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Life Cycle Assessment of Construction Components of Schools in Southern Brazil

By Julia Rataichesck Fiates[1], Enedir Ghisi[2]

ABSTRACT:
Introducing energy efficiency techniques in schools can significantly reduce energy consumption, as Brazil has a large public education system. The main objective of this work was to select the set of construction components with the lowest environmental impact for use in schools in Florianópolis, southern Brazil, through life cycle assessment (LCA). Two types of walls, four types of roofs, and two types of window frames were studied. Ceramic bricks measuring 14x9x19cm and 9x19x19cm were considered for the walls. Wood and aluminium were used for the window frames, with single glass panes on all windows. For the roofs, fibre cement tiles with a PVC ceiling, a drywall ceiling, and a concrete slab were considered, as well as ceramic tiles with a PVC ceiling. Computer simulations were conducted using the EnergyPlus program in order to determine the building's energy consumption. SimaPro was used to run the LCA. The construction of the building and one year of its energy consumption were analysed to select the combination of components with the lowest impact on the building's life cycle. Finally, the set consisting of 9x19x19cm ceramic brick walls, wooden frames, and roof with fibre cement tiles and PVC ceiling presented the lowest environmental impact.

Keywords: Life Cycle Assessment; public schools; computer simulation; buildings; EnergyPlus; SimaPro

1. Introduction

The construction industry plays a significant role in a country's economy. However, construction activities have significant environmental impacts, as it is the industry that generates the most waste and consumes about 75% of natural resources (Asadollahfardi, Asadi & Karimi, 2015; John, 2000). The construction industry has a significant environmental impact due to waste and resource use. Integrating sustainable practices is crucial but often hindered by high costs, lack of awareness, and resistance to change (Hwang & Tan, 2010). Overcoming these challenges requires industry commitment and supportive government policies, which can drive innovation and provide long-term benefits (Olanipekun, Xia, Hon & Darko, 2017).

In Brazil, the current construction methods result in various environmental damages, as they utilize non-renewable natural resources and consume high amounts of energy in the extraction, transportation, and processing of inputs (Roth & Garcias, 2009). Nevertheless, the construction sector is considered to have the greatest opportunities and potential to save energy and reduce carbon emissions (Kylili, Ilic & Fokaides, 2017). Using advanced materials and technologies can reduce the environmental impact of construction (Ortiz, Castells & Sonnemann, 2009). However, successful implementation also requires

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|[1]Federal University of Santa Catarina, Brazil.
[2] Federal University of Santa Catarina, Brazil

engaging stakeholders and effective collaboration to overcome challenges and achieve sustainability goals (Jones & Bebbington, 2015).

Social, economic, and ecological indicators also impact the sustainability of a building. The construction sector directly affects the natural environment, human health, and resource availability, but its magnitude is commonly disregarded in engineering project development (Zararah, 2018). Considering all these influences is essential for the construction sector to adapt to sustainable development (Buyle, Braet & Audenaert, 2013). In Brazil, according to Schenini, Bagnati & Cardoso (2004), the lack of ecological awareness in the construction industry has resulted in permanent environmental damages. The migration process in the second half of the 20th century aggravated the ecological impacts, leading to a huge demand for new buildings.

Currently, with the growing awareness of the problems generated by the construction industry, several tools have been developed to assess sustainability from different perspectives and for a variety of users (Buyle, Braet & Audenaert, 2013). Consequently, the demand for the development of building projects with low energy consumption has also increased. Such a recent environmental awareness has led to interest in the life cycle assessment of products and services offered to the public. Life Cycle Assessment (LCA) methods have been used for environmental assessments of product development processes in other industries for a long time, but their application to the construction sector is current (Zararah, 2018). Morales, Moraga, Kirchheim & Passuelo (2019) state that there is currently an increased interest in incorporating LCA methods into building construction decision-making, either for selecting environmentally preferable products or for assessing and optimizing construction processes.

An analysis of the entire life cycle of a building enables the identification of the main components generating environmental impacts, facilitating decision-making to reduce the project's impact. Without this global view, measures may be adopted only to change the type of impact caused or simply to reposition it within the cycle (Asadollahfardi, Asadi & Karimi, 2015; Buyle, Braet & Audenaert, 2013; Curran, 2013; Rashid & Yussof, 2015).

