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URFD: PHYSICS AND APPLICATIONS

ENERGY, ELECTRICAL SYSTEMS AND ELECTRONICS

RESIDENTIAL BUILDING DESIGN UNDER CONSTRAINT EFFECTS OF CLIMATE CHANGE: CASE OF NGAOUNDERE IN CAMEROON

A thesis submitted for the degree of Doctor of Philosophy in Physics.

Option: Energy and Environment

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ATTESTATION DE CORRECTION DE LA THESE DE DOCTORAT/Ph.D

Nous, Professeur, **MELI'I Jorelle Larissa,** et Professeur **BEN-BOLIE Germain Hubert** respectivement Examinateur et Président du Jury de la thèse de Doctorat/Ph.D de Monsieur **WIRBA Ignatius TARDZENYUY** Matricule **13P2982**, préparée sous la direction de **MOUANGUE Ruben Martin,** Professeur Université de Douala **et VONDOU Derbetini Appolinaire**, Professeur Université de Yaoundé1, intitulée : « **Residential building design under constraint effects of climate change : Case of Ngaoundere** », soutenue le **Lundi 27 janvier 2025**, en vue de l'obtention du grade de Docteur/PhD en Physique, Spécialité **Energie Et Systèmes Electriques Et Electroniques,** option **Energie et Environnement,** attestons que toutes les corrections demandées par le Jury de soutenance ont été effectuées.

En foi de quoi, la présente attestation lui est délivrée pour servir et valoir ce que de droit.

Fait à Yaoundé le 10 JUIL 2025

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Ndjaka Jean-Marie Bienvenu

Professeur

Dedication

This work is dedicated to my FAMILY

Acknowledgement

Let me use this opportunity to render sincere thanks to those whose contributions had let to the realization of this research project.

My sincere thanks first of all go to the Almighty God, for giving me the strength and wisdom needed for the accomplishment of this work

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Nomenclature

AR4: Fourth Assessment Report

ASHRAE: American Society of Heating, Refrigerating and Air-Conditioning Engineers

BIM: Building Information Modelling

BLAST: Building Loads Analysis and System Thermodynamics

CEMAC: Economic and Monetary Community of Central Africa

CEN: Comité Européen de Normalisation

CFD: Computational fluid dynamics

CI: Carbon intensity

CIS: Commonwealth of Independent States

CV (RMSE): Coefficient of Variation of the Root Mean Square Error

DOE: Department of Energy

EC: Embodied Carbon

ECO_2: Embodied Carbon dioxide

EE: Embodied Energy

EEPFD: Evolutionary Energy Performance Feedback for Design

EI: Energy intensity

EMPD: Effective moisture penetration depth

ESP-r: Energy Simulation Software tool

GBS: Green Building Studio

GHG: Greenhouse gas

GWP: Global warming potential

HTB2: Heat Transfer in Building: version 2

HVAC: Heating, ventilation and air conditioning systems

Nomenclature

IDA ICE: Indoor Climate Energy

IES VE: Integrated Environmental Solutions - Virtual Environment

IPCC: Intergovernmental Panel on Climate Change

LCC: Lifecycle costs

LCTV: Laboratory of combustion and green technology

MAPE: Mean absolute percentage error

MBE: Mean Bias Error

MV: Mean vote

MVHR: Mechanical Ventilation Heat Recovery System

NAFTA: North American Free Trade Agreement

NDC: Nationally Determined Contribution

NMF: Neutral Model Format

NOAA: National Oceanic and Atmospheric Administration

OECD: Organisation for Economic Co-operation and Development

PMV: Predicted Mean Vote

PPD: Predicted Percentage of Dissatisfied

Ppm: Parts per million

SDK: Software development kit

TAR: Third Assessment Report

TRNSYS: Transient system simulation

TSC: Transpired Heat Recovery

Abstract

The emission of CO_2, due to space conditioning, and the thermal comfort of occupants were the investigated building performance metrics in the present study. Results from the simulation of the building showed that CO_2 emitted from the operation of heating systems would decrease with an increase in average temperature. These results, however, showed a contrary with the installation of the cooling system. Overheating, caused by an increase in the average global temperature, was then seen as a big problem in the building sector as the building would have to fight to keep its occupants in thermal comfort and to reduce the emission of CO_2. Ensemble of strategies like: choice of building orientation; building material; use of insulation; block thickness; and window opening area were seen to be instrumental in reducing CO_2 originating from the operational phase of the building. A house built with mud bricks, insulated outside with wood cellulose and oriented in the southeast direction reduced emission by 68.6% during cooling moments and by 13.6% during heating moments. The results analysis presented in this work can serve as basis for best construction practices which can help in delaying the rate at which global temperature is expected to rise and hence reduce the effect of climate change on buildings.

