Comparative Analysis of Thermal Performance and Life Cycle Cost of Residential and Commercial Buildings; A case study of one of the Largest Islands in the World.

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Abstract

Indoor comfort, energy demand, carbon emissions and the cost of building maintenance vary according to the building structure and occupant's behavior. The main goal of this research is to evaluate and analyze the bioclimatic potential of different Malagasy climate zones. In addition, this study analyzes and compares energy consumption and carbon emissions in six building categories (residence, school, hospital, office, restaurant, and shopping center), designed in thirteen cities unequally distributed in the six climate regions in Madagascar. These different types of analyzed buildings are commonly found in Sub Sahara African cities. Hourly weather data for the last thirty years were analyzed for this purpose. The investigation was carried out over two seasons in the different buildings. The adaptive comfort model ASHRAE 55 was the reference for the evaluation of different passive design potentials. The results showed that in the sub-Saharan or hot zone, the range of comfort varies according to the regions associated with their geographical position, indeed, the number of hours of thermal comfort and of thermal acceptability is in the majority of the cases outside the recommended range of the international standards (CIBSE, ASHRAE and ISO). Madagascar Island, such as other countries, should develop their own standard. The demand for average cooling energy increases every year up to 3.4% in the coastal towns of Madagascar Island. More than 80% of carbon emissions can be reduced in hospitals in Madagascar as well as in Sub-Saharan Africa by increasing the maintenance cost, between

7% and 10% of the total life cycle cost of buildings.In Madagascar Island, the building Life cycle cost ranges from 12% to 14% for the construction cost, 0 to 1% for the renovation cost, 36% to 73% for the energy cost, 2% to 3% for the maintenance cost on the whole LCC.

Keywords: Simulation, bioclimatic zones, energy consumption, CO_2 emission, Life Cycle Cost, buildings.

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1. Introduction

The increase of average temperatures on the globe surface is the direct and expected result of massive greenhouse gas emissions [1]. However, the weather recordings testimony positive temperature anomalies which are confirmed, from year to year, in comparison with the recorded temperatures since the middle of the 19th century [2]. This sudden change in the outside climate will have many consequences. Several summits were convened by the Intergovernmental Panel on Climate Change (IPCC) to try to find a solution to this major problem. Among the many resolutions proposed by intergovernmental bodies, one of the most common is the implementation of many concepts related to sustainable development. Nowadays, in Europe and all over the world, ecological buildings more adapted to the current climate are flourishing. The cities are experiencing rapid demographic, social, environmental, and economic growth. Urbanization is undergoing a very rapid change. By 2030, it is likely that 6 out of 10 people live in urban areas [3]. About 90% of this growth will be in Africa and other underdeveloped countries. The impacts of this urbanization can be dramatic in the absence of adequate urban planning [3].The building sector is the key for reducing carbon emissions. According to the last report of the European Union, the construction sector is responsible for over 35% of carbon emissions and for more than 40% of total energy consumption [4].The history of construction is closely linked to the availability of materials, and most of the materials and techniques used in construction have been improved in the last century. In its quest for modernity, the African building has unfortunately been cut off from its bioclimatic tradition. A set of traditional techniques allowed the inhabitants to face sometimes extreme climates. Today, on the continent, buildings are often poorly adapted to the hot, thermally uncomfortable, and energy-consuming climate [5].According to UN-Habitat [5], 80% of the buildings that will be inhabited in 2050 in Africa, are not yet built. In recent years, architects, contractors, engineers and international organizations have been working with passion on the issue, including research in the field of the most innovative building materials[4].The housing situation in Madagascar is characterized, both in quality and in quantity, by absolute insufficiency, which is explained by both demographic (population growth, rapid urbanization) and socio-economic factors (underdevelopment of the productive forces) [6].Madagascar island ranks among the most vulnerable countries to the effects of climate change; it is ranked among the top ten countries in the world for the cyclone mortality risk index [7]. Since the 1970s, the country has been shaken by four political crises (in 1972, in 1996, in 2002, and in 2009), plunging it into an economic recession, marked by a drop in GDP [8]. Currently, no urban plan has been applied in this country.

The study on the bioclimatic of a country is not recent; several researchers produced important work in this area. The bioclimatic diagram of a residence allows to know if the conditions of indoor comfort are respected. The first group who studied in this field includes the oldest researches that used bioclimatic maps to describe the operation of buildings [9-13].The second group of studies in this area focused on the simulation of habitat performance, as showed in[14].The third research group on bioclimatic analysis showed a dual approach, simultaneously combining habitat performance simulations and bioclimatic maps [15]. In 2016, Kumar et al.[16]carried out a study on thermal comfort in 32 naturally ventilated buildings in India,for4 years. The results showed that occupants found their surroundings comfortable with air velocity in the 0-0.2 m/s when temperatures are up to 32°C and for air velocities greater than 1.5m/s when temperatures are up to 35°C.In 1979, the research of Givoni and Milne [17] allowed to associate the bioclimatic design strategies on a diagram. In 2015, Katafygiotou and Serghides [18] conducted a climate analysis of three zones in Cyprus: coastal, continental, and mountainous. The results of the bioclimatic maps showed a big difference in the range of comfort between these different climatic zones. In 2017, Khambadkone and Jain [19] established the bioclimatic maps of 21 sites and simulated the cooling and heating energy loads of these different regions. The results showed a large variation in design potential within the composite passive zone and thermal comfort. Several other researches were carried out, where bioclimatic analysis was applied in order to evaluate thermal comfort [20-21] or cooling and heating potential [22-24].Energy efficiency is recommended in buildings for better energy management.