Education is an essential element for human development, encompassing the social, political, historical, and cultural relations of individuals (Santa Catarina, 2015). To ensure access to education, the construction of public education systems is a responsibility of the State (Brasil, 1996). The country has about 141 thousand public schools. Of these, 12% do not have bathrooms in the building; 33% do not have internet; 31% do not have access to drinking water; 58% do not have sewage collection and treatment; 68% do not have libraries; and 67% do not have sports facilities (Brasil, 2018). Trevisan, Chizzotti, Ianhez, Chizzotti & Verillo (2003) concluded that the quality of construction in educational institutions is affected, as public works, by the diversion of public resources and the pursuit of reducing delivery times.

The Collaborative for High Performance Schools (CHPS) (2006, v.1) qualifies a high-performance school as one that employs the best design strategies and construction technologies of today to offer healthy and comfortable environments; save energy, resources, and water; function as a teaching tool; offer spaces and services to the community; ensure easy operation and maintenance; create a safe and protected educational atmosphere.

Considering the large number of public schools spread throughout the country, improving projects through the adoption of energy efficiency techniques has great potential for reducing the total energy consumption of institutions. The main objective of this work was to select the set of construction components with the lowest environmental impact for use in schools in Florianópolis, southern Brazil, through LCA.

2. School Infrastructure

The core principles of the Brazilian educational policy stress public action to ensure students' access to quality school environments. Silva (2015) states that school infrastructure, including facilities and equipment, plays a crucial role in student learning and academic performance. Efficient resource allocation is essential for improving infrastructure and enhancing student outcomes. Quality infrastructure promotes citizenship and enriches educational experiences, encompassing spaces for various pedagogical activities. In Florianópolis, the Municipal Education Plan aims to create sustainable educational establishments with harmonious designs, prioritizing environmental comfort and mitigating pollution effects. Technical guidelines emphasize the importance of diverse environments in school buildings to support early childhood education.

3. Life Cycle Assessment

Buyle, Braet & Audenaert (2013) indicate that the first environmental impact studies of consumer goods emerged between the 1960s and 1970s, focusing on the evaluation and comparison of these products. In 1980, life cycle thinking in construction began to stand out through a study by Bekker (1982), focusing on the use of renewable resources. However, initial analyses were diverse and divergent due to the lack of scientific discussions. It was not until the 1990s, with standardization procedures, workshop organization, and scientific publications, that LCA began to be accepted as an analytical tool, harmonizing structure, methodology, and terminology (Buyle, Braet & Audenaert, 2013; Rashid & Yussof, 2015; Van Ooteghem & Xu, 2012). Today, LCA is considered an environmental management technique, allowing for a comprehensive analysis of products and services. Understanding each part of the process and the origin of the data is crucial for decision-making (ABNT, 2014; Curran, 2013).

NBR ISO 14040 establishes that an LCA study consists of four phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (ABNT, 2014). LCA is an iterative approach where each phase depends on the information obtained in the previous phases to ensure the accuracy of the conclusions. The goal and scope of an LCA must be clearly defined, including the product system studied, functional unit and system boundary. Inventory analysis involves the collection and quantification of data related to the inputs and outputs of the system.

An LCA has limitations, such as the lack of method standardization, uncertainties associated with factors like lifespan and climate, and the non-consideration of aesthetic and economic aspects alongside environmental ones (Buyle, Braet & Audenaert, 2013; Van Ooteghem & Xu, 2012). To improve LCA validity, it is prudent to enhance data quality and use sensitivity and scenario analyses to address such uncertainties (Finnveden, Hauschild & Hellweg, 2009).