Keywords

Climate change, residential buildings, building design, overheating, building energy performance, thermal comfort, CO_2 emission

Résumé

La quantité de CO_2 émis à cause de l'espace conditionné et le confort des usagers sont les paramètres d'investigation sur la performance du bâtiment dans ce travail. Les résultats préliminaires de simulation sur le besoin en énergie montrent que la quantité de CO_2 émis à l'utilisation des systèmes de chauffage diminue lorsque la température moyenne augmente. Dans le même sens, la quantité de CO_2 émis à l'utilisation des systèmes de climatisation augment avec l'augment de la température moyenne. Le réchauffement général causé par l'augmentation de la température moyenne globale met ainsi une pression sur le secteur de bâtiment à assurer le bienêtre de ses occupants d'une part et d'autre part à contrôler également la quantité des CO_2 émis dans la nature. Les effets de changement climatique sur les bâtiments peuvent être ralentis par une réduction de l'émission de CO_2 dans la nature. Un ensemble des stratégies comme le choix de la direction d'orientation du bâtiment, le choix des matériaux de constructions, l'utilisation de l'isolant, la variation de l'épaisseur, et la proportion des surfaces des fenêtres ouvertes ont été important pour réduire la quantité de CO_2 pendant la phase opérationnelle du bâtiment. La maison construit avec la brique de terre, avec une cellulose de bois à l'extérieur, une orientation sud-est permet de réduire le CO_2 émis de 68.6% pendant la période de base température et 13.6% pendant la période de haute température. L'analyse des résultats présentés dans ce travail forme une base des meilleurs pratiques de construction permettant de ralentir le taux d'augmentation de la température globale ainsi nous assistons à une réduction des effets de changement climatique sur le bâtiment.

Mots clés: changement climatique, bâtiment résidentiel, conception du bâtiment, confort thermique, dioxide de carbone.

General Introduction

Nowadays, climate change is a serious global systemic risk that threatens the economy and human life. Generally driven by economic growth and increasing use of fossil fuels, global GHG (greenhouse gas) emissions have doubled since the early 1970s. The environmental impact of this sector can be categorized into ecosystem impacts, natural resource impacts, and public impacts (Zolfagharian et al., 2012). Climate scientists have noted that carbon dioxide (CO_2) is the most emitted gas and accounts for about 75% of global GHG emissions (IPCC, 2014). The Intergovernmental Panel on Climate Change (IPCC) reports that the global average temperature is expected to increase from 4.1–4.8°C and the change in carbon dioxide equivalent (CO_2-eq) emissions compared to 2010 will reach 74-178% in 2100 if emissions continue to increase at the same rate (Parry et al., 2007). The concentration of this gas in the atmosphere is currently estimated at more than 400 ppm and is expected to reach 530 and 650 ppm in 2050 and 2100, respectively. This will lead to an increase in global average temperatures of 2–5.6 °C by 2100 (IEA, 2017) making life impossible on our planet.

A lot of damages have been observed in many parts of the globe as a result of GHG emission (Hanewinkel et al., 2013; Iglesias et al., 2012). The reduction of GHG emissions is then frequently considered to be more important than the absolute energy consumption. In order to combat global warming, humanity decided to keep the temperature below 2 degrees (UNFCCC, 2015), and the achievement of this goal requires a significant reduction in the CO_2 content in the atmosphere. CO_2 emissions need to be reduced by 77% in the building sector by the year 2050 (IEA, 2013). Currently, GHG emissions, especially CO_2, tend to increase in developing countries, while they tend to decrease in developed countries (IPCC, 2014; UNFCCC, 2015). This shows the urgency of the need to optimize policies to reduce CO_2 emissions in these countries, given the deadlines of the Paris agreement. The building, industrial and the transportation sectors are globally depicted as the major emission sectors. Global CO_2 emission in the building sector is seen to be the highest. The exploitation of non-renewable energy resources, poor building design, and lack of sustainability consideration in urbanization has been holding back CO_2 emission mitigation measures in the building sector. The implementation of building design strategies appropriate for each climate zone are promising ways through which emission from the building sector can be reduced.