Embodied and operational carbons have significant impacts on classification of buildings. In a study conducted in three different European cities: Brussels (Belgium), Coimbra (Portugal), and Luleå (Sweden), Babara et al. [25] found that carbon emissions are very high during the operational phase of the building. In 2019, Nematchoua et al.[26] found that carbon dioxide emissions were up to 37% lower in sustainable buildings with respect to old ones. Due to the considerable increase in energy production, the BRICS group, consisting of countries such as Brazil, Russia, India, China, and South Africa, become a major contributor to the growth of the world economy, with more and more questions about high carbon emissions. The results of Zhang's research [27] showed that all the countries constituting the BRICS group represent a net exporter of embedded flows. In a study conducted in Ankara (Turkey) in 2019 by Kayaçetin and Tanyer [28], the results showed an average carbon emission of 409.2 kgCO$_2$-eq/m^2.A more reliable policy of reducing carbon dioxide emissions in buildings should be developed.

In all the proposed investment projects, profitability is a motivating factor for the investor. Cost Analysis (LCC) is a method for evaluating the total cost of a project related to its expected value. LCC can be assessed at each stage of the project. It provides decision-makers with more reliable financial information on their investment. Several investigations were conducted in this area, as detailed in references [29-33].

This research contributes to research efforts that analyze and visualize climate data for the sustainable development of cities. Overall, different architectural designs based on bioclimatic characteristics have attracted many designers for decades. The use of climate indicators is one of the principles recommended for a less energy-consuming design. The determination of bioclimatic comfort zones is a very important act for the planning process of new cities in Africa and in the world.

Madagascar is considered one of the most fragile and vulnerable countries in the world in terms of climate change. Climatic considerations have to be considered in the assessment of the quality of outdoor built environments.

In hot areas, and more particularly in Sub-Saharan Africa, no research has yet been carried out, to evaluate , analyze and compare, simultaneously, the bioclimatic potential of several climatic zones, thermal comfort, energy consumption, emission carbon and the cost generated throughout the life cycle of residential and commercial buildings; while combining experimentation and simulation. It is clear that the coastal zones are the most vulnerable places to the impacts of climate change. The buildings located in these regions deserve a new standard more adapted to the current climate. The position of African countries with regard to the implementation of regulations energy is poorly documented. This makes it very difficult to put energy efficiency standards into practice.

This study analyses and compares thermal comfort, energy consumption, dioxide carbon emission, and Life Cycle Cost (LCC)in six categories of buildings (school, hospital, residence, office, shopping center, and restaurant), designed in thirteen city in Madagascar island.The main objective is to evaluate the future effects of climate change on thermal comfort, energy consumption in a standard residential building(traditional building) and in several standard non-residential buildings (shopping center, office, school, hospital, and restaurant),built with the same design techniques and located in 13 cities in different climate zones. In addition, this research evaluated their operational carbon and Life Cycle Cost.

2. Materials and methods

In this research, the method is based on a new approach showed by Shady et al.[34] allowing to assess the bioclimatic potential of different cities in Madagascar by means of the most recent data. The bioclimatic potential was based on psychometric charts, considering global climate of each city. This approach was inspired by the research carried out by Khambadkone and Jain [35].Figure 1 describes step by step the conceptual framework applied in this research.

3.1. Studied locations

The Indian Ocean consists of 6 islands (Seychelles, Mauritius, Reunion, Madagascar, Mayotte, and Comoros). The island of Madagascar is considered as the largest in terms of area and population. It is actually the fourth largest island in the world. Madagascar, with an estimated area of 592 000 km^2, stretches between 20°0 South latitude and 47°0 East longitude. This country is strongly dominated by the tropical climate. It is closed to the Mozambique Channel by an estimated distance of about 400 km. Unlike temperate countries (France, Belgium, Germany, Italy ...),dominated by four seasons (Winter, Autumn, Spring and Summer), the biggest Africa island (Madagascar), such as all other Sub Sahara African countries and the ones located in a hot zone, are essentially governed by two seasons: a rainy season, ranging from November to April, and a dry season, from May to October. They also have two short seasons spanning 1 month each. It is noticeable that in the rainy season, most of these areas are cyclone-covered and regularly directed towards the south-east of the country. According to recent research carried out in Madagascar by Nematchoua [7], it was found that the country can be divided in six climatic regions:

- the North region, dominated by transition tropical climate;
- the North west, dominated by hot tropical climate;

- the South west, dominated by Sub arid tropical climate;
- the South, dominated by arid tropical climate;
- the Center, dominated by altitude tropical climate;
- the North East and South east, dominated by humid tropical climate.

All the thirteen studied cities are distributed in all these six climatic regions. All them are located in the coastal zone, except Antananarivo city, which is located in the center of country. The choice of these cities was not random, in fact their geographical position facilitate their access to trade and tourism. In addition, these cities have significant unexploited potential for renewable energy, such as wind speeds ranging from 3m/s to 9m/s[36], and over 2800h of sunshine per year[37].These cities are considered as the regional capitals in this country. Other important cities were detailed by Nematchoua et al.[7].Some characteristics are showed in Table1, while the map showing the thirteen studied cities is presented in figure2.The climate date are analysis in the next subsection.

