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ENERGY CONSUMPTION AND THERMAL COMFORT ANALYSIS OF PUBLIC HOUSING IN SAO PAULO, BRAZIL

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ABSTRACT

This research examines energy consumption of public housing in Sao Paulo, Brazil and how changes in the current design practice affect building's energy consumption and comfort level. The hypothesis is that energy-efficient design concepts applied to the public housing design in Sao Paulo could significantly reduce energy consumption in buildings. Computer simulation is used to evaluate the current buildings' energy performance and to simulate the performance of new energy-saving design strategies. The findings show that energy consumption can be reduced by as much as 54% by implementing the new design strategies. This study highlights the many opportunities for architects to change the public housing scenario in Sao Paulo. It showed that changes carefully applied to the current design process can significantly enhance building's energy performance and comfort level inside the envelope.

Keywords: Energy, Public housing, Brazil, Computer simulation, Optimization, Thermal comfort.

Contribution/ Originality

The paper's primary contribution is showing that small changes in the design thinking, such as adopting more efficient building materials and considering the site's natural features, can change the public housing scenario in Sao Paulo improving people's life while promoting a more sustainable use of natural resources.

1. INTRODUCTION

Efficient energy use has become a trend in recent years all around the world. It is known that the Earth's temperature has increased over the past decades [1] and one of the main causes has been the large amount of carbon emissions released into the atmosphere. Climate change has been the outcome of a succession of reckless events since the industrial revolution, which has brought economic and social developments, but also the extensive use of energy. "Electricity, mostly

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generated from fossil fuels, is at the core of this challenge, accounting for more than 40% of global energy-related CO_2 emissions" [2]. "Brazil is the ninth largest energy consumer in the world and the third largest in the Western Hemisphere, behind the United States and Canada" [3]. Most of Brazil's electricity generation capacity comes from hydropower, which is a renewable energy resource. Nevertheless, emissions from hydropower, such as the ones in Brazil, are often underestimated, but in fact can exceed emissions of fossil fuel for decades [4]. Among the most energy consuming sectors building design has accounted for a great part of energy consumption worldwide. Man-made structures have been responsible for several types of pollution, such as carbon emissions, waste, and depletion of natural resources. The Energy Information Agency has identified thermal control inside the building envelope as one of the main issues associated with buildings' high energy consumption [5]. Hence, in order to contribute to a more sustainable environment, building design must become more efficient and designers must develop creative strategies to enhance buildings' performance in an economical fashion. Efficient building design becomes more challenging when applied to areas with economic challenges. Among the numerous challenges that developing countries have faced, housing has been a major one. In addition, developing countries' population has grown at such a higher rate that has impacted the number of low income families lacking resources for basic needs, such as housing. This scenario has been especially true in large metropolitan areas of developing countries and even more complex in one of the largest metropolitan areas in the world, Sao Paulo city. Sao Paulo is the largest city in Brazil, a developing country in South America, with a population of over 193 million [6], of which 84.2% are urban residents. In spite of the fact that the development of Sao Paulo over the past years has brought economic and industrial growth, this fast development contributed to increasing environmental issues, such as water and air pollution, as well as social and economical problems. The large number of people attracted to the city's promise of a better life increases exponentially, and the low quality public housing built to accommodate migrant workers and their families, for example, has been negatively impacting the city's natural resources and quality of life.

Therefore, this research addressed the issue of public housing design practices, in the city of Sao Paulo, and its potential improvements aiming a more sustainable, but still affordable architecture, in order to improve living conditions and promote a more efficient use of energy.

2. LITERATURE REVIEW

2.1. Best Practices

Public housing, also called "affordable housing," is the latest in a long list of synonyms used to denote housing for those who cannot afford the free-market price [7]. The concept embraces a wide range of variants and a "combination of services: space, environmental (water supply, waste disposal, energy use), and location (access to jobs and social infrastructure such as education and health)" [8]; however, the only basic concept of public housing that can be applied to all cultures is that it is a governmental initiative to battle poverty. The quality of spaces and types of construction vary widely among countries, cities, and even locations within the same city.