The present work studied building design strategies that should be implemented in subtropical region of Cameroon in order to better combat buildings negative impact to the climate. The study used simulation; using energy plus coupled with design builder software. The simulation software was first of all calibrated with the mean result accepting it as good for the work engaged. The work then proceeded with the evaluation of comfort situation of the locality investigated and discovered that most of the months were generally in comfort except the month of November, December and January which were observed to be too cool. The building CO_2 emission capacity as a function of operative temperature, when the building was either under the influence of the heating or cooling system, was then evaluated and predictive models brought out. CO_2, operative temperature and discomfort hours then served as evaluation metrics for the rest of the work, where they are used to make right choices for strategies developed. Choice of orientation, building material, window opening area are seen by the study as promising ways for the build environment to reduce it green gas emission to the atmosphere.

Nowadays in new cities, lifestyle has changed dramatically, especially in sub-Saharan Africa. In these regions, very few designers take into account the climate of the surroundings and the variety of building construction methodologies usually employed in Europe and America, are becoming increasingly more prevalent in Africa. As a result, thermal discomfort dominates these types of buildings, and necessitates the occupants using artificial heating, ventilation and air conditioning systems (HVAC). This increases the energy consumption of buildings which accounts for the destruction of local ecosystems and the overall lowering of comfort due to heat island phenomenon in densely packed cities. This results in higher temperatures locally that can furthermore increase the energy consumption for cooling, lower the overall thermal comfort levels, and even increase the health risks of the vulnerable populations (Santamouris, 2015). Existing studies analyzing energy and GHG emissions across the life cycle of buildings provide insights for residential and office buildings but are limited in their geographic scope. Building energy consumption and potential of emission reduction varied remarkably by climatic region. Therefore, the formulation of CO_2 emission reduction strategies should be specific to each type of building and climatic region (McNeil et al., 2016).

The existing body of literature mostly analyzed buildings located in cold and temperate climates. Hence, there is a research gap regarding GHG emissions across the life cycle of buildings located in warm and humid, subtropical and tropical climate regions. This gap in the literature is appalling, considering the geographic extent of these climate regions and the number of people inhabiting them. By 2060, more than half of new residential buildings are expected to be constructed, with remarkably rapid growth, in Africa, Asia and Latin America, regions that have humid subtropical and tropical climates (Abergel et al., 2017). The importance of studying buildings in these regions is further emphasized, as warm climates are nearly twice as sensitive to local temperature changes due to global heating and, hence, more affected by related harmful effects than cold or temperate climate regions. Consequently, there is an urgent need to address the impact of climate and buildings on each other in these regions, especially climate and the residential construction sector, by implementing building design strategies that enable significant reduction of GHG emissions.

The goal of this study is therefore to study and evaluate the degree and the extent to which the building sector need to be modified in the locality of study in order to respond positively to the call for CO_2 reduction in the atmosphere. To this effect the present work has been structured into three chapters as follows: in chapter one there is literature review on thermal comfort, greenhouse gasses, statistical methods of analyzing results; in chapter two there is the presentation of the studied residential building, the study methodology, and the calculation methods considered and used in the study; in chapter three there is presentation and discussion of results; and finally there is presentation of recommendations.

Chapter I: Literature review

Introduction

This section presents the knowledge that is related to building most especially residential buildings. Building materials, their embodied carbon dioxide emission, the nature of carbon emission in the world, Africa and in Cameroon are presented as well. Thermal comfort is also review and presented. Lastly the various simulation softwares are also considered.

I.1. Types of residential buildings

Building energy performance is influenced by a number of factors; climate, building size, building operation and maintenance, efficient technologies, and human behaviour (Li et al., 2014; Abanda and Cabeza, 2015). Hence, the size of residential buildings constitutes an important component that depicts energy consumption. In Cameroon, the Ministry of Housing and Urban Development classifies residential buildings in the country into six different categories (Manjia et al., 2015) based on the components of the building as shown in Table 1. The environmental assessments conducted in this study will be based on a T4 residential dwelling as shown in Table 1.

I.2. Thermal comfort

Thermal comfort is defined as '*that condition of mind that expresses satisfaction with the thermal environment*' (ASHRAE A, 2005; Enescu, 2017; Hoppe, 2002). It affects people comfort in their buildings (Al-Horr et al., 2016; Frontczak and Wargocki, 2011), in addition to their health (Nicol et al, 2012) and productivity (Freire et al., 2008). It also affects buildings' energy consumption as a large amount of the consumed energy in buildings is directed towards achieving thermal comfort (Yang et al.,2014), which leads to increasing CO_2 emissions (Elaiab, 2014). Because of these reasons, thermal comfort has been investigated by researchers since the beginning of the 20th century, when air-conditioning systems were first introduced (Fabbri, 2015; Nicol and Roaf, 2017). Since that time many studies have been conducted to determine thermal comfort limits around the world. National and international thermal comfort standards have been established and developed, such as ISO Standard (7730), ASHRAE Standard 55 and CEN Standard EN15251 (Nicol et al., 2012; Rupp et al., 2015; Humphreys et al.,2015b).