3.2. Climate data

In this research, current data of Antananarivo city, Mahajunga, Toamasina and Toalanaro were provided by Design Builder software. Other data were downloaded by the most recent version of Meteonom software. This tool has been used by many researchers [36-37]; it is possible to have weather data for more than 2100 weather sites around the world. It is also possible to download the new weather sites in this software, by knowing latitude and longitude of the place. Output data are constituted of hourly outdoor parameters for each city freely selected under the form of Epw file, implemented by Energy-Plus software. All data produced by Meteonorm tool are checked by U.S. Department of Energy (DOE), Energy Efficiency and Renewable Energy. In this study, data were grouped into three periods: current, 2030, and 2050.The next subsection describes the annual bioclimatic potential.

3.3. Evaluation of the annual bioclimatic potential

To evaluate the bioclimatic potential of the thirteen studied sites, the adaptive comfort model ASHRAE 55-2017wasused, associated with a psychometric map. All the recommendations given by some researches, previously carried out in this region, were taken into account, such as the ones of Rakoto-Joseph et al. [38] in 2009, which delimited several zonings in this region. However, one of the limitations of this study was that some essential parameters, such as solar radiation and humidity, which have a considerable impact on the comfort of the habitat, were not considered. In 2018Attia et al. [34] continued this research. Although this new research was innovative, it also had some limitations, as it was only driving for two cities in Madagascar (Antananarivo and Toamassina). It has to be noticed thateach point found on the psychometric graphs represents each hour of the day. All the plots observed on the curve used two design strategies (Natural Ventilation and Direct Evaporative Cooling).Some researchers showed that these two strategies are the most effective and the most adapted to the coastal regions of Madagascar [34,39,40]. On the psychometric diagram, it is seen that the zone of thermal comfort is crossed by the zone of direct cooling. According to Givoni's [41] recommendations, in hot and dry countries, the maximum temperature of the dry thermometer was around 45°C and the wet thermometer in summer is set around 25°C. Givoni [41] affirmed that the design of the building has a significant effect on the cooling zone and passive solar heating. The description of each studied building is given in next subsection.

3.4.Selected Buildings

In general, there are two broad groups of buildings (residential and non residential buildings). This study groups together these two main types of buildings. Indeed, the case study took place in a traditional building, a shopping center, a building consisting of several administrative offices, a school, a reference hospital in the region, and a popular restaurant. All these selected buildings are located in Antsiranana city, in the North of Madagascar island. It was chosen as a reference for several reasons: it is a coastal town, touristic, with habitats built in accordance with African and European standards. The Antsiranana city (or Diego-Suarez) is the largest city in the north of the country and is considered as the second most beautiful and largest bay in the world (after the one of Rio de Janeiro).This extraordinary harbor offers 156 km of coastline and many bays of incomparable beauty, with traditional fishing villages, deserted beaches, and wonderful underwater worlds. Antsiranana city, a member of the club of the most beautiful bays in the world, is surrounded by four bays, which open to the west on the Mozambique Channel, to the east on the Indian Ocean by a narrow channel. Figure3 shows the studied buildings while in Table 2 shows the thermos-physical properties of building elements according to Malagasy thermal regulations for commercial and residential buildings are reported; they are similar to those of the countries of the French colony Overseas.

Each of the selected buildings had its own characteristics, which have a significant impact on the energy consumption and the operational carbon emitted.

For example, the selected traditional building was mainly constructed of sheet metal (Aluminum), as observed for most local habitats in this region(Figure 3a). The sheet was the most requested for local construction because of its very low purchase cost on the market. This type of habitat can be found in all thirteen studied cities. Some characteristics of this building are detailed in Table3.

Secondly, the selected Shopping Center (called Score) was managed and financed by a French company. The same configuration was built in several cities across the country (Figure 3b). This building is more than 50 years old . It is the most visited super market in the city.

Thirdly, the restaurant selected in this study(Restaurant La Cantine) was one of more visited by native inhabitants and tourists(figure 3c),because in this restaurant variable menus are available in European and Malagasy styles. The menus are cheap and especially well cooked. The hostesses are clean, well dressed, and very respectful. Other characteristics of this restaurant are detailed in Tables 2 and 3.

All the offices present in an administrative building were studied in this research. Indeed, The administrative building (figure 3.d) consists of more than 85 offices, distributed between the first and the fourth floor. This building is considered the largest and most visited in the city. It is here that administrative decisions are taken for this region. Even though it is 60 years old, this building, built by the French colonists, always keeps its physical beauty.

In addition, the selected hospital (figure3e) is one of the largest in the area, and one of the most visited of this city. It is in its enclosure that most of the doctors of this city are lodged. The hospital building is more than 60 years old and its medical equipments are less adapted to international standards.

Finally, the selected school is one of the most famous primary schools in the city. It has a staff of more than 50 students and two teachers per classroom (Figure 3f). This establishment is surrounded by a large barrier of two meters high, ensuring the safety of students. Other characteristics about the school are detailed in Table3.The simulation tool is detailed in next subsection.

3.5. Software

In this research, Design Builder was used as the main simulation tool. Design-Builder is a dynamic simulation software, with a graphical interface and offering many features not simultaneously available in other existing software. Design-Builder allows calculation of thermal losses/gains of the envelope in winter/summer. Dynamic simulation (STD) restores comfort data, balance etc. The simulation tool integrates the Energy Plus software, which is a very solicited software to evaluate the thermal performance of the building [42]. The duration of the simulation depends on the capacity of the simulator. All the used formula for the calculations of energy consumptions, carbon emissions, cooling energy, and other parameters are available in the modules "Components Libraries; and Help ", integrated in Design-builder tool [42].

