 6 p.m.), likely related to the occupants' daily activities, such as waking up and returning home, i.e., the heating demand shows significant variability throughout the day, with distinct peaks during certain hours, suggesting a daily pattern in heating usage. Demand appears lower during midday and afternoon, possibly indicating more moderate outdoor temperatures or that the facility is unoccupied during these hours. Some hours show a more concentrated distribution (thinner violins), indicating more consistent demand. Near-zero values at certain hours suggest periods of very low or no heating demand. These patterns can help design more efficient heating systems, scheduling heating to turn on before demand peaks and off during low-demand periods. Overall, Figure 5 suggests a clear daily pattern in heating demand, with peaks in the early morning and evening. This understanding can be valuable for energy management and optimizing heating usage to improve energy efficiency. The behavioural pattern remains consistent across all months.

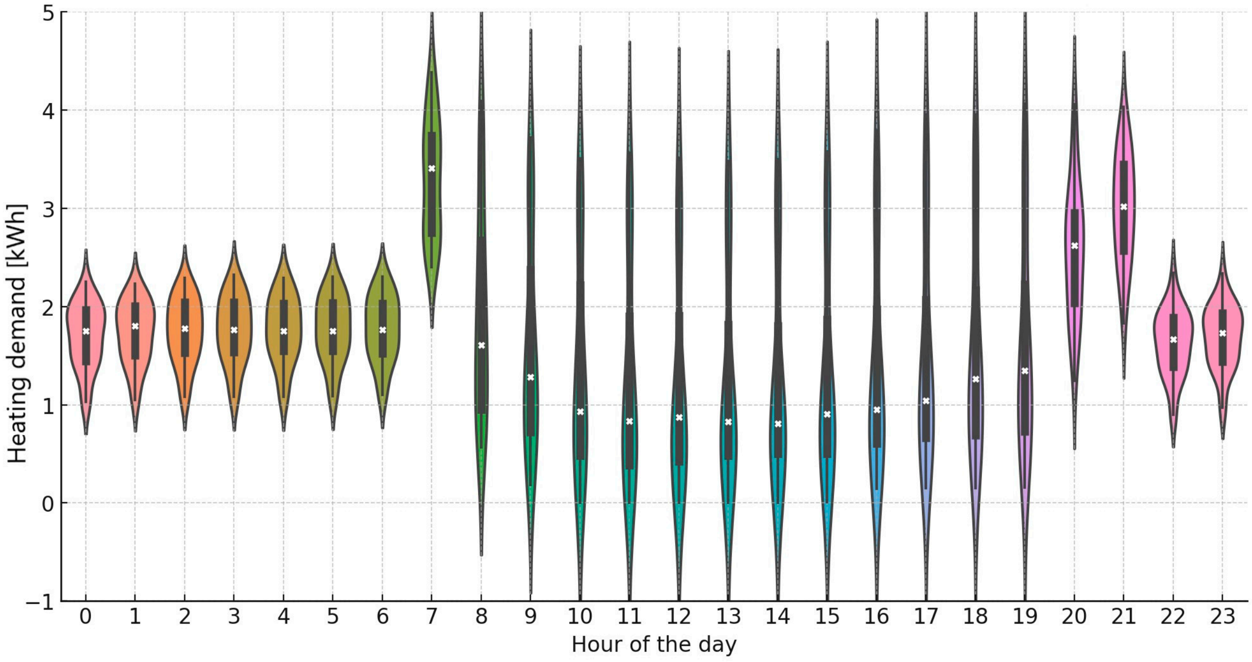

Figure 5. Violin plot of heating demand for January (hourly counts).

The average hourly heating demand in the months of November, December, and January was compared (Figure 7). The pattern of heating demand remains consistent across these months, with higher usage in the early morning and evening hours and lower demand during midday. This suggests a similar daily heating usage pattern throughout the winter. Among the winter months, January exhibits the highest overall heating demand, reflecting typically colder temperatures, while November shows the lowest, indicating milder conditions. December's demand is higher than November's but slightly lower than January's, positioning it as a mid-winter month. There is a noticeable dip in heating demand around midday, likely due to warmer temperatures and reduced residential occupancy. Heating demand rises again in the evening around 6 p.m., according with dropping temperatures. These observations highlight the need for heating systems to manage high demand effectively during early morning and evening peaks, particularly in December. Energy management strategies should optimize heating during these critical times to enhance efficiency and reduce costs.