In the traditional industry, LCA methods are widely disseminated and used to assess the environmental impact of processes and products. However, buildings present unique challenges due to their complexity, including large size, variety of materials, and construction methods. The adoption of LCA practices in construction increased in the 21st century, especially in residential and commercial buildings, covering aspects such as materials, construction process, and operation (Buyle, Braet & Audenaert, 2013; Ramesh, Prakash & Shukla, 2010; Rashid & Yussof, 2015; Van Ooteghem & Xu, 2012). The definition of system boundaries, such as "cradle-to-gate," "gate-to-gate," and "cradle-to-grave", is crucial for a comprehensive analysis. The operation phase is usually the most significant in terms of environmental impact due to its long duration. Standardizing specific methods for the construction industry and creating reliable databases are necessary to facilitate the application of LCA in the sector (Rashid & Yussof, 2015; Van Ooteghem & Xu, 2012). Recent studies demonstrate the applicability of LCA in buildings, identifying significant contributions from specific construction systems to the life cycle of structures.

3.1 SimaPro

SimaPro is a software, developed by PRé Sustainability in 1993, that facilitates the visualization of processes in LCA, ensuring coherent decision-making aligned with study objectives and data accuracy. It offers sustainability reports, carbon and water footprint assessments and environmental declarations. With twelve databases and 28 assessment methods, SimaPro enables quick visualization of results and collaborative analysis among users (PRé Sustainability, 2024).

4. Whole building simulation

Computer building simulation, developed in the 1970s, aids decision-making for constructing environmentally efficient environments. It influences various aspects of building design, engineering, operation, and management. Building modelling can be experimental or theoretical, with the latter dividing the system into smaller parts. This approach allows for the independent treatment of zones with their unique load characteristics. Early theoretical modelling estimates output values, saving time and money. The procedure involves determining climatic and building data, HVAC system characteristics, occupancy pattern, simulating the desired period, and predicting energy consumption. The choice of simulation software depends on its application, frequency of use, available hardware, and user experience, with EnergyPlus following the standard of early theoretical modelling (Wang & Zhai, 2016; Harish & Kumar, 2016).

4.1 EnergyPlus

EnergyPlus is a software developed by the United States Department of Energy for energy analysis and thermal load simulation. It inherits many features from BLAST and DOE-2 programmes from the 1970s, created in response to the energy crisis and the recognition of building energy consumption's significance. The programme facilitates thermal simulation and energy analysis of buildings, catering to engineering professionals seeking to size HVAC equipment, conduct retrofit studies, or optimize energy performance. Through a building's description, EnergyPlus simulates its behaviour, calculating parameters like heating and cooling loads and energy consumption. It was not designed for LCAs, but its results can be used for such (United States, 2022).

5. Methodology

A flowchart of the methodology to perform an LCA of construction components of schools in southern Brazil is shown in Figure 1 and described in the following sections.

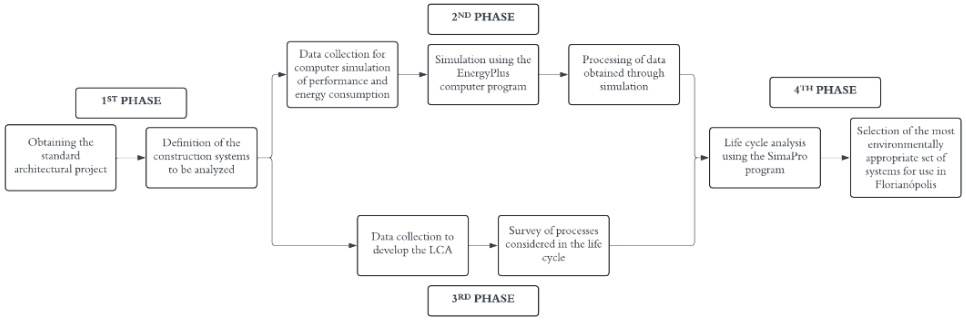

Figure 1: Flowchart of the methodology

5.1 Standard architectural project

Diretoria de Infraestrutura Escolar da Secretaria do Estado da Educação (DIPE) of Santa Catarina provided a model project for this study, featuring the architectural design of the Irineu Bornhausen Basic Education School in Florianópolis. DIPE's Infrastructure Planning Management team made it available, deeming it representative of regional public educational institutions, with all essential spaces for a fundamental education institution. Figure 2 shows a simplified version of the floor plan.