3.6.Simulations and model validation

The reference buildings were designed and modeled in Design-Builder Software. The 3D reference models of buildings, drawn and simulated in this tool, are shown in Figure 4. The different geometries of the buildings (figure 3), and its constituents, detailed in tables 2 and 3, served as input in this simulation. Air conditioning systems were implemented on the basis of a building audit, in accordance with occupancy, lighting, and air conditioning schedules [43].Some details regarding experimental campaign are given in next section.

3.7. Experimental data

An experimental study was conducted in 2017, in 25 Districts located in the North of Madagascar, by 25 students trained for three days and took place in two seasons (dry and rainy season). During this experimental campaign, 50 shopping centers, 5 hospitals, 67 traditional buildings, 25 schools, Restaurants, and Hotels were investigated. The new adaptive approach, with measurements and simultaneously distributing questionnaires [44],was used for this purpose. Overall, 1092 people were surveyed through 842 questionnaires and 250 interviews. The questionnaires were written in French and Malagasy language, which are the two official languages of the country. These questionnaires were distributed twice a day, while physical measurements were taken every 5 minutes. The different opinions of the voters were obtained after interpretation of these questionnaires. The height of the voters was between 1.41 m and 1.89 m in all the places studied and the measuring devices were installed at 1.2m height from the floor. All the results were analyzed with IBM SPSS Statistical software, which is recognized software in this area. All analyzes were performed with 95% of the confidence level (CL), considering equal to 5%a significance level, as mostly used in statistics. The results were analyzed, interpreted, and integrated in the literature. The different stages of the experimental study are detailed in [43,45]. Data from the experimental campaigns were used in this study. The calibration model is presented in the next section.

3.8. Calibration

In any simulation and data projection study, calibration is one of the most important steps for data validation. In this study, calibration is based on the comparison of simulation results with those measured in the buildings (see paragraph 3.8). Calibration is carried out on the basis of the recurrent energy consumption patterns and the conditions arising from the physical behavior of the buildings. There are several guidelines in the literature for calibrating a new model. In this study, two recommendations mentioned in ASHRAE guideline 14 [46] were applied: Coefficient of variation or square root error (RMSE) and mean bias error (MBE). The different RMSE and MBE values were evaluated taking into account the two equations reported below [46].

$$RMSE(\%) = \frac{1}{m}\sqrt{\frac{\sum_{i=1}^{n}(mi-si)^2}{n}} \quad (1) \text{ and} MBE(\%) = \frac{\sum_{i=1}^{n}(mi-si)}{\sum_{i=1}^{n} mi} \quad (2)$$

Where s_i and m_i represent simulated and measured data over a given interval I , respectively the total number of data implemented. In Guideline 14 by ASHRAE [46], it is recommended that a simulation model can be considered calibrated if the following conditions are followed:

- Hourly MBE between ± 10% and hourly RMSE smaller than 30%.

- Monthly MBE between ± 5% and monthly RMSE less than 15%.

In this study, the simulation model was calibrated using as references the average indoor air temperatures and the consumed electricity. Other physical parameters, such as relative humidity and air speed ,can also be used for validating the model. Several calibrations were performed on the reference model, in order to detect all the errors. The different schedules of air conditioning, lighting, occupation were inserted as input data; air tightness data and the set temperature values for the different buildings were adapted during calibration. After each simulation, the different values of RMSE and MBE were evaluated and compared to the standard referenced in Guide 14, ASHRAE. Tables 3 and 4 show in detail the final values of this model. The more detailed results of validation of the adopted simulation model are presented in section 4.2.

3.9. Scenario

In order to evaluate the impact of climate change on building interior comfort and energy for cooling (heating energy being zero in hot zone), the IPCC Scenario A2wasconsidered. The choice of this scenario was not randomly undertaken, indeed, several current research carried out in tropical climate were made on the basis of this scenario[47-48].Scenario A2 describes a very heterogeneous world (self-sufficiency, preservation of local identities). The population continues to grow as fertility rates move more slowly, while economic development is mainly regional.

3.10. Sensitivity study

Madagascar is spread over an area of 580.000km^2, with an estimated population of 25 millions. The construction standard adapted in Madagascar is similar to that of the French overseas countries. All six categories of buildings evaluated in this study are easily adaptable in other regions of the country, as explained in [34,45]. The occupancy rate in Madagascar is similar to the one of the countries of Central Africa: 0.2-0.5 occupants/m^2 [49]. The building construction cost in Madagascar is slightly lower than the one of other African countries, but very similar in all the regions of the country.

3.11.Calculation of data

After a comparison between the measured and simulated values, the model was validated and the different values of thermal comfort, energy consumption, embodied carbon, and costs were evaluated in the thirteen selected cities.

4. Results

4.1. Bioclimatic potential and thermal comfort parameters

The different adaptive comfort temperature ranges for the thirteen selected cities in the six climate regions were calculated using the ASHRAE55-2004 adaptive model [50]. Monthly average weather data for the last ten years were used for this purpose. By analyzing Table 5, it can be noticed that each of the selected cities has its own monthly comfort beaches.

Global adaptive comfort temperature with 90% of acceptability range is from 19.5°C to 29.9°C in the six buildings categories in Madagascar island. Figure 5 shows the bioclimatic diagrams of the selected cities. These diagrams are derived from the hourly meteorological data of each city.