Today, there are many public housing initiatives in several developing countries; however, the majority of sustainable practice examples are concentrated in public housing projects in developed countries. First, because these countries have more advanced construction standards for public housing, and therefore, better buildings. Second, because they are also ahead in offering information and educating the population about environmental issues. In this study, the researcher gained various insights by studying design for public housing in countries such as Australia, Hong Kong, Singapore, United Kingdom, and the United States. Though all countries share the same goal of reducing the housing deficit and dealing with social issues, the design strategies differ considerably. For example, Australia showed a competent public housing program with a variety of design patterns that serve different levels of low income population. The latest projects offer great design standards and are good examples on how sustainable architecture practice can also be applied to low income classes. For example, the "K2 apartments", finished in 1997, were a new concept of public housing [9] that encompassed social and economic aspects of sustainability while respecting the natural environmental. The government focus on sustainable initiatives for public housing projects include some design considerations such as the use of energy efficient lighting, the inclusion of environmentally sustainable construction techniques, as well as the use of more efficient construction materials such as insulation, weather seals, and water saving devices.

Another successful example is the Singapore housing program that has greatly incorporated energy saving strategies in low income buildings' design. The adoption of the program "Energy Save" provides sustainable solutions for buildings such as passive design and active design to reduce energy use post occupation [10].

The major insights taken from other countries are:

- Concern with the environment when designing public housing buildings
- Use of building materials that reduce energy consumption
- Use of energy strategies incorporated into the building to save energy after construction
- Understanding that thermal comfort within the building impacts residents' quality of life.

2.2. Public Housing in Brazil

Throughout the years, several social housing programs and autarchies were developed at federal and state level in Brazil, and among all, Sao Paulo's public housing history has stood out due to the size of its program and the number of housing units delivered. More specifically, the housing deficit in Sao Paulo is the largest of all regions in the country. As of 2007, the housing deficit in the state was more than 1.2 million, while Brazil's total housing deficit was about 6.2 million houses, but most surprisingly is that the city of Sao Paulo and its Metropolitan Region alone account for half of this deficit [11].

Not only the large and fast population growth contributed to this deficit but also a combination of decades of social, economic, and political issues related to large metropolitan regions. Though housing has been a long-lasting issue, it was only in the 20th century that governmental initiatives of public housing began. They were mainly privatized programs, motivated by the government's aggressive capitalist thinking, which envisioned profit by construction and rental investments and targeted the low income labor class coming to the city to work in the fast growing industrial sector [12]. It was only after the dictatorships (Vargas: 1937 to 1945 and Military: 1964 to 1985) that new initiatives emerged trying to solve the deficit.

It was not until the 1960s that Sao Paulo state implemented the first social housing initiative with the creation of the State Company of Social Housing (CECAP). Throughout the years, the company had several changes in its structural organization and adopted different names, currently known as CDHU- Housing and Urban Development Company of the State of Sao Paulo [13]. CDHU's budget is nearly US$750 million per year. According to the United Nations Human Settlements Programme [14], since its inception, CDHU has built and sold approximately 440,000 units to benefit approximately two million people in 617 municipalities throughout the state of São Paulo. Meanwhile in the architecture field, the construction of multi-story buildings was one of the modernist influences that changed the face of public housing in Sao Paulo, which then started to focus on apartment buildings instead of houses, accommodating more people in smaller pieces of land. But this was not enough to solve the series of economical and political issues encountered by the government with the increasing demand. The high demand for social housing and low governmental commitment directly affected the quality of the housing programs, and the standards for social housing communities.