Tab 1: Category of residential buildings in Cameroon

Type	Component	Quantity	Minimal area (m²)	Entire minimal area (m²)	Average number of incandescent bulbs
T1	Bedroom	1	12	20	1
	Kitchen	1	3		
	Toilet	1	3		
	Corridor	1	2		
T2	Living room + dining room	1	10	32	3
	Bedroom	1	12		
	Kitchen	1	3		
	Toilet	1	5		
	Corridor	1	2		
T3	Living room + dining room	1	20	62	4
	Bedroom	2	12		
	Kitchen	1	10		
	Toilet	1	5		
	Corridor	1	3		
T4	Living room + dining room	1	25	89	5
	Bedroom	3	12		
	Kitchen	1	10		
	Toilet	2	5		
	Corridor	1	8		
T5	Living room + dining room	1	30	106	6
	Bedroom	4	12		
	Kitchen	1	10		
	Toilet	2	5		
	Corridor	1	8		
T6	Living room + dining room	1	35	130	4
	Bedroom	5	12		
	Kitchen	1	10		
	Toilet	3	5		
	Corridor	1	10		

I.2.1. Parameters that affects thermal comfort

To assess and predict people's thermal comfort levels, studies, first, have worked on exploring the factors that affect people's thermal sensation. They have found that they are of two groups:

quantitative factors and qualitative factors. The former includes air temperature; air velocity; humidity; Mean Radiant Temperature (radiation); people activity level and people clothes (Reiter and Herde, 2003; Nikolopoulou, 2011; Setaih et al.,2013). The latter includes not measurable factors such as people's previous experience, thermal expectations, time of exposure to climatic conditions, psychology, available adaptation opportunities, and cultural and social backgrounds (Reiter and Herde, 2003; Nikolopoulou, 2011).

I.2.2. Thermal comfort Models

Depending on these factors, two thermal comfort models have been developed to assess and predict thermal comfort: the Static Model and the Adaptive Model (Yao et al.,2009; De Dear and Brager, 2002a). The former was developed by Fanger during the 1970s. It assumes that thermal comfort can be universally defined by determining the impact of the six quantitative factors on the human body's thermal balance. It has been developed by doing thermal comfort surveys in special thermal comfort chambers (De Dear and Brager, 1998; Fanger, 1970). The latter was developed and introduced later by researchers, including Humphreys, Nicole, and de Dear. It states that there are factors that affect people thermal sensation other than the factors of the human body's thermal balance. It argues that people from different places and cultures have different thermal comfort limits and that people adapt themselves to their surrounding climatic conditions (De Dear and Brager, 2002a; Nicol and Humphreys, 2002). This model has been developed through doing thermal comfort surveys in people's actual contexts doing their normal activities (Nicol et al.,2012; Alison et al.,2010). It predicts people's thermal sensation by making correlations with outdoor running temperature (Humphreys et al., 2010). Both of these two models have been used to determine people's thermal sensation and comfort limits. However, studies have found that the Static Model overestimates the discomfort of occupants in buildings that depend on natural ventilation (Nicol et al.,2012). It is also not able to tackle and consider the psychological, social and cultural factors that affect people perception of thermal comfort (Dear and Brager, 2002b).

I.2.2.1. The rational or heat-balance approach

The heat-balance approach is based on Fanger's experiments (Fanger, 1970) in controlled climate chamber on 1296 young Danish students, using a steady-state heat transfer model. In these studies, participants were dressed in standardised clothing and completed standardized activities, while exposed to different thermal environments. Depending on the ranges PPD and PMV admissible, three kinds of comfort zones can be accessed. However, the laboratory studies offer static and consistent conditions for measurement not possible in the field studies. It is now widely accepted that the previously used climate chambers fail to provide the participating humans with so-called ‘‘experiential realism’’ in determining thermal comfort, since ‘‘real’’ people live in changeable, inconsistent environments, which may cause concerns when the standards are applied to residents living in real world situations (Han et al., 2007).

In Figure 1, Givoni (1991) presented a "Comfort zone", on a diagram, with a range of climatic conditions within which the majority of persons would not feel thermal discomfort, either of heat or of cold.