4.1.1. Annual thermal comfort frequency

Figure 6shows the different frequencies of annual thermal comfort in each studied city. This potentially represents the number of annual hours of comfort (h) in each building, without implementation of a bioclimatic strategy. In Figure 6a, it is highlighted that currently, in the different cities studied, hospitals have the lowest number of comfort hours during the year (5.1%), whereas the offices have the greatest number of hours of comfort (88.5%). Moreover, it is noticed that the weather of Morondava city has the greatest number of hours within the comfort limits (61.6%), when compared to other cities of Madagascar. Meanwhile, in the northern province of Madagascar, Antsiranana's annual comfort frequency is 45.5%: the weather of this city shows the greatest number of discomfort among all the different studied cities. In Figures 3b and 3C, it is shown that in the future (in 2030 and 2050), the potential of the number of comfort hours that will be recorded in hospitals will further decrease (2.5%)and will be the lowest of the six studied buildings .In the mean while the comfort hour numbers in offices will remain the highest (84.9%). During these two periods, the weather in the cities of Antsiranana and Tulear will show the greatest number of hours within the discomfort limits (39.4%).

4.1.2. Predicted Mean Votes and Thermal Sensation votes

In this section, five parameters related to the thermal comfort of the inhabitants in the different selected buildings were evaluated:

- Predicted Mean Votes (PMV), initiated by Fanger; its values range from -3 to +3 (-3 (very cold), -2 (cold), -1 (slightly cold), 0 (neutral), +1 (slightly warm), +2 (warm), and +3 (very hot) [51];
- mean Thermal Sensation Votes (TSV) initiated by Kasas [43];
- Operative temperature,defined as the uniform temperature inside a building(T_{op}) taking into account both convective and radiation heat transfer [52-54];
- mean Effective Temperature index (ET);
- Standard Effective Temperature index (SET) of Pierce [55].

Figure 7 shows the variation of Predicted Mean Votes (PMV) and Thermal Sensation Votes (TSV) with uniform temperatures in residences, offices, shopping centers, hospitals, schools and restaurants located in the thirteen studied cities. Good correlations were found between the Predicted Mean Vote (PMV) and the Operative Temperature (Top). The equations detailed in Table 6were established. In schools and offices, when the uniform temperatures were in the 22.7-27.2°C range, PMVranged between -0.82 and 1.38, while TSV were between -0.31 and 1.38. At this time, the neutrality temperature was 24.1 °C in schools and 24.6 ° C in offices (the neutral temperature is evaluated for PMV = 0), while the temperature of thermo-neutrality was 22.9°C in schools and 23.9 °C in offices (the temperature of thermo-neutrality is evaluated for TSV = 0). In addition, in the residences and hospitals, when the uniform temperature was in the 23.6-30.5°C, the PMV ranged between -0.27 and 2.12, and TSV between 0.1 and 1.82. The neutral temperature was24.4°C in residences and 24.2°C in hospitals, while the temperature of thermo-neutrality was 22.7°C in residences and 24.6°C in the hospitals. Finally, in restaurants and shopping centers, the operating temperature was in the 17.9-25.4°C range, with PMV values ranging from -1.66 to0.49and TSV from-0.4 to0.55. Neutrality and thermo-neutrality temperatures were24.6°C and 23.1°C, respectively .Considering the same conditions of occupation of the different buildings, it was possible to evaluate PMV, ET, and SET for the years 2030 and 2050 in the different cities; results as shown in Table 7.

4.2. Validation and calibration of new simulation model

The different values of MBE and RMSE allowed to compare simulated and measured data. Table 8 shows the different results from the MBE and RMSE calibration, which can be used to calibrate this new simulation model. The comparison between different measured and simulated indoor mean temperatures for the periods investigated is shown in Figure 8. The MBE value is 0.6%, while the RMSE value is 0.2%. The recommended values in ASHRAE Guideline 14 are ± 10% (MBE) and ± 30% (RMSE). Thus, it can be deduced that the different hourly values of MBE and RMSE are within the range recommended by ASHRAE. The new simulation model is calibrated with the hourly data. In addition, in Figure 9, a comparison between the different energy values simulated and measured during the survey periods in the buildings is shown. The value of the MBE found is -4.6%, while that of the RMSE is 0.7%. In accordance with ASHRAE, the acceptable limits are± 5% (MBE) and ± 15% (RMSE). From these results it can be deduced that both MBE and RMSE values for the different monthly data are within the range recommended by ASHRAE. The new simulation model is calibrated with the different monthly data, in order to validate it.

4.3. Energy consumption

The selected school, as well as the hospital and the residence, were naturally ventilated. To evaluate the cooling energy consumption in these different buildings, a simple ventilation system of the same type as the one found in other schools in the city was considered.

Summarized in this study, thermal comfort of each type of building was evaluated in natural ventilation. While, energy consumption was assessed with air conditioned system.

4.3.1. Cooling energy

Figure 10 shows the different cooling energies in the selected buildings during three scenarios (present, 2030, and 2050).School has the highest cooling energy consumption (103.7 kWh/m^2 currently, 110.3 kWh/m2 in 2030, and 113.7kWh/m^2 in 2050), while residence showed the lowest one(25.2kWh/m^2 currently,28.8kWh/m^2 in 2030, and 34.1kWh/m^2 in 2050). The Mahajunga city, located in hot tropical climate, has the highest cooling energy among all the selected cities (from 130.3kWh/m^2 to 175.7kWh/m^2 currently, between 104.2 kWh/m^2 and 176.0kWh/m^2 in 2030,from 113.7kWh/m^2 to 183.5kWh/m^2 in 2050).However, the Antananarivo city located in altitude tropical climate, showed the lowest cooling energy (from 4.5kWh/m^2 to 50.0kWh/m^2 currently; from 7.9kWh/m2 to 55.0kWh/m^2 in 2030; and, from 11.4kWh/m^2 to 59.0kWh/m^2 in 2050).