2.3. Energy Consumption and Comfort Level

The amount of energy consumed by buildings before and after construction has become a concern worldwide. Moreover, given that building construction is proportional to population growth, the trend in energy consumption is expected to significantly increase in the next decades. Though strategies for energy conservation in buildings have become more popular, gaps still remain. Much has been done regarding energy-efficient building design, but there is still an association between efficiency in design and high costs. Moreover, environmentally friendly design has been related to state-of-the-art buildings, created by upper-class designers for their clients; however, as shown in this research, a more sustainable approach in building design can be done in social housing too. One of the main steps towards a more sustainable design approach is the understanding of building's dynamics and ways to achieve thermal comfort in order to provide a comfortable space consuming the least amount of energy.

"One primary function of a building is to modify or filter the outside climate to produce pleasant indoor conditions" [15]. Buildings are human shelters that should provide comfort for their dwellers and comfort is a subjective concept. It depends not only on temperature, humidity, and wind, but more importantly on people's comfort levels, which vary depending on region and even culture. Comfort is not only related to the human body's ability to dissipate heat, but it is also related to environmental conditions and natural conditions that allow heat dissipation to occur.

According to Lechner [16], four conditions simultaneously contribute to human comfort: air temperature, humidity, air velocity, and mean radiant temperature. Thermal comfort must be a target concept for designers when designing buildings. Site-specific characteristics, as well as building materials are fundamental elements to achieve good indoor comfort conditions. Moreover, indoor comfort levels depend on human reactions to temperature within a certain area and consequently affect energy consumption in a building. So, the goal should be to incorporate design strategies to improve indoor conditions while saving energy.

2.4. Thermal Comfort

Two different approaches can be used to achieve thermal comfort within a building envelope:

- Passive techniques, which take advantage of interactions with natural elements, such as sun and wind, to provide comfort.
- Active techniques, such as air-conditioning and heating systems that consume energy to achieve the same goals within an enclosed envelope.

Though passive design is the goal for all types of buildings, there are some constraints to utilizing it in multi-family buildings. Due to the reduced surface area exposed to environmental factors, such as sun and wind, apartment buildings present a disadvantage when compared to single-family homes. Moreover, different tenants might use each unit differently, thus interfering with natural ventilation, daylight incidence, lighting, and air conditioning. According to Rouse [17], in a study on passive solar programs for multi-family buildings in Massachusetts, "… inappropriate multi-family passive solar solutions may replace heating bills with bills for cooling and lighting, saving little energy, or worse, increasing total energy costs."

On the other hand, relying on active systems to provide thermal comfort will increase energy consumption. Lechner [16] states, "The more insulation, the better," referring to the improvements that insulation materials can offer and comfort levels that can be achieved when insulation is incorporated into a building. Some improvements to increase thermal comfort are relatively inexpensive, very durable, functional in summer and winter, and simple to install during construction. Insulated building envelopes are becoming increasingly common. By using insulation improvements, such as blankets, loose fill, foamed-in-place, boards, and radiant barriers [16], decreased heat loss, moisture, and fire resistance can be expected, all of which add value to the building envelope. Some elements, such as the roof, play an important role in the building envelope, because it usually represents the largest area of heat transmission. Strategies for a more effective building include light-colored roofs, which due to their high albedo, reduce thermal load on the building envelope by reflecting heat. Roof temperatures can reach 65–90°C in summer [18], which affects internal temperatures of the building envelope as well as building's energy performance. Other elements such as windows also affects thermal comfort in the building envelope due to the fact that they allow light and heat into the building, as well as provide external air to penetrate the envelope, in the case of operable windows. In addition, energy conduction through windows affects a building's energy performance. Window performance can be measured by: Solar Heat Gain Coefficient (SHGC), Visible Transmission (VT), and Thermal Resistance- U-value [19]. Window categories vary by number of glass panes (single glaze, double-glaze, and triple-glaze) as well as by construction details (frame material and gas fill between glass panes). In summary, thermal comfort within the building envelope can be achieved though passive and active design. Both methods have to be carefully designed to be efficient in terms of energy consumption and to improve comfort conditions for dwellers. Thermal comfort through passive design can be harder to achieve in multi-family buildings than in single-family units. Moreover, specific design solutions incorporated into the project positively impact thermal comfort and energy consumption.