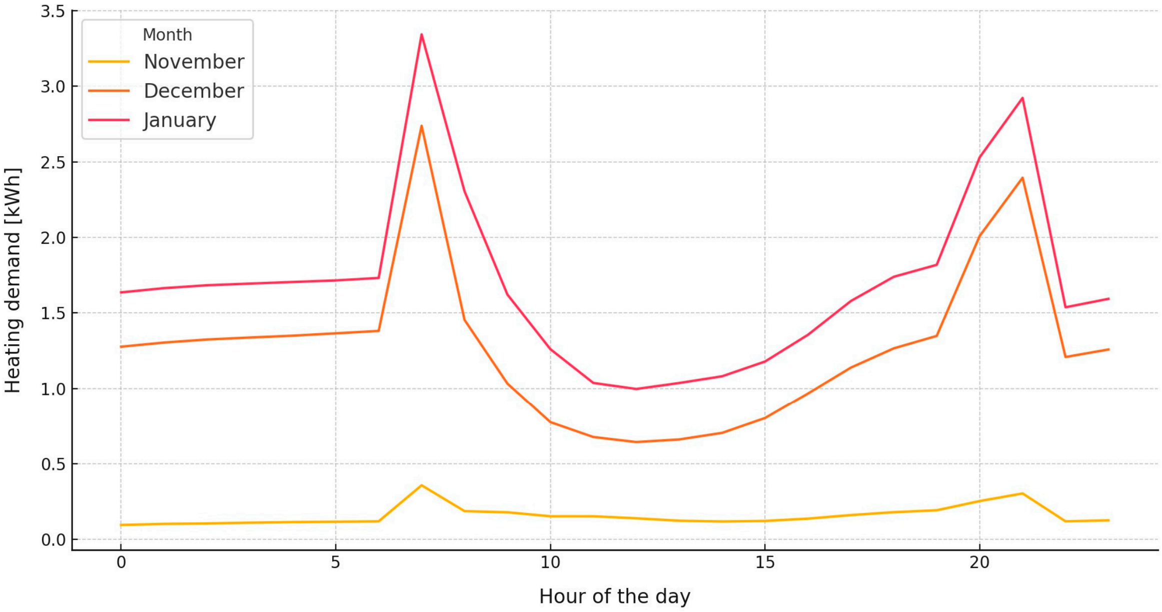

Figure 6. Hourly heating demand patterns for the months of November, December, and January.