4.3.2 Total energy consumption of the site

Table 9 shows the total energy consumption in the different buildings located in each city in the three scenarios (current, 2030 and 2050).It can be noticed that residence has the lowest total energy consumption, between 55.8kWh/m^2 and 291.3kWh/m^2 currently and between 60.3kWh/m^{2}and 345.7kWh/m^{2}in 2050. Hospital shows the highest total energy consumption, between 539.9kWh/m^{2}and714.4kWh/m^{2}in 2030 and 543.2 kWh/m^{2}and 739.1kWh/m^2 in 2050. Total energy consumption will increase up to 18.7% in the traditional residence and 3.5% in the hospital. In addition, it was found that Antananarivo city shows the lowest total energy consumption in the six building categories, from 55.8kWh/m^{2}to 530.8kWh/m^{2}in 2017, between 58.6kWh/m^{2}to 537.1kWh/m^{2}in 2030, and from 60.2kWh/m^{2}to 543.2kWh/m^{2}in 2050. The energy demand will increase up to 2.4% in Antananarivo city and up to 113.8% in Mahajunga city, between 2017 and 2050 .

4.4. Analysis of Operational and Embodied Carbon

In this section, Operational and Embodied Carbon coming from the different building categories (Residence, School, Hospital, Restaurant, Shopping Center) on three periods (current, 2030 and 2050)are analyzed.

4.4.1. Operational carbon

Figure 11 shows detailed monthly Operational Carbon in the different selected cities. The hospital shows the highest concentration of carbon, between30894.9kgCO$_2$ and 61145.9kgCO$_2$, with an average around 43600 kgCO$_2$; the traditional residence presents the lowest carbon quantity, estimated from 317.1 $kgCO_2$ to 1616.0 $kgCO_2$, with an average of 507.7 $kgCO_2$. Globally, in the thirteen selected cities, carbon concentration varies between 317.1 $kgCO_2$ and 61145.9 $kgCO_2$. Indeed, Mahajunga city shows the highest carbon quantity, in the 711.5-61145.9 $kgCO_2$ range, while Antananarivo city shows the lowest carbon concentration (317.1- 50262.1 $kgCO_2$. Maximum and minimum operational carbon in 2030 and 2050 in the six selected buildings categories are showed in table 10. Operational carbon is expected to be between 32.9 $kgCO_2/m^2$ and 388.8 $kgCO_2/m^2$by 2030 and from 33.9 $kgCO_2/m^2$ to 396.0 $kgCO_2/m^2$ by 2050 in the six cities.

4.4.2 Embodied Carbon

Embodied Carbon is the carbon coming from any material. It is important to evaluate it, in order to know the carbon concentration of each building material.Table11 shows the different values of embodied carbon in the selected buildings. It can be noticed that embodied carbon varies from 14.8 $kgCO_2/m^2$to 251.1 $kgCO_2/m^2$, with an average of 88.9 $kgCO_2/m^2$. The hospital shows the lowest embodied carbon(14.8 $kgCO_2/m^2$), while, the shopping center shows the highest one (251.1$kgCO_2/m^2$).

The summary results in this sub section showed that in Madagascar, amongst the six selected building categories (school, office, restaurant, residence, hospital and shopping center), the hospital produce the most important quantity of dioxide carbon during its operational period and the lowest embodied carbon during its life cycle .

4.5. Life Cycle Cost

Life Cycle Cost is the cumulative cost of a product throughout its life cycle, from conception to decommission. The analysis and evaluation of this cost is a managerial decision-making tool to: (a) guide design choices; (b) enlighten a buyer or the public for the choice of a product. Table 12 includes the regional cost parameters used for this study as detailed in[74]. To assess the total acquisition cost, the respective acquisition, ownership, and decommissioning costs should be analyzed, as shown in the following equation[56]:

$$LCC = C_a + C_i + C_e + C_O + C_p + C_m + C_{ps} + C_{en} + C_d \qquad (14)$$

with : C_a =acquisition cost for the end customer (initial investment);C_i =installation and start-up costs; C_e =energy cost; C_O = operating expenses (labor); C_p =protection costs (insurance, video surveillance, fire); C_m =maintenance and repair costs; C_{ps} = production stop costs;C_{en} =environmental costs;C_d =decommissioning and removal costs. Table 13 showsLife cycle Cost (LCC) of each selected building, taking into account a study period of 100 years. This table was built considering the reference model proposed by Langdon in 2007[57].The different values were evaluated according to the local context, more common to those of Sub-Saharan African countries. It can be noticed that the standards of international construction costs are not respected in the big island. Global results are showed in figure12.In the five selected buildings, it can be seen that Operational cost is the highest (82%) among the different inventory costs, while renewal cost (0.2%) is the lowest. It is very important to notice that the hospital shows the lowest maintenance rate (0.04%).