3. MATERIALS AND METHODS

3.1. Objectives and Methodology

The objective of this study was to investigate the current design practice of public housing in Sao Paulo and to analyze the effectiveness of specific materials and design techniques in achieving a reduction in energy consumption. The methodology used to achieve the objective was as follows:

- Assess public housing design strategies around the world
- Identify current design practices in Sao Paulo for public housing
- Identify the best tool to achieve the research objective
- Investigate opportunities and constraints in the current design to further analyze improvements of passive strategies to the current design process
- Simulate elected buildings to understand the current state and further remodel the best case scenario with alternative materials in order to evaluate changes in energy consumption and thermal comfort.

3.2. Building a Hypothesis

The concept explored in this study was influenced by the possibility that specific design strategies could reduce energy consumption, as well as provide comfortable temperatures in public housing buildings in Sao Paulo. In addition, public housing construction in Sao Paulo has increased exponentially in the past years and so has the amount of energy consumed by these buildings. Thus, investigating whether new design techniques decrease energy consumption and provide higher levels of comfort in the apartments can ultimately impact the country's energy generation, as well as the population's quality of life. During winter, energy consumption rises because of the increased use of space heaters. And in the summer time, the use of fans and portable air conditioning systems cause an increase in energy consumption. The hypothesis of this investigation is that by incorporating energy efficient building elements into the current design, public housing should consume less energy while providing a better environment for dwellers.

3.3. Selected Research Method

Computer simulation was found to be the best method to assess the research objectives due to time constraints and the availability of high-quality computer modeling tools. Energy modeling simulation has recently become a popular tool used by researchers and designers alike. Designers tend to use such tools in the design phase to ensure a highly efficient building performance. On the other hand, researchers utilize these tools in conducting studies and investigations on the built environment in timely manner, minimal human and financial resources. Building simulation has proven to be a reliable research method with several software packages available both on commercial and academic scales. A Building simulation program enables researchers to conduct CFD analysis, thermal modeling, energy simulation, daylight analysis, and many other parameters. Software such as Energy Plus [20], eQUEST [21], ENVImet [22], IES Virtual Environment [23] and Ecotect [24] have been utilized for researches to assess energy consumption and thermal comfort. Due to its wide acceptance by architects and researchers and its unique features, Ecotect has been proven an accurate analysis tool in the field [20-24]. Also the second author has significant experience in using energy modeling software, including Ecotect, in similar type of research [22-24]. Utamaa and Gheewala [25] used Ecotect to simulate the cooling load of residential high-rise buildings in Indonesia. For this study, the software was used to calculate the load associated with the building fabric (envelope). Haase and Amato [26] used Ecotect to analyze climatic conditions related to thermal comfort in buildings and the impact of building location, climate, and orientation on thermal comfort. Another study utilized Ecotect to model a detached house in Sydney to evaluate heating and cooling requirements to determine when artificial systems were no longer required [27]. The study used the software to determine the specifications for the solar pergola shade over the north-facing window.

3.4. Scope of the Research

Through a standard decision process, the researchers determined that the optimal first step was to define the scope of the research. The scope was defined based on the following parameters:

- Location. The buildings should be located within the same region and same climate.
- Construction date. The buildings should have been built in different years, to evaluate whether there was an improvement in design, as well as to understand the quality and standard of public housing architecture in Sao Paulo.
- Typology. Buildings must have average floor height for public housing which according to the literature reviewed was four stories.
- Building area. According to the Secretary of Housing records, a great part of public housing comprises two bedroom units in a roughly comparable square area, which varies

from 45 to 60 square meters. Thus, the study buildings must have two bedroom units and a square area between 45 and 60 square meters.