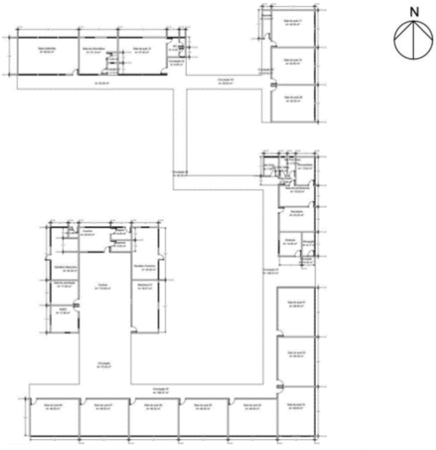

Figure 2: Floor plan of the school analysed herein

5.2 Construction components

The materials studied were selected using data from Palhoça's Municipal Government, which listed building components commonly used in educational projects in the city. Structural, plumbing, and electrical installations were standardized across all scenarios to disregard their influence in the LCA. Consequently, quantifying materials for these systems is unnecessary.

5.3 Whole building simulation

The computer simulations progressed in two phases. Initially, simulations were run without artificial cooling systems to evaluate the building's thermal performance and calculate the total annual hours of thermal discomfort. Secondly, simulations were conducted with air-conditioning systems in classrooms to assess energy efficiency. Additionally, the building's solar orientation was adjusted by 90° clockwise at each step to account for the project's four main orientations.

The simulations were conducted using EnergyPlus, requiring input data on the building's geometry, local climate, materials used in each component along with their thermal characteristics, and operational details such as occupancy, equipment usage, and window opening. Figures 3 and 4 show the building modelled and its thermal zones.

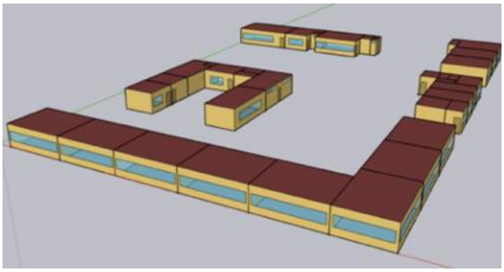

Figure 3: Building model

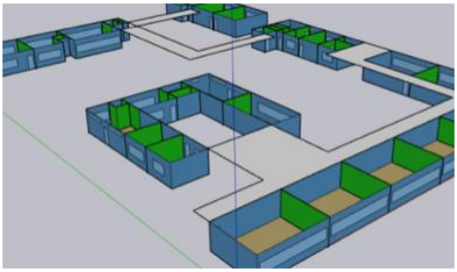

Figure 4: Thermal zones

5.4 Life Cycle Assessment

The LCA process comprises several stages, including objective and scope definition, inventory analysis, impact assessment, and data interpretation.

5.4.1 Objectives and scope

The objective is to determine the environmental impacts of various building models, comparing different components. The analysis considers components such as walls, windows, and roofing, modelled in SimaPro with a functional unit of m^2. The scope excludes renovations and material disposal, focusing on the building's construction and operation over a 50-year lifespan.

5.4.2 Life cycle inventory

This stage involves quantifying materials for each building component using the Revit programme. Data on materials and transport distances are collected from databases and local suppliers.

5.4.3 Impact assessment

Conducted in the SimaPro programme using the IMPACT 2002+ method, which evaluates both classical and recent impact prediction methods. The results include impact and damage categories, such as DALY and PDF.m2.yr, representing different environmental aspects.

5.4.4 Interpretation of life cycle environmental impact data

Results are manipulated to represent the construction of an educational institution. Impact values per area of each building component were calculated and multiplied by the total floor plan area. The interpretation follows a method presented by Humbert, Schryver, Bengoa, Margni & Jolliet (2012), considering damage and impact categories. The analyses encompass different combinations of building components and solar orientations, detailed in the flowchart shown in Figure 5.