5.Discussion

5.1.In-depth discussion of main results

This research, in its entirety, combines four main areas of study (thermal comfort analysis, energy consumption analysis, embodied and operational carbon analysis, and Life Cycle Cost), allowing to evaluate in detail some characteristics of residential and non-residential buildings located in tropical zone. It was found that in Madagascar island, adaptive comfort temperature grouping 90% of acceptability concentration was estimated to be in the19-30°C range. This range is beyond the recommendations of the international standard ASHRAE 2004 [58], which estimates values in the 23-26°C range. Indeed, most part of the studies adapted by the ASHRAE standard are in a temperate zone. Among the six studied buildings, the hospital showed the lowest comfort hour numbers, while the offices showed the highest. This situation is commonly encountered in Madagascar and several other countries in Sub-Saharan Africa. In 2018, in a research carried out in the hospitals selected in six India Ocean islands, Nematchoua et al.[48] found that the discomfort hours were estimated to be more than 90% of total hours per year, with a significant impact on the healing of patients. The number of comfort hours seems slightly moderated and more reasonable in the residences. These results further testify the conclusions of the study led by Invidiata and Ghisi [59] in a family house in hot zone (Brazil), who found the number of hours of comfort at more than 30% during the summer. As statedAli-Toudert et al. [60],comfort hours also depend on micro-climate conditions of each city. Indeed, in this research, it was found that Antsiranana and Tulear, which are two cities located in transition tropical and arid tropical climates respectively, showed the highest discomfort hour numbers. It can be due to their geographical position and altitude. In the various international standards proposed today, several neutrality and comfort temperature ranges are recommended. For example, in the case of the CIBSE[62]the temperature range recommended is between 22°C and 24°C; while in ISO 7730 standard [61] the neutral temperature range is 23-26°C. In this study, it was found by simulation that the thermo-neutral temperature range is in the 22-29°C range. Taking into account these results, it can be concluded that the neutrality and comfort temperature range varies according to the studied climate, associated with the activity of the occupants.

In this research, it was found that school has the highest cooling energy consumption, while the residence building showed the lowest one. This result is surprising and is practically the opposite of what was expected. Indeed, in table 3, in the case of the residential building the different characteristics of the wall are reported: thermal conductivity (230W/mK), thickness(3cm),and U-Value (5.882 W / m^2.k), while in school it can be noticed that thermal conductivity (0.5-1.63W/mK), thickness (0.17m), and U-Value (3.11W /m^2.k) are better. The analysis of these different characteristics showed that the thermal transfer is higher in the residential building than in the school. Therefore explanation has to be found elsewhere. It can be observed that the effect of orientation of the building and shading is not respected in the case of school, but it was respected in the case of the traditional building. So this is the main explanation. These results justify the conclusions of some authors, who explained the effect of orientation and shading in hot zone [63-64]. Indeed, it was demonstrated that, except for materials which should have a low thermal conductivity, orientation and shading effect have significant impact on the indoor air quality and energy consumption. The cooling load in far North and far South of country was estimated to be around 50% higher than cooling load in the central Madagascar. This finding agrees with some results obtained by Ghedamsi et al. [68], and Belkacem et al.[69]. In addition, it was found that embodied carbon varied in the14.8-251.1 $kgCO_2/m^2$.This concentration of carbon is slightly high when compared to that found by Rossi et al. [65] in the case of a residential building located in three countries in temperate zones (Belgium, Portugal and Sweden). Indeed, the embodied carbon emission depends on the chosen type of construction materials. However, in the case of this study, the building materials used are known for their high carbon production. In addition, the concentration of carbon in hospitals is very high. The hospital produce the most important quantity of carbon dioxide during its operational period because a patient produces more dioxide carbon than a healthy human. Nevertheless, the majority of these results ranged in the zone required by Lotteau et al.[66], which is between 11 $kgCO_2/m^2$ and 140 $kgCO_2/m^2$.Finally it is noticed that any study of the LCC, characterizes a precise project. LCC varies from project to project, taking into account country context and realities [66] . In the case of Madagascar, it was found that LCC of operational building was estimated at 82% of total LCC. Moran et al. [72] carried out a life cycle cost study and an environmental analysis in a few buildings located in Ireland, using global warming potential and energy as indicators. The results showed that Life Cycle Energy is 13.867 MJ / m^2, emission is 789 $kgCO_2$ / m^2, while Life Cycle Cost is 1228 € / m^2. It is seen that the concentration of the three main parameters evaluated by Moran et al. in the specific case of Ireland are higher when compared to those evaluated in Madagascar. The occupant behavior especially affects the energy consumption and the CO_2 emissions.

The maintenance cost is very low in Madagascar island, such as in many African countries. It may be the reason for the reduced life cycle of buildings in this area. In addition, these very poorly maintained buildings emit significant amounts of carbon dioxide.

The results found in this study greatly depend on the type of climate and the choice of local building material. Indeed, under basic of TRNSYS 17 software, Rodríguez et al.[70] evaluated the performance of several residences in five different places in Spain, with various climatic characteristics. The results showed that the energy consumption is in the92.95-125.73kWh/m^2 range, emission in the23.91 -29.73$kgCO_2$/m^2 range, and Life Cycle Cost in the162.79-199.21 €/m^2 range. On the basis of these results, the total energy consumption per year in residences in Spain is higher when compared to those in Madagascar, otherwise carbon emissions are higher in Madagascar. The shape and area of the building can have a significant impact on energy demand. Indeed, studies carried out by Chel and Tiwari [71], in a residential building with six interconnected rooms in India, showed that the annual energy consumed was around 4946 kWh in the most traditional buildings in India. Based on this result, it can be deduced that the energy consumption in traditional residences in Madagascar is lower than that found in India.

Several other types of research, such as this one, should be carried out, to help the countries located in hot zones to better implement the concept of sustainable development. The continent is struggling to take off towards globalization, because of the lack of initiative of this kind of research of new researchers coming from this region.