- Function/Use. The buildings must be residential, because of the goal to evaluate public housing and quality of construction for low-income families in Sao Paulo.

With all the criteria established, the search for potential buildings was narrowed. Throughout the selection process, the researchers noticed that there was no complete database on public housing in Sao Paulo. The information available covered basic statistics, such as name of housing complexes, year of construction, and location. There was no architectural database of floor plans, sections, and other architectural drawings. The accessible information on housing programs and buildings was scattered in dissertations and publications; nevertheless it was not a complete set of information. During the selection process, it was evident that due to the relatively long history of public housing in Sao Paulo, it would be important to understand whether architectural design had evolved for public housing and whether the quality of design had improved throughout the years.

3.5. Case Studies

After the identification and selection of four buildings based on the parameters previously discussed, the next step was the modeling of all the selected buildings in the Ecotect software, followed by simulations to analyze their comfort levels and energy performance. The buildings selected were a sample of public housing design for the region of Sao Paulo. All buildings had the same construction material and finishes. They also presented similar floor plans, a rectangular with a central staircase, small openings and no exterior rooms, such as balconies. For this assessment, the inside partitions, walls, and openings were not detailed nor considered in the simulations. The goal was to assess the overall building performance, not the individual zones within the envelope. Table 1 shows a summary of the information about the four buildings chosen for the initial study, while Figure 1 shows the building floor plans.

Table-1. Summary data of buildings chosen for this study

Building Name	Year of construction	Floor area (m^2)	Number of floors
Juta Housing Complex A	1993	623.36	4
Juta Housing Complex C	1996	632.35	4
Voith Housing Complex	2001	482.51	4
Paraisopolis Housing Complex	2005	486.72	4

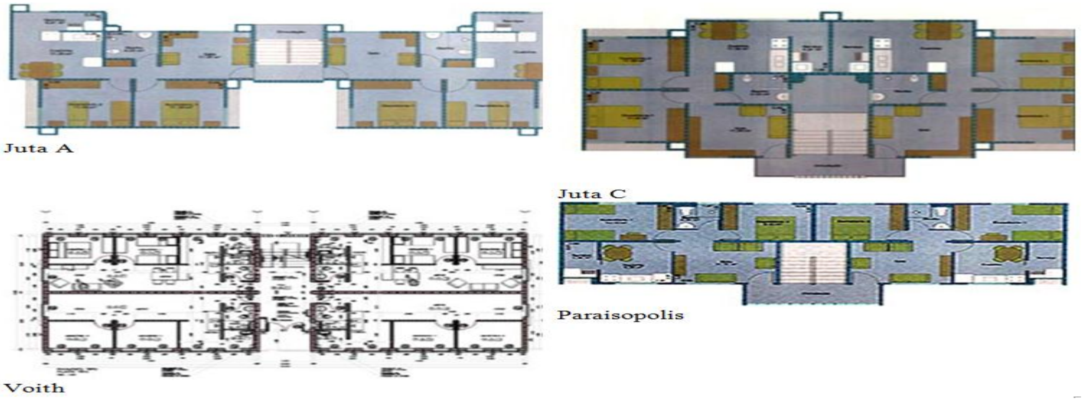

Figure-1. Floor plans of buildings chosen for this study

The weather information for Sao Paulo city used for the climate data in Ecotect was the EPW file format- Energy Plus Weather - available from the Energy Plus Energy Simulation software. The file was an ext-based format derived from the Typical Meteorological Year 2 (TMY2) weather format. Although Sao Paulo is located in a subtropical region, with usually mild weather, severe weather in winter and summer can occur. Latitude was an additional factor for consideration, due to the fact that solar radiation was one of the major causes of heat gain and influenced building's energy performance. No actual detailed energy consumption data was available for the buildings used in this case study. Thus, direct validation of the software was not possible. The authors were relying on the wide acceptance of Ecotect in published journal papers as well as their own experience to overcome this point.