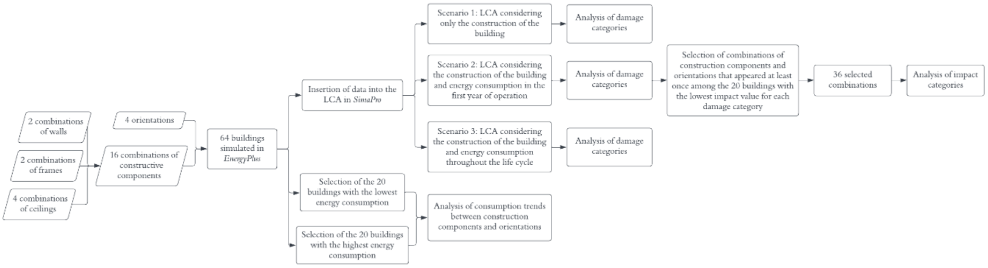

Figure 5: Different scenarios analysed throughout the study

6. Results

6.1 Analysis of the construction components survey

The Municipal Government of Palhoça gathered the information regarding the building materials used in ten public educational institutions in Greater Florianópolis. The study considered information on walls, floors, roofs, and frames of the buildings.

The survey found ceramic blocks to be the dominant building material for walls in public schools. The blocks are used in both dry and wet areas. All schools analysed had ceramic block walls, often finished with cement plaster. The specific block dimensions varied between institutions. Wood and aluminium were identified as the materials used for window and door frames in public schools. All windows are designed for curtains, without blinds. Additionally, all windows use standard glass, regardless of frame material. The roofing's structural components include tiling and ceiling: fibre cement and ceramic tiles are most common, along with PVC or drywall ceilings. Table 1 outlines the combinations of elements for the construction components.

Table 1: Construction components

(a) Walls	(b) Windows and Doors	(c) Roofings	
Block	Frame	Tile	Ceiling
14x9x19 ceramic	Wood	Fibre cement	Drywall
9x19x19 ceramic	Aluminium	Fibre cement	PVC
		Fibre cement	Solid concrete slab
		Ceramic	PVC

6.2 Analysis of computer simulation data

The simulations using EnergyPlus established sets of building constructions based on representative components for educational institutions in the region. This included two options for walls, two for windows, and four for roofs, totalling 16 combinations. Considering the four main project orientations, a total of 64 models were simulated. The data obtained were evaluated based on thermal discomfort hours and temperature maintenance throughout the day.

The analysis evaluated annual discomfort hours for each scenario without artificial cooling systems. The total discomfort hours for each environment were analysed across four orientations based on construction combinations. Orientation at 0° showed the lowest discomfort hours, with classrooms mainly on the south facade and multimedia rooms to the north. The 270° orientation had the lowest discomfort hours in six cases, while the 90° and 180° orientations had the highest occurrences of discomfort hours. Buildings with drywall ceiling components had the highest discomfort hours, while those with ceramic tile roofs and PVC ceiling performed the best. Wall construction showed similar behaviour across different roof and window combinations.

The energy consumption analysis considered discomfort hours derived from simulations conducted without the use of artificial cooling systems, annual energy consumption with the use of artificial cooling, various combinations of construction components, and building orientations. Computer simulation analysis showed that orientations with the most discomfort hours – 90° and 180° – also had higher energy consumption. Selecting the 20 combinations with the lowest and highest consumption enabled listing standard characteristics for reducing energy consumption over the operation phase. Figures 6 and 7 show component frequency for these combinations.