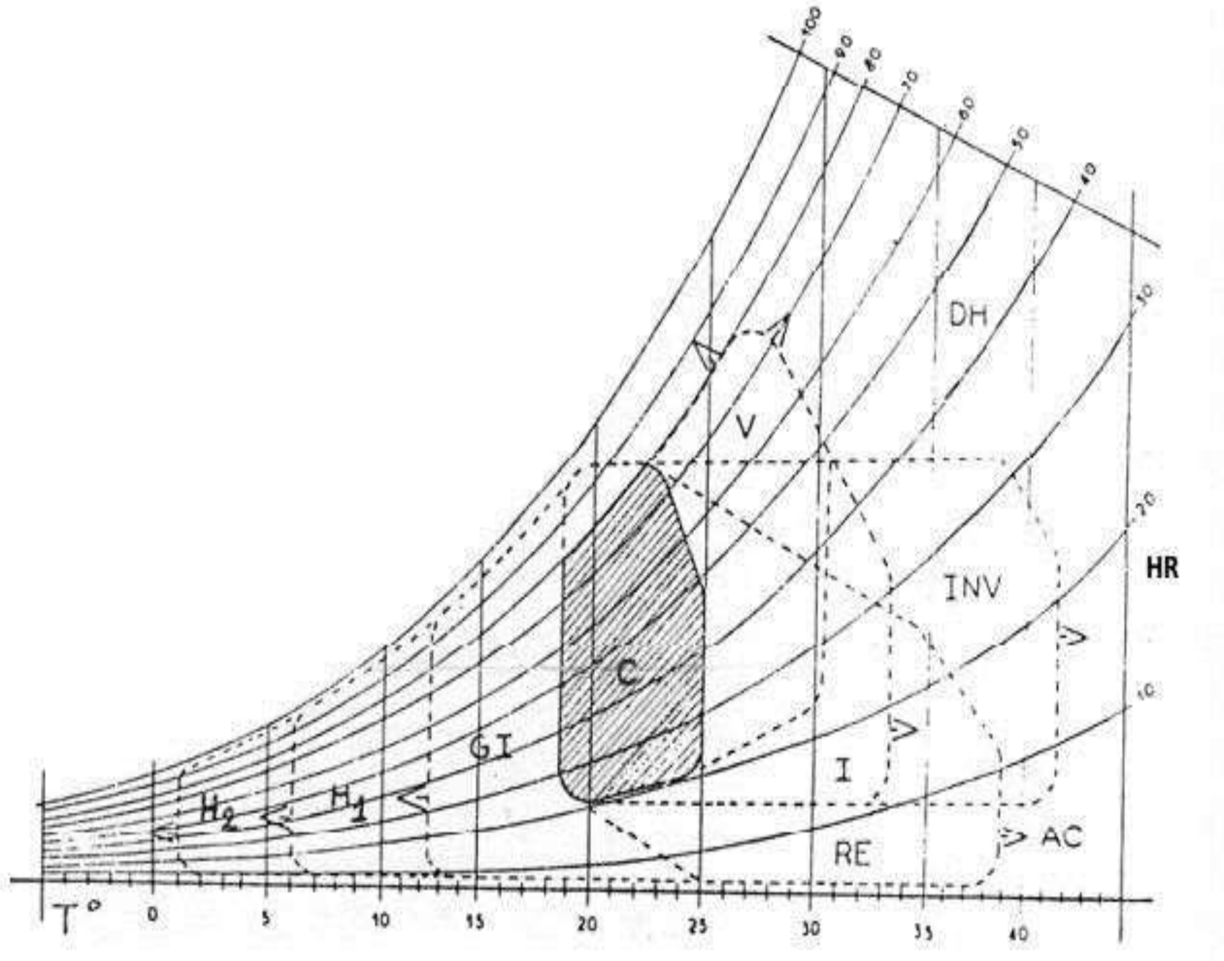


Fig 1: Givoni comfort diagram

For an accurate description of the indoor relative humidity, a relative humidity scale was used to characterize the data according to the location. The developed scale is shown in Table 2 (Djamila, 2017).

Tab 2: Indoor relative humidity classification

Range	Description	Notation
<=20	Very Dry	VD
21-40	Dry	DR
41-60	Nether Dry nor Humid	NDH
61-80	Humid	HD
>81	Very Humid	VH

Steady-state experiments showed that, cold discomfort is strongly related to the mean skin temperature and that warmth discomfort is strongly related to the skin wettedness caused by sweat secretion. Dissatisfaction may be caused by the body as a whole being too warm or cold, or by unwanted heating or cooling of a particular part of the body (local discomfort) (Hensen, 1991). These relations are the basis for methods like, Fanger's (1970) comfort model that incorporates the six factors mentioned by Macpherson, and the two-node model of Gagge et al. (1986). In an evaluation by Doherty and Arens (1988), it was shown that these models are accurate for humans involved in near-sedentary activity and steady-state conditions.