4. RESULTS

The results from the simulations of the four cases revealed differences in energy consumption. The objective was to observe the energy consumption performance of the building envelope with different types of materials within the same temperature range and under air conditioned system. Based on the simulation results for thermal comfort and energy consumption, later, one building was chosen to be further studied.

From the thermal comfort analysis, in all four cases, the number of hours the buildings were outside the comfort zone was significant. To maintain the internal comfort conditions and to more accurately assess energy performance, air conditioning and heating systems were incorporated to the building models. In an air-conditioned zone, the interior comfort level will always be maintained at a comfort zone; however, the amount of energy required to keep the comfort level depends also on external conditions and building configuration. Another important consideration regarding the use of an air conditioning and heating system was the current comfort level observed throughout the year inside the buildings during the initial simulations. In low income buildings in Brazil, cooling or heating systems are never considered as design elements, first because of the typical climate characteristics, usually mild as mentioned before, and second because of the high cost. Therefore, the comfort levels evaluated in this research were focusing on not only improving energy consumption but also improving dwellers' quality of life.

The buildings' simulations in their current natural ventilation state showed great discomfort levels throughout the year as shown in Table 2. The simulations to analyze the current thermal comfort state in the buildings were done using the "discomfort degree hour" measurement in Ecotect, which is the sum of the number of degrees above or below the comfort band for each hour of each month. An algorithm was used to define the comfort temperature in the building. The "monthly average temperature" measured where the hourly variations were outside the comfort band for each month. "Comfort band" refers to temperatures that provide humans the sensation of complete physical and mental well-being [28].

Table-2. Summary of the thermal comfort and energy performance of all buildings

Data	Juta A	Juta C	Voith	Paraisopolis
Discomfort (Degrees/hour)	5,933	11,125	6,926	12,361
Discomfort (hours/year)	2,472	3,131	2,491	3,118
Discomfort (% of year)	28.2%	35.7%	28.4%	35.6%
Total annual energy consumption per unit area (heating plus cooling loads, kWh/m^2)	156.23	253.19	78.12	271.86

Comfort temperatures vary from person to person, by place, and by specific climate variables. "Most people will feel comfortable at 21°C doing sedentary work dressed in a suit or sweater; however at 26–27°C people should wear light clothes while doing light activities" [29]. "Temperatures in the winter should range from (20–23°C) and (22–26°C) in the summer" [28]. Based on the data, the thermal comfort temperature range for Sao Paulo city was set to 20–26°C for the purpose of this research. The comfort temperatures obtained from the simulations showed that each building had significantly different performance, despite having similar design patterns, shapes, areas, and materials. The annual energy consumption of the buildings varied considerably from a low of 78.12 kWh/m^2 to a high of 271.86 kWh/m^2, almost 3.5 times that of the low end. The building with the lowest number of hours outside the comfort zone was also the one that had the least energy consumption to maintain the comfort level throughout the year. Similarly, the building with the highest number of hours outside the comfort zone had the highest energy consumption. It is also interesting to note that the newest building had the highest energy consumption of all. This indicates that energy efficiency as well as comfort have not yet been considered a priority in housing design in Sao Paulo. Table 3 summarizes the results from the initial simulations. The building simulations results were compared and the most efficient building was chosen for further analysis in more depth in subsequent simulations. The Voith building was selected for further analysis because it represented the most efficient case among the four. The building was simulated under the different variables in order to evaluate energy consumption. For each variable the results were recorded and transferred to a database. The first objective was to observe the energy consumption performance of the building envelope with different types of materials within the same temperature range and under heated and air conditioned environments. Furthermore, the investigation evaluated whether orientation, materials, and shading adjustments implemented in a single model at the same time would improve the building's energy use. Thus, the Voith case study was simulated again using all of the previously identified optimum parameters for each category and the results were interpreted and compared with the existing building situation.