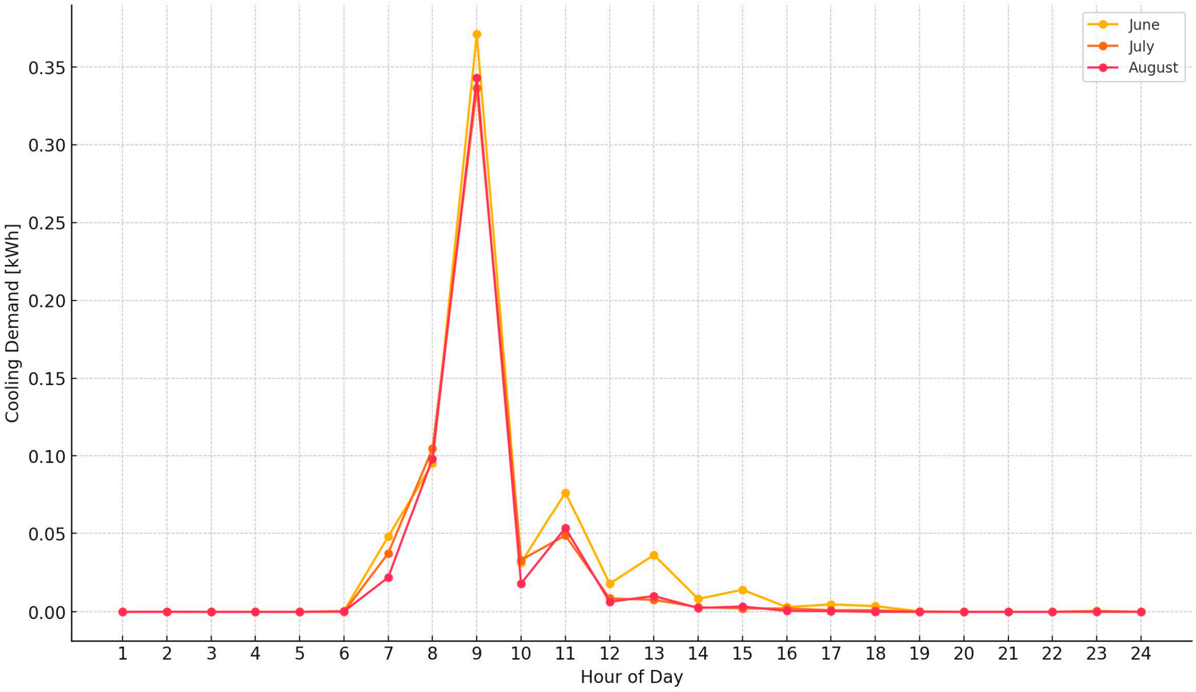

Figure 7. Hourly cooling demand patterns for June, July, and August.

Cooling demands were also analyzed (Figure 7). The cooling demand also follows a consistent daily pattern, significantly increasing from the morning hours and peaking in the afternoon before decreasing again at night. The highest peaks occur between 7 AM and 9 AM, before decreasing again towards the afternoon. This is likely due to the higher outdoor temperatures and the intensity of solar radiation in the early hours of the day. These results are also consistent with dwelling use schedules. June exhibits the highest average cooling demand during peak hours compared to July and August, suggesting it is the hottest month in terms of thermal load. The cooling demand is minimal during nighttime hours (from midnight to around 6 AM), which is expected as outdoor temperatures are lower and solar radiation is absent. This information is valuable for planning more efficient cooling systems, ensuring capacity can handle afternoon peaks, and implementing energy-saving strategies during low-demand hours. It is also helpful in planning the use of renewable energy sources, such as solar panels, to cover peak cooling demand. August follows a similar pattern to July but with slightly reduced demand, suggesting temperatures begin to decline towards the end of summer. Overall, Figure 7 highlights the importance of afternoon hours for cooling load in the dwelling, emphasizing the need to optimize air conditioning systems and improve energy efficiency.

Influence of Climate on Energy Demand

To study the influence of climate on demand, the thermal behaviour of the dwelling at the initial location was compared with a nearby location with a different climate. For this purpose, the Köppen–Geiger climate classification was used. Climates are classified into the following categories: A (tropical), B (arid), C (temperate), D (continental), and E (polar). Moreover, the precipitation amount is categorized and labelled as follows: f (no dry season), s (dry summer), w (dry winter), m (monsoon), and w (desert). In conclusion, Koppën–Geiger offers a temperature-based classification: h (hot and dry), k (cold and dry), a (hot summer), b (warm summer), c (cold summer), d (freezing winter), and F (everlasting frost) [79].

The climate of the initial location is Cfb (temperate without dry season with mild summer). To compare the effects of climate change, it was decided to use a nearby location with a different climate, based on the Köppen–Geiger classification. For this purpose, a recent study developed by the Spanish State Meteorological Agency (AEMET) was used as a reference [79]. This study states a Csb-type climate (temperate with dry and mild summer) is common in Northwest Spain. Using the Ladybug tool, an .epw file was obtained from a location close to the location of origin with a Csb-type climate [N 43°22′; W 8°25′] [80,81]. The dwelling's thermal performance in both locations was compared, assuming that the main façade was south facing. Table 4 shows the results.

Table 4. Comparative monthly energy demand for two different climate locations.