Fanger's model combines the theories of heat balance with the physiology of thermoregulation to determine a range of comfort temperatures which occupants of buildings will find comfortable. According to these theories, the human body employs physiological processes (e.g. sweating, shivering, regulating blood flow to the skin) in order to maintain a balance between the heat produced by metabolism and the heat lost from the body. Maintaining heat balance is the first condition for achieving a neutral thermal sensation (KE, 2003). However, Fanger (1970) noted that ''man's thermoregulatory system is quite effective and will therefore create heat balance within wide limits of the environmental variables, even if comfort does not exist''. To be able to predict conditions where thermal neutrality would occur, Fanger investigated the body's physiological processes when it is close to neutral.

He determined that the only physiological processes influencing heat balance in this context were sweat rate and mean skin temperature, and that these processes were a function of activity level. He used data from a study on 183 college-age participants exposed to different thermal conditions while wearing standardised clothing to develop a linear relationship between activity levels and sweat rate. He also conducted a study using 20 college-age participants who wore standardised clothing and took part in climate chamber tests at four different activity levels (sedentary, low, medium and high), to derive a linear relationship between activity level and mean skin temperature. After substituting these two linear relationships into heat balance equations, a 'comfort equation' was obtained.

The comfort equation predicts conditions where occupants will feel thermally neutral. That comfort equation was expanded (Fanger, 1970) using data from 1296 participants. The resulting equation described thermal comfort as the imbalance between the actual heat flow from the body in a given thermal environment and the heat flow required for optimum (i.e. neutral) comfort for a given activity. This expanded equation related thermal conditions to the seven point ASHRAE thermal sensation scale, and became known as the ''Predicted Mean Vote'' (PMV) index. The PMV was then incorporated into the ''Predicted Percentage of Dissatisfied'' (PPD) index. Fanger's PMV-PPD model on thermal comfort has been a path breaking contribution to the theory of thermal comfort and to the evaluation of indoor thermal environments in buildings. It is widely used and accepted for design and field assessment of thermal comfort (Lin and Deng, 2008).

In addition to Fanger's PMV-PPD model, a two-node model also known as the Pierce two-node model developed by Gagge et al. (1986) was based on the heat balance equation developed in (Gagge and Nishi, 1977). That comfort model used a two-compartment body structure, dividing a body into two concentric cylinders. The inner cylinder for the body core whose temperature Tcr is 37.18°C, and the outer one for the skin layer whose temperature Tsk is 33.18°C. The PMV-PPD model is useful only for predicting steady-state comfort responses while a two-node model can be used to predict physiological responses or responses to transient situations (Lin and Deng, 2008).

- **The predicted percentage of dissatisfied (PPD)**

The PPD predicts the percentage of the people who felt more than slightly warm or slightly cold (i.e. the percentage of the people who inclined to complain about the environment). Using the seven-point scale of thermal sensation (-3 to +3), Fanger postulates: are declared uncomfortable all those who responded 2 and 3. Those who responded 1 and 0 are declared comfortable. The percentages of subjects who responded 2 and 3 are determined for each class of PMV; that variable has been called PPD. The relationship between PPD and PMV is given in equation (1) (Fanger, 1972):