The proposal behind re-modeling the best performing building was to find the top energy performance building model for low-income public housing design. The Voith building was the most efficient of all four cases. It was understood, by analyzing energy consumption, thermal comfort and building shape, that the Voith building had more shading elements and openings than the other ones. The pitched roof and the windows' position in the building acted as cooling elements, since they provided shade and protection from the direct sun light. It was clear that not only the energy results alone were the main factor to analyze the energy performance of the four buildings. Table 3 shows a summary of the changes in total energy consumption related to building orientation, wall material, insulation, roof, window type, and shading.

Table-3. Summary results of simulations for each parameter of the Voith building (The optimum value for each parameter is highlighted.)

Parameter	Parameter variations	Annual energy consumption (kWh/m^2)	Reduction (-) or increase (+) in annual energy consumption compared to current status (%)
Orientation	North (current status)	**78.12**	----
	South	78.39	0.3
	East	82.97	6.2
	West	83.44	6.8
	Southwest	82.16	5.2
	Southeast	81.42	4.2
	Northwest	81.71	4.6
	Northeast	82.63	5.8
Insulation	No Insulation (current status)	78.12	----
	Brick Plaster w/Polystyrene 50 mm	58.93	-24.6
	Double Brick Cavity Plaster (air gap)	54.15	-30.7
	Reverse Brick Veneer - R20	**47.46**	-39.2
Wall material	Brick Plaster (current status)	78.12	----
	Concrete Block Plaster	77.01	-1.4
	Concrete Block Render	80.35	2.9
	Double Brick Solid Plaster	**54.03**	-30.8
	Brick Concrete Block Plaster	57.91	-25.9
Shading devices	Pitched Roof - Clay Tiled (current status)	78.12	----
	Roof Expansion - South Side	77.84	-0.4
	Roof Expansion - South and North Sides	76.93	-1.5
	Roof Expansion - East and West Sides	77.82	-0.4
	Roof Expansion - All Sides	**76.84**	-1.6
Window configuration	Single- glazed Aluminum Frame (current status)	78.12	----
	Single- glazed Timber Frame	76.62	-1.9
	Double- glazed Aluminum Frame	70.57	-9.7
	Double- glazed Low-e Aluminum	**67.66**	-13.4

Parameter	Parameter variations	Annual energy consumption (kWh/m²)	Reduction (-) or increase (+) in annual energy consumption compared to current status (%)
	Frame		
	Double- glazed Low-e Timber Frame	67.68	-13.4
Roof material	Clay Tiled Roof (current status)	78.12	----
	Concrete Roof Asphalt	**71.14**	-8.9
	Clay Tiled Roof - Ref Foil GYPROC	98.74	26.4
	Plaster Foil Heat Retention Ceramic	73.36	-6.1
	Corrugated Metal Roof	98.75	26.4

(The optimum value for each parameter is highlighted.)

For the orientation setting, the model was simulated for North, South, East, West, Southwest, Southeast, Northwest and Northeast. Orientation towards the North, the original building orientation, was the best option in terms of energy consumption. Compared to the worst result, orientation to the North was 6 percent more efficient.

The parameters simulated for insulation were brick timber frame with air gap insulation, brick plaster with polystyrene 50 mm, and reverse brick veneer R20 assembly, which consists of brick on the inside of the building and the timber frame on the outside. The reverse brick veneer allows the brick to stay within the insulation using the high thermal mass of the brick for insulation. The results showed that the reverse brick had the best performance with 47.46 kWh/m² compared to 78.12 kWh/m² for the original design, representing an improvement of 39.2%.

For wall materials, the standard for the building was concrete block and plaster. Variables for the simulation were concrete blocks plastered, concrete blocks render, double brick wall with solid plaster, and brick-concrete-block wall with plaster. Though the brick-concrete-block wall with plaster had a good performance, the double brick wall with solid plaster decreased energy consumption by 30%.