Bioclimatic measures to improve occupant comfort and reduce energy/CO_2 emissions in residential and commercial buildings are suggested. It is important to make our buildings energy efficient as soon as possible, using renewable energy to have low greenhouse gases associated with the production and use of envelope materials. Many metal products have well documented performance in all of these aspects and can help to reduce the carbon footprint when used in a building envelope. We can also modify energy efficiency a little more by choosing roofing materials with the appropriate solar reflectance values suited to the location and occupation of the building. The choice of color strongly affects the solar reflectivity and the choice of the right color for the climate can reduce energy consumption by up to 3%.We believe that one of the major problems is that architects often find it difficult to access all the information and data they need to make informed decisions to reduce the carbon footprint. It is therefore recommended to seek the help of building science consultants, energy modelers, life cycle analysis practitioners and in particular manufacturers of construction products, at the start of the design process.

5.2 Limitations and Strengths of the study

5.2.1. Originality and novelty

The originality and novelty of this study resides mainly in the implementation of a new approach, combining a simple bioclimatic analysis, under the base of several diagrams, merged with an in-depth study of the performance of six categories of buildings. A systematic analysis of the cooling loads and more briefly the energy consumption over three periods (present, 2030 and 2050) was carried out. The concept of sustainability with the analysis of the carbon dioxide produced by some building materials and also during the operational phase of the building was implemented. Finally, an analysis of the cost of the different studied buildings was carried out. Nowadays, most studies focus solely on data simulation, and other ones only on the investigation. This study combines simulation and investigation. The region studied is still virgin in this field and needs such type of research, in order to apply its sustainable development policy. This research employed the most recent hourly climate data from the past 30 years, from representative cities in Madagascar's six climatic regions. The combination of several recent approaches already used by Nematchoua et al. (2018) [36,43,73], Attia et al. (2019) [34],Barbara et al. (2012) [64], and Langdon (2007) [57] will allow to have a new, more consistent, and more efficient approach. This research is the first to combine a more precise estimate of the bioclimatic potential, the life cycle cost of buildings, and the carbon inventory in sub-Saharan Africa. This study demonstrates the possibility to better understand the evolution of the cooling degree of the six climatic regions of Madagascar, based on a new validated simulation model. Reliable results, related to the thermal performance of the various studied buildings, are found.

5.2.2.Limitations

This study, such as any other scientific research, shows some weaknesses. Each building was studied in its natural state of operation. It would have been better to use new techniques and passive strategies to reduce energy consumption, reduce carbon production and improve indoor air quality in the buildings. The selected buildings do not represent totally different typologies of housing encountered in tropical zone. Moreover, they are not always the most adapted to the microclimate of every city in the country. The indoor temperature data selected for calibration of the simulation model does not extend over a full year, except for electricity. The probability of validation of the results should reach more than 95%, if the internal measurements were spread over a long period (at least two to three years), with the implementation of an automated calibration. Nevertheless, this research was carried out with the most available reliable data.

5.3.Practical implications

Several results found in this research will allow to identify the most reliable bioclimatic design models in each of these climatic regions. These results can be useful for designers, engineers, and other building specialists to provide more sustainable, less consumable, and less polluting buildings in this region. Indoor comfort has a significant effect on occupant health and productivity. The different results shown in the tables and figures can be exploited for the creation of a standard or database more reliable and specific to this region, and other region. This research can be an introduction to the creation of a new classification map of buildings in this region. This study confirms that it is necessary to create a data-base of energy efficiency of buildings in Madagascar. Direct collaboration with the policy in Madagascar for the implementation of the results of our study for a more sustainable construction and more adapted to the climate is essential. Future research should focus on the implementation of passive strategies in new constructions in the big island.

6. Conclusions

This research reports the results of the analysis of the bioclimatic potential of the different climate zones in Madagascar.13 cities were investigated, based on the psychometric diagrams and also simulations of performances of six categories of buildings. The following conclusions can be drawn from this research:

(1)Climate change has a more significant impact on the building thermal performance in the coastal than continental regions, in the tropical climates;

(2) the thermo- neutral temperature is expected to reach up to 30°C, in the residential buildings located in coastal tropical regions in 2050;

(3)the results sometimes show some contradictions in the estimates of the bioclimatic potential for the exceptional case of the coastal towns, dominated by a hot and dry climate;

(4) unlike western cities, equally characterized by cooling and heating demand, in general the coastal towns of Madagascar are dominated by cooling. Indeed, in hot tropical regions in Madagascar, the cooling energy demand in the buildings is expected to increase up to 30% between 2030 and 2050;

(5) globally, the average potential of comfort hours gathering all the climatic zones of Madagascar is 15.3% (residences), 70.9% (shopping center), 88.8% (office), 67.6% (school), 5.1% (hospital), and 67.7% (restaurant);

(6) Mahajunga and Tulear cities, located in the hot and arid tropical climate respectively, showed the highest cooling energy, estimated in 175.7kWh/m^2;

(7)in Madagascar, such as in several countries in Sub Saharan Africa, the hospitals can be considered as one of place the most polluted in the building sectors. Indeed, their emission concentration can be up to 98.7% higher than the one of residences.

It is recommended to improve hygienic living conditions in hospitals in Madagascar, in order to reduce the high carbon emissions. The operational cost was estimated to be around six times higher than investment cost and 40times higher than maintenance cost, on over 100 years of life cycle. It is recommended to improve maintenance cost in Madagascar, in order to increase life cycle of buildings in this country and also in Sub Saharan Africa. Future studies will focus on applying passive strategies to reduce cooling energy consumption and carbon emission rates in coastal cities, while improving indoor comfort.

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