$$PPD = 100 - 95exp[-(0.03353PMV^4 + 0.2179PMV^2)] \quad (1)$$

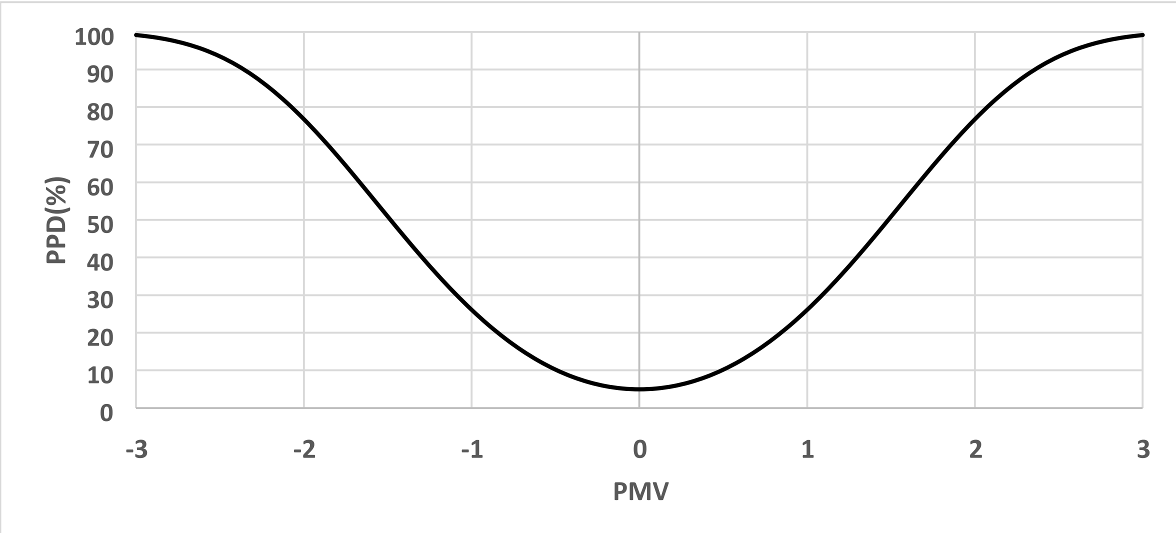


Fig 2: Relationship between PPD and PMV

The merit of this relation is that, it reveals a perfect symmetry with respect to thermal neutrality (PMV = 0). It can be seen (Figure 2) that, even when the PMV index is 0, there are some individual cases of dissatisfaction with the level of temperature, although all are dressed in a similar way and that the level of activity is the same. This is due to some differences of approach in the evaluation of thermal comfort from one person to another. It is shown that at PMV = 0, a minimum rate of dissatisfied of 5% exists (Fanger, 1972). Other studies have seen the need to monitor buildings and occupants' performance during their operations (Yousef et al., 2016).

I.3. Climate change situation in the world and in Cameroon

I.3.1. Greenhouse gasses emitted into the atmosphere

Before the institution of the Paris Agreement, the key GHGs emitted through human activities that are considered to transmit harmful toxics into the environment are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and fluorinated-gases (F-gases). Amongst all the GHG emissions, total carbon dioxide emissions account for 76% of GHG emissions globally (IPCC, 2014; United Nations, 1998; Gaussin et al., 2013). Global GHG emissions are presented in Figure 3. Table 3 shows the most common GHG emissions associated with building construction and their respective GWP impact.

I.3.2. CO_2 emission from various regions of the world

The level of CO_2 emissions from developing countries has been rapidly exceeding that of the developed countries and in 2003 accounted for almost 50% of the world's CO_2 emissions (Figure 4). This trend was expected to grow if the path used in terms of energy consumption was maintained. Since CO_2 is one of the main contributors to global emissions, it is of great interest to determine which policy measures will be more effective in curbing it emission.

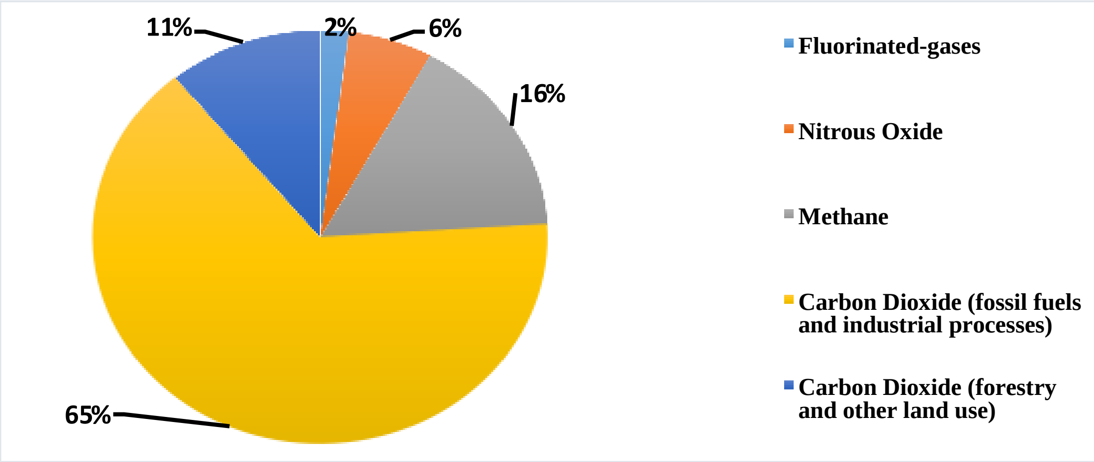


Fig 3: Global greenhouse gas (GHG) emissions. Source: Intergovernmental Panel on Climate Change (IPCC, 2014)

Tab 3: Most common GHG emissions associated with building construction and their respective GWP impacts, lifetime, and typical use, adapted from (EPA, 2018; Pachauri and Reisinger, 2007; EPA, 2017)

Greenhouse Gas (GHG)	Atmospheric lifetime (years)	GWP (100-year lifetime)	Most typical sources in the building environment
Carbon dioxide (CO_2)	50-200	1	Fossil fuel combustion from activities including electricity generation, manufacturing, transportation, and solid waste combustion.
Methane (CH_4)	12	25	Natural gas and fossil fuel combustion, enteric fermentation, solid and organic waste,
Nitrous Oxide (N_2O)	114	298	Industrial activities, combustion of fossil fuels, solid waste, and wastewater treatment.