	Cfb Climate		Csb Climate	
	Heating Demand [kWh]	**Cooling Demand [kWh]**	**Heating Demand [kWh]**	**Cooling Demand [kWh]**
January	213.17	0.00	186.74	0.00
February	190.68	0.00	176.56	0.00
March	180.15	10.73	148.73	10.61
April	199.52	23.12	162.08	26.32
May	164.27	94.12	130.85	122.23
June	114.51	140.34	65.50	194.73
July	61.22	112.31	41.73	156.07
August	34.37	107.5	10.98	144.89
September	113.28	127.59	61.59	125.84
October	179.69	166.55	112.04	149.23
November	198.46	63.64	191.20	63.24
December	226.31	16.77	189.40	14.03
Total	1875.63	862.67	1477.40	1007.19

As expected, in the Cfb climate, the one chosen for the initial location of the container, heating needed predominate during most of the year [57,82,83]. At the same time, cooling demands were lower than heating ones due to moderate temperatures during the summer. The Cfb climate is an oceanic climate characterized by mild temperatures throughout the year with abundant and relatively evenly distributed rainfall. Insulation is essential in reducing heat loss during the colder months and maintaining a comfortable environment without much heating demand.

It should also be noted that the simulations were performed with .epw files, which are the result of a collection of selected meteorological data for a specific location, i.e., the values were generated from a data bank for much more than a year. Thus, in January and February, with the meteorological data used, the cooling demands were non-existent, while in November and December, to maintain the comfort temperature in the thermal zones analyzed, it was necessary to use cooling. In addition, as pointed out by the Spanish governmental meteorological agency (AEMET), recent autumns have been warmer.

The Csb climate shows a significant increase in cooling demand in summer due to higher and drier temperatures. Heating is still required in winter, although to a lesser extent than in the Cfb climate. The Csb climate is a Mediterranean climate characterized by dry and mild summers with mild and rainy winters. Insulation is essential to reduce the need for cooling in summer, as it can keep the interior cooler, thereby reducing energy use. It also helps to prevent heat loss in winter, although to a lesser extent.

Although it may seem strange, in the locations studied, it is expected to have small heating demands in the summer months if a comfortable temperature is maintained in the facility throughout the day. These findings are in accordance with what has been found in previous studies [73,84,85].

Peak demands were studied and contrasted, paying particular attention to the installed capacity's peak value. Notably, the peak heating demand for both climates manifests during winter months, especially in January and December. In the Csb climate, this peak is comparatively less pronounced. Conversely, the peak cooling demand occurs in summer, particularly in July and August. In the Csb climate, managing peak demand is critical, as inadequate dimensioning of the HVAC system could result in peak demand exceeding 100% of the installed power on particularly hot days when temperatures surpass 35 °C. In a typical year, peak heating demand values of approximately 22 kWh for the Cfb climate type and peak cooling values for the Csb climate type of 31 kWh were found.

5. Discussion and Conclusions

The pursuit of housing solutions intertwines with the imperative to integrate circular economy principles into the current production system. In the case of the maritime transport sector, the growing number of retired or damaged containers shapes a pivotal scenario highlighting the necessity to reuse them. In the last 25 years, the alternative uses of shipping containers have been extended to the construction of schools and offices, but above all, houses. The implementation of shipping containers as housing units presents several unique regulatory challenges, particularly related to compliance with local building codes, zoning regulations, and safety standards. These challenges often arise because most traditional building regulations do not account for the specific structural and material characteristics of shipping containers. For example, in Spain, container houses must comply with Law 38/1999 on building regulations and the technical building code (CTE), which can be restrictive due to the unconventional nature of container structures.

To address these regulatory barriers, adjustments to building codes could be considered. Some countries, such as New Zealand and Australia, have already started to modify their building codes to accommodate container homes, recognizing their potential as sustainable and affordable housing solutions. A similar approach could be explored in other regions to facilitate the adoption of container housing. Policy incentives, such as tax breaks, subsidies, or grants, could also encourage the use of containers for housing, especially in areas with a high demand for affordable solutions. Local pilot projects can serve as practical demonstrations of the feasibility and benefits of container housing; these projects could help revise local regulations and increase acceptance. Engaging the community through awareness campaigns, workshops, and public consultations can also help mitigate concerns and foster acceptance of container housing as a viable option. Successful implementation examples, such as those in the United States and the Netherlands, demonstrate how flexible zoning and building regulations can enable innovative housing solutions using containers.

In addition, in order to improve public perception and social acceptance of container housing, integrating architectural innovations with local styles, high-quality materials, and creative landscaping is crucial. Community engagement, such as workshops and open houses, helps demystify container housing and involves local residents in the planning process, fostering acceptance. Additionally, studies indicate that effective communication about container housing's benefits, like affordability and sustainability, can enhance social acceptance by addressing concerns related to esthetics, functionality, and environmental impact [86–88]. (Bhanye, et al., 2024; Ling, et al., 2019; Zhang, et al., 2022).