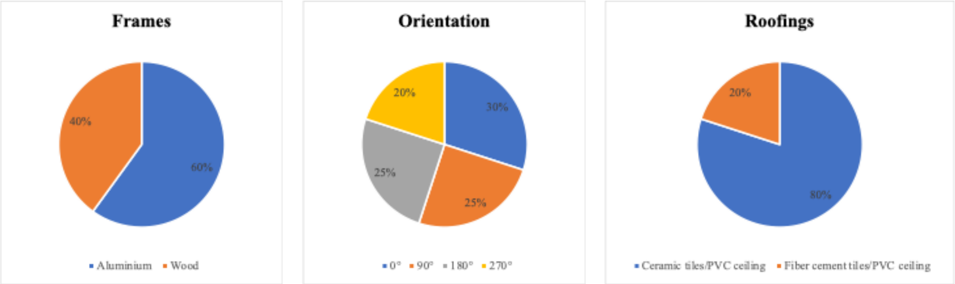

Figure 6: Characteristics of buildings with the lowest annual energy consumption

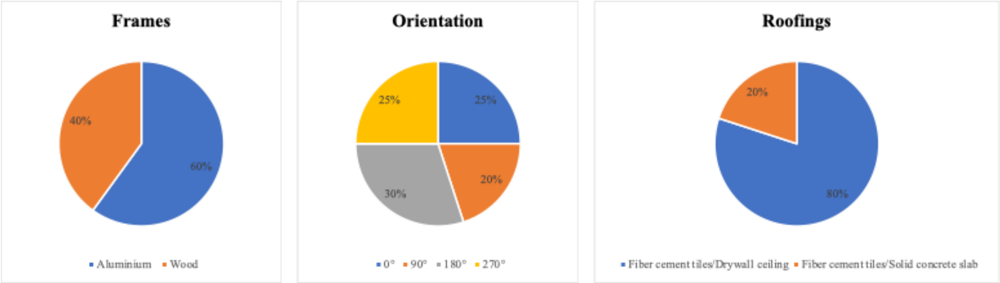

Figure 7: Characteristics of buildings with the highest annual energy consumption

Buildings with lower energy consumption commonly featured ceramic tile roofs with PVC ceilings, followed by fibre cement tile with PVC ceilings. Aluminium windows were more frequent than wooden ones. Walls had minimal influence on energy consumption.

For buildings with higher energy consumption, wall elements had no significant influence. Fibre cement tile with drywall ceiling was common, followed by fibre cement tile with solid concrete slab. Aluminium windows predominated over wood. The most common orientation was 180°, with 270° being least common. Roof elements significantly influenced energy consumption. Ceramic tile roof with PVC ceiling and aluminium windows were common among the sets with the lowest consumption. All windows used common glass. Building orientation aligned with thermal discomfort hours, with 0° and 270° presenting the lowest values. The results obtained align with studies by Azevedo (1995). Buildings oriented at 0° and 270°, with classrooms facing north/south, are deemed most convenient for reducing sun exposure.

6.3 Interpretation of environmental impact data from LCA

6.3.1 Damage categories

The environmental impact considered in damage categories initially focused on the first scenario, consequently only on the building's construction. As only materials were evaluated, building orientation was not considered. In the human health damage category, 9x19x19 cm ceramic blocks had the lowest impact among wall components, close to those of 14x9x19 cm blocks. Wooden windows generally had lower impact. Ceramic tiles and fibre cement showed higher impact than other roofing materials, while drywall and PVC ceilings showed no significant variation. Solid concrete slabs had an intense impact on ecosystem quality. Climate change and resource damage categories mirrored this pattern, with significant influence from slab use. Cement and steel used in solid concrete slabs had a notable aggregate impact on the building. Among construction components, 9x19x19 cm ceramic blocks had the lowest impact on walls, while aluminium windows had the highest on frames. However, impact variation was low for walls and windows.

For the second scenario, the analysis considered the building's solar orientation, energy consumption for the first year, and construction materials. Ceramic blocks of different sizes showed varying impacts on human health, while aluminium windows had a greater impact. Roofing materials like ceramic tiles and solid concrete slabs had significantly higher impacts. Despite energy consumption's influence, orientations had minimal variations. Energy consumption predominantly affected the ecosystem quality category. Windows and walls showed slight variations in impact, with aluminium windows showing the least impact. Roofing materials followed an energy consumption pattern, with ceramic tiles and PVC ceiling showing reduced impact. Wooden windows had the lowest impact in the resources category, while solid concrete slabs in roofing continued to have the highest impact. This highlights the importance of computational simulations for building operation, especially in understanding changes in ecosystem quality.

Finally, for the third scenario, the impact values for the four damage categories are studied, considering both construction and operation of the building over a 50-year lifespan. Analysis showed that the damage category patterns over 50 years of energy consumption align closely with those observed for one year of consumption. This highlights the significant impact of the materials manufacturing stage in LCA, underscoring its importance. These findings corroborate previous studies by Rashid & Yusoff (2015) and Van Ooteghem & Xu (2012), indicating minimal environmental impact during the construction phase. Combinations of construction components and orientations that appeared among the 20 models with the lowest impact for each damage category were selected, totalling 36 combinations. Figure 8 shows the frequency of occurrence of each construction component and orientation among the different combinations selected.