The shading device variable evaluated energy performance by incorporating changes in the existing roof. Because a tiled roof was already part of the initial design, a decision was made to modify the existing roof and evaluate changes in energy consumption. The incorporated changes included extension of different sides of the roof to understand how blocking sunlight into different areas of the building would affect energy performance. The results showed that the expansion of all sides of the roof simultaneously reduced energy consumption by almost 2% compared to extending only one side of the roof at a time. That indicates that more shaded areas were the best way to reduce energy consumption in this specific case.

The standard for window material in the Voith building was single-glazed window with aluminum frame. Among all materials simulated, the double-glazed low-e aluminum frame window had the best performance. It was 13.4% better than the original single-glazed windows.

The different options investigated for roof material were concrete rooftop with asphalt surface, clay tiled roof with foil and Gyproc—a thermal insulating plaster board that provides additional performance for thermal control, plaster foil with heat retention ceramic, and corrugated flat metal roof, which is sometimes used in public housing in Sao Paulo to decrease construction costs. Among all roof materials, the concrete roof with asphalt had the best performance. The roof consisted of 150 mm concrete lightweight, 6 mm of asphalt cover, and 10 mm of plaster cover molded, dry. This option was 6% better than the original clay tiled pitched roof.

A final (optimal configuration) simulation was done using the optimal value of each parameter as highlighted in Table 3.The results for the simulation of the optimum model showed that both cooling and heating loads improved as a result of all parameters working together. From the initial 78.13 kWh/m^2 of energy consumption, the final optimum building consumption dropped to 36.73 kWh/m^2, showing an improvement of 52% in energy consumption. The final optimum model had north orientation, reverse brick veneer R-20, double-glazed low-e aluminum frame windows, and the current pitched tiled roof expanded on all sides with concrete and asphalt base. When more than one building element, that had previously showed potential to reduce energy consumption, was combined in one model, the result improved exponentially. Among all the variables simulated in isolation, insulation was one of the greatest performers to decrease energy consumption.

The simulation of a final model provided various insights about public housing design in Brazil. It showed that building elements alone are sometimes not enough to improve energy consumption performance, but if combined with other elements, they can potentially be successful. Thus, a holistic design approach that evaluates different building elements is essential. The study also showed that the existing public housing design in Sao Paulo can potentially be improved in several different ways. It is possible to improve comfort levels within the building envelope and at the same time reduce energy consumption.

These results provided insights for future studies, where more variables could be incorporated into the building's simulation. Generally, residents' comfort levels are not taken into consideration during the design process; however, by carefully analyzing materials, orientation, and shading elements, better and more efficient buildings can be designed.

5. CONCLUSION

This study assessed energy performance of low-income public housing in Sao Paulo. It provided an overview of the current state of the issue. The literature showed that great attention has been given to sustainable practices in affordable housing around the world. The research methodology was presented, followed by analysis and results. The simulations performed as described herein reflected the reality of the current public housing situation in Sao Paulo. The results showed that changes carefully applied to the current design process can significantly enhance building's energy performance and comfort levels inside the envelope.

Furthermore, by assessing the environmental characteristics of the site, understanding climate elements such as solar patterns, or using more efficient building materials, it is possible to improve public housing design in Sao Paulo. It was also shown here that windows can improve energy consumption levels significantly. Moreover, insulation material was a resourceful system to improve indoor environmental conditions and lower energy consumption. Because insulation has not been part of the construction process in Brazil, this research showed how significant this component could be among all of the materials investigated. In addition, shading devices should always be considered throughout the design process; this study showed that they significantly reduced energy consumption when assessed separately.

In conclusion, this study showed that it is possible to improve Sao Paulo's public housing scenario by having a more efficient building, based on sustainable practices, which do not require extensive amounts of funds but will require less energy and will be more comfortable for dwellers. With small changes in the design thinking and construction process, the public housing scenario in Brazil has the potential to improve people's life and promote a more sustainable use of natural resources.

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