CFC-11 (CCl_3F)	45	4750	Refrigeration, aerosol insulation, propellants, solvents, and air conditioning.
CFC-12 (CF_2Cl_2)	100	10900	
HCFC-22 ($CHClF2$)	12	1810	
Hydrofluorocarbons (HFCs)	Up to 270	Up to 14,800	Air conditioning, refrigerants, manufacture of foam-blowing agents for insulation, fire extinguishing systems, and aerosols.

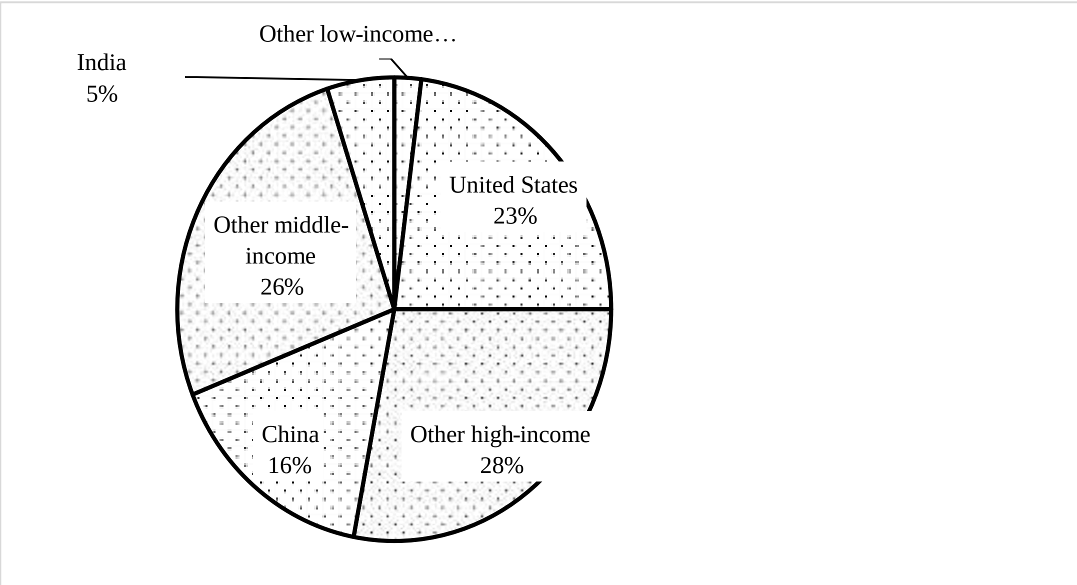


Fig 4: Carbon dioxide emissions in 2003(Source: World Development Indicators 2007.)

Although, Africa accounts for very low share of global CO_2 emissions, the region continues to experience upsurge in its emissions rate. The continent accounts for 1.9% of the global emissions in 1973 to the current rate of more than 3%. A typical African country generates 13 times less GHGs than his counterpart in North America (Brief, 2007). Total CO_2 emissions in Africa, from the 1980s up to 2015 is represented in Figure 5. North African countries have generated one of the biggest growth rates in global emissions, while South Africa, which depends greatly on coal, accounts for over 65% of the region's entire emissions, which makes it the 11th biggest emitting country in the globe (APF, 2008).

Change in Cameroon's CO_2 emissions during the introduction of natural gas in the country energy package in percentage is represented in Figure 6. According to Md. Afzal Hossain (2020) Cameroon's carbon intensity increased by 75 and 47% during the periods before (1971–1984) and after (1984–1994) the economic crisis, while it decreased significantly by - 135%

during the crisis period (1994–2014). At the same time, the country's emission factor increased by 30% between 2007 and 2014. (2) The effect of the demographic change was the main driver of Cameroon's CO_2 emissions during the periods 1984–1994 and 1994–2014, whereas the effect of economic activity was the main driver of the increase in these emissions between1971 and 1984. (3) The energy intensity effect contributed to the increase in CO_2 emissions during the period 1984–1994 in the same way as the effect of demographic change. However, this factor helped reduce CO_2 emissions in the other two periods. (4) Although the effect of substitution of fossil fuels and the effect of renewable energy all contributed to reducing CO_2 emissions during the period of this study, we found that the effect of renewable energy behind CO_2 emissions remains insignificant compared to the renewable energy potential available in Cameroon.