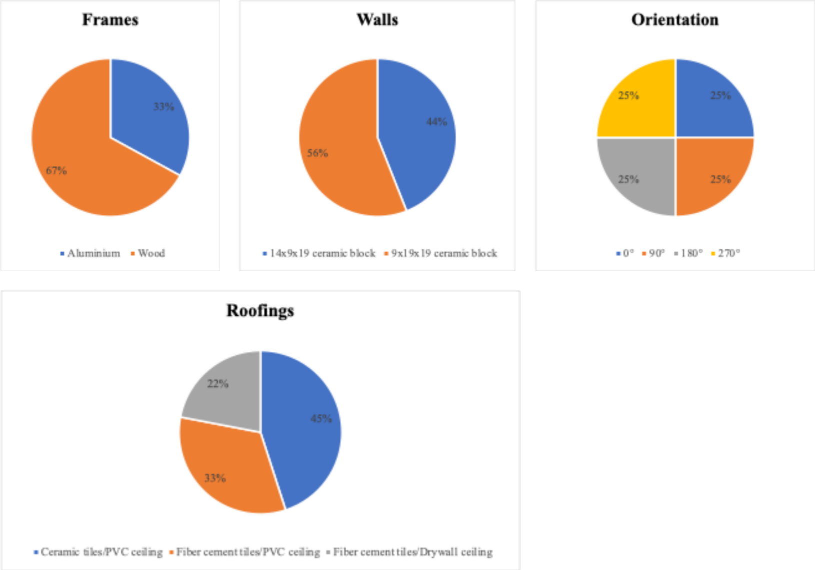

Figure 8: Frequency of occurrence of construction components and solar orientation of buildings with lower impact in damage categories

Despite the prevalence of walls made of 9x19x19 cm ceramic blocks, no specific wall construction component stood out significantly. Orientation was observed not to influence the impact, while wood had a positive influence on frames. Among roofing components, the combination of ceramic tiles with PVC ceiling was most common, followed by fibre cement tiles with PVC ceiling and fibre cement tiles with drywall ceiling.

Roofing with solid concrete slabs did not feature among the combinations with the lowest impact values.

The results confirm findings from the analysis conducted by Medeiros, Durante & Callejas (2018), indicating that roofing with solid concrete slabs significantly impacts environmental variation during the building construction phase, making it the most impactful among the construction components analysed.

6.3.2 Impact categories

Figure 9 shows the aggregated impact percentages for each category in the second scenario, considering the building's construction and the energy consumption during its first year operating.