The thermodynamic properties of a house situated in A Coruña, a city in northwestern Spain have been examined in this study. The house was built from six containers, comprising three 20′ dry van HC containers and three 40′ dry van HC containers, encompassing a total area of 132 m^2.

Another conclusion drawn underscores the significance of conducting an energy analysis of the proposed construction during the design phase to facilitate informed interventions. This approach will allow the sizing of the necessary equipment and the cultivation of energy-efficient behaviour in building operations by enabling informed decision-making in the initial stages.

In this study, a house made by shipping containers was considered to evaluate the impact of different insulations on the building envelope. Temperature parameters of 25 °C for cooling and 21 °C for heating were used, according to ASHRAE guidelines. In addition, internal gains and infiltration loads were also included to predict the benefits of using various insulations. For lighting, it was estimated at 54 W of electricity, whereas the infiltration rate was calculated at 0.63 air changes per hour. It is also important to note that a constant occupancy schedule was assumed throughout the year, with internal gains equivalent to three occupants per day.

Furthermore, heat gains due to occupancy values based on ASHRAE 90.2-2010 were used. Lighting was calculated using LED luminaires with an estimated consumption of 12 W and 960 lumens and building infiltration was calculated using an empirical technique based on previous research and described by ASHRAE. In this way, coefficients were established for a building constructed using traditional construction methods, and the Kusuda and Archenbach model was used to define the soil temperature.

In total, a simulation was performed for a whole year using weather files downloaded from the EnergyPlus website for a location in Galicia, Spain. Window and door materials were not modified for the different simulations, taking standard models as reference. Windows were selected according to the ASHRAE 189.1-2009 ExtWindow ClimateZone 3 configuration for the climate zone defined by ASHRAE for the selected location.

This study evaluates four of the most representative orientations, i.e., north, south, east and west, taking the main windows of the house as a reference point. When this study was carried out with different insulation level scenarios, different results were obtained. In the case of the configuration without insulation, the least demanding orientation was the eastern orientation, but in any case, the demand was higher than any orientation that might be given to any of the building configurations with insulation. If insulation is achieved through the incorporation of SIPs, the most energy-efficient orientation would be the western orientation, which yields a reduction in demand of 10% compared to the least favourable one, which is the southern orientation. In any case, the incorporation of insulation is crucial to achieving energy efficiency since the configuration without insulation presents an energy demand that is 24% higher than the most favourable orientation option.

In addition, this study also examines the impact of climate on residential energy demand. A comparative analysis of the thermal performance of a house between two locations with different climate classifications according to Köppen–Geiger was carried out. The conditions of a Cfb climate were contrasted with a Csb climate, typical of Northwestern Spain. Using data from the Agencia Estatal de Meteorología and the Ladybug tool, it was evaluated how climate variations can influence the energy efficiency and thermal comfort of the dwelling, providing valuable insight into the possible effects of climate change on domestic energy demand.

In the context of the Cfb and Csb climates, this research highlights the predominance of heating demand in the Cfb climate, the one applicable to the geographical location of this case study example, with an oceanic climate that requires effective insulation to minimize heat loss. On the other hand, the Mediterranean-type Csb climate experiences an increased need for cooling during dry summers, although heating is still required in winter. This study of peak demand reveals the importance of proper sizing of the HVAC system to avoid exceeding the installed capacity, especially in the Csb climate during the hottest days of the summer.

The methods used in this study to evaluate the energy efficiency of container homes can be adapted or modified to suit different climatic regions by tailoring the insulation strategies, ventilation systems, and building orientations to the specific climatic conditions of those regions. For instance, in colder climates, such as those in Northern Europe or Canada, enhancing insulation with materials of higher thermal resistance (R-value), using triple-glazed windows, and incorporating passive solar design features could effectively reduce heating demands. In contrast, for hotter climates, like those found in Southern Asia or the Middle East, strategies might focus on minimizing cooling loads through reflective roof materials, external shading devices, and optimized cross ventilation. These adaptations demonstrate that while the core principles of the optimization methods—such as improving thermal efficiency and minimizing energy consumption—remain applicable, their specific implementation must be tailored to address the distinct thermal challenges posed by different climates.