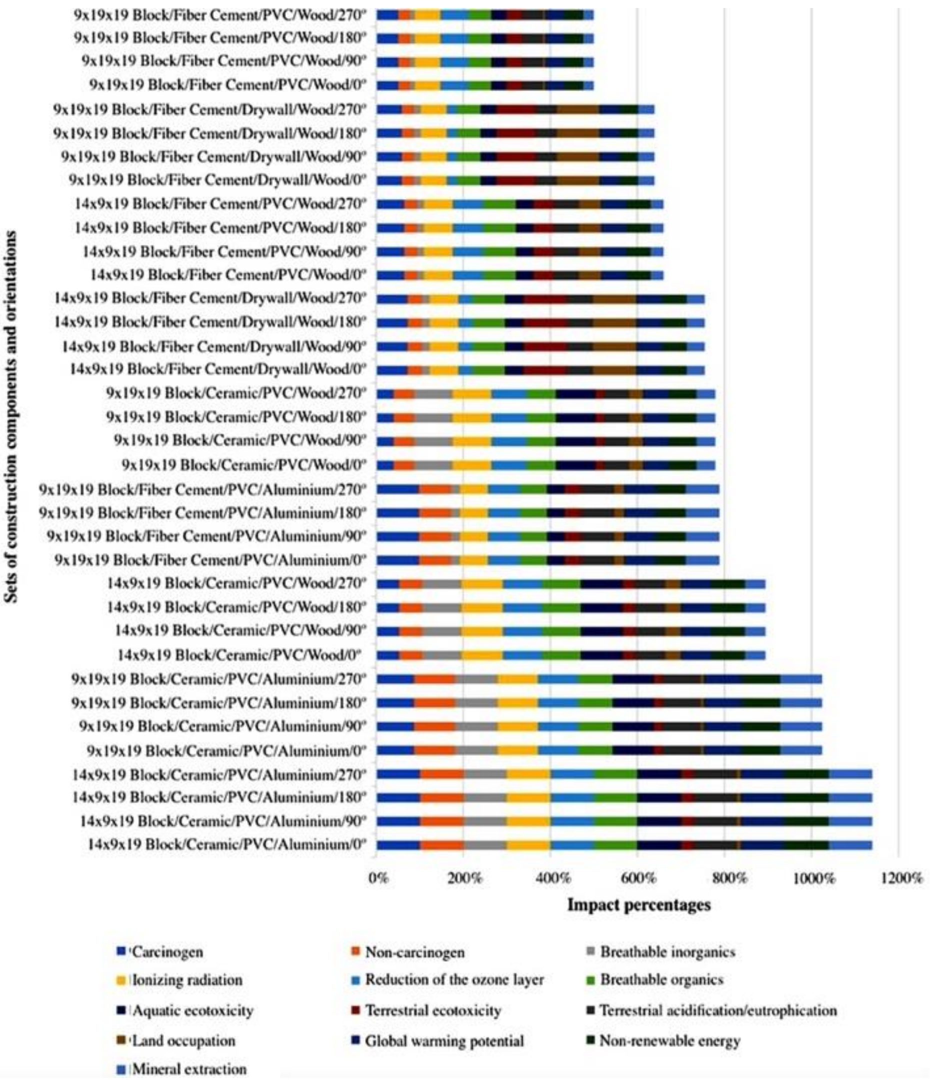

Figure 9: Sum of impact percentages for each model analysed

The construction components with the lowest impact value, considering construction and one year of building operation in the LCA, were walls made of 9x19x19 ceramic blocks, wooden windows, and a roof with fibre cement tiles and PVC ceiling. No variation in impact values was observed for different orientations. The second combination with the lowest life cycle impact had a drywall ceiling instead of PVC in the roofing. None of these sets stood out among buildings with lower energy consumption. This highlights the importance of considering the building's life cycle in achieving low environmental impact during a project development.

7. Conclusions

This study enabled the LCA of various wall, window, and roofing configurations, employing computer simulation to evaluate buildings' thermal performance over their lifespan. Data on annual discomfort hours and energy consumption were obtained, with solar orientations affecting these parameters. The combination of ceramic block walls, aluminium windows, and ceramic tile roofing with PVC ceiling showed the lowest annual energy consumption.

Different scenarios were considered, highlighting the significant influence of construction materials on environmental impact. Trends in building components' impacts were identified, with specific arrays showing lower impacts. Ultimately, a set of components with the lowest impact for public educational institutions in Greater Florianópolis was determined, considering both construction and initial operation phases. The chosen set comprises ceramic block walls measuring 9x19x19 cm, wooden windows with common glass, and fibre cement tile roofing with PVC ceiling.

The results of this study are key to promoting sustainable building practices in southern Brazil, especially by identifying materials and methods that reduce environmental impacts. However, in order to apply the study's results into other projects, further research is needed to assess how these materials perform in different climates and building types, as construction materials can have significant performance variations across environmental contexts. Additionally, incorporating these sustainable components into educational facilities requires a holistic approach, considering their specific needs such as energy efficiency, indoor air quality, and durability. This will allow designers to make decisions that enhance sustainability and resilience in educational facilities globally (Finnveden, Hauschild & Hellweg, 2009; Klöpffer & Grahl, 2014).

Further research could explore how sustainable design, which enhances environmental quality and resource efficiency, contributes to the effects the educational institution's infrastructure has on educational outcomes. Research by Earthman (2004) and Barrett, Moffat & Kobbacy (2015) shows that sustainable features such as natural lighting and improved ventilation create healthier learning environments, leading to better student well-being, academic achievement, and teacher satisfaction. High-quality infrastructure supports cognitive functions and reduces stress, benefiting both students and teachers.

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