While the current study focuses on the specific climatic conditions of Southwest Europe, characterized by mild winters and warm summers, it is essential to consider how these findings could be adapted to different climatic contexts. In regions with colder climates, container homes may require enhanced insulation strategies and more efficient heating systems to cope with lower temperatures. For instance, in Nordic countries, the use of triple-glazed windows, higher R-value insulation materials, and the integration of passive solar heating could be more effective. Conversely, in hot climates, strategies should focus on reducing cooling loads through reflective roofing materials, external shading devices, and optimizing ventilation to prevent overheating. Certain design principles, such as maximizing natural ventilation, optimizing window-to-wall ratios, and using sustainable materials, can be universally applied to improve energy efficiency in container homes regardless of the climatic conditions. A comparative analysis of studies conducted in different climates, such as Australia's arid regions, Canada's cold climates, and Brazil's tropical climates, highlights the adaptability of container housing designs to maintain energy efficiency and comfort levels.

These results have similarities and differences with other studies. In the case of Boafo et al. [89], the authors estimated that the annual energy savings are between 1 and 10% but conclude that the southern orientation is the best for houses in the northern hemisphere in those cities where the case studies were analyzed (Chicago, USA; London, UK; Incheon, Republic of Korea; and Abu Dhabi, UAE). In Ruiz and Romero [90], the location of the house was much closer geographically, since the case study is based on the construction of a house built in the north of Spain about 450 km away from our location. In this case, the southern orientation is also the most suitable for energy saving. Moreover, the southern orientation is optimal for the main façade of residential buildings in different areas of Spain in the article by Fernández-Antolín et al. [91]. In this case study, the most favourable orientation is west, contingent upon the incorporation of insulation with SIPs. Nevertheless, in scenarios where insulation is not utilized, the eastern orientation, followed closely by the southern orientation, would be deemed more suitable due to its lower energy consumption levels.

Repurposing unused containers in ports is a proper way to address environmental, social, and economic challenges. By integrating them into the circular economy, the reduction in waste and maximization of resource efficiency should be obtained. It is a win-win situation that demonstrates how innovative thinking can lead to sustainable solutions. In addition, the use of shipping containers for housing presents a viable solution, given the rapid population growth in developing countries. Thus, the social pressure can be managed by public authorities [21,26,92–95].

Nevertheless, even though this paper defines the geometric parameters and the energy characteristics of a house in order to determine the most energy-efficient orientation given certain climatic and locational characteristics, the analysis is not translated into economic results. Therefore, this might represent a limitation of the research, in addition to the lack of calculation of the carbon footprint, or the degree of reuse of materials. In this way, it would be easier to conduct a comparative analysis of the sustainability degree between housing constructed using standardized sea containers versus traditional housing methods.

The incorporation of real-world case studies and empirical data is crucial to support the theoretical models presented in this study. Recent studies monitoring the performance of container homes in different regions provide valuable empirical data. For example, research in the United States showed that container homes with proper insulation can achieve energy savings of up to 40% compared to conventional homes. Real-world examples, such as the Keetwonen student housing project in Amsterdam, which comprises 1000 container units and successfully addressed a student housing crisis, demonstrate the potential scalability and adaptability of container housing in urban settings. Another example is a single-family container home in Texas that achieved a 30% reduction in heating and cooling loads compared to local building standards through appropriate insulation and passive design strategies. However, challenges such as community acceptance, regulatory approvals, and logistical constraints were evident in these case studies, and addressing these barriers was key to their success.

The findings of this article provoke further inquiry, thereby prompting the emergence of new research questions that delineate future avenues for exploration, supplementing those previously addressed. One prospective research direction would entail examining the incorporation of construction elements, both within the house and on the property, to assess their impact on the air conditioning and energy performance of the dwelling. Another avenue of research would entail conducting more detailed simulations over an extended timeframe, in order to attain greater precision in selecting the equipment that forms the air conditioning of the space. Weather conditions play a crucial role in energy demand; therefore, another future research direction involves utilizing meteorological files based on data projections to analyze the dwelling's behaviour considering the anticipated climatic conditions expected throughout its lifespan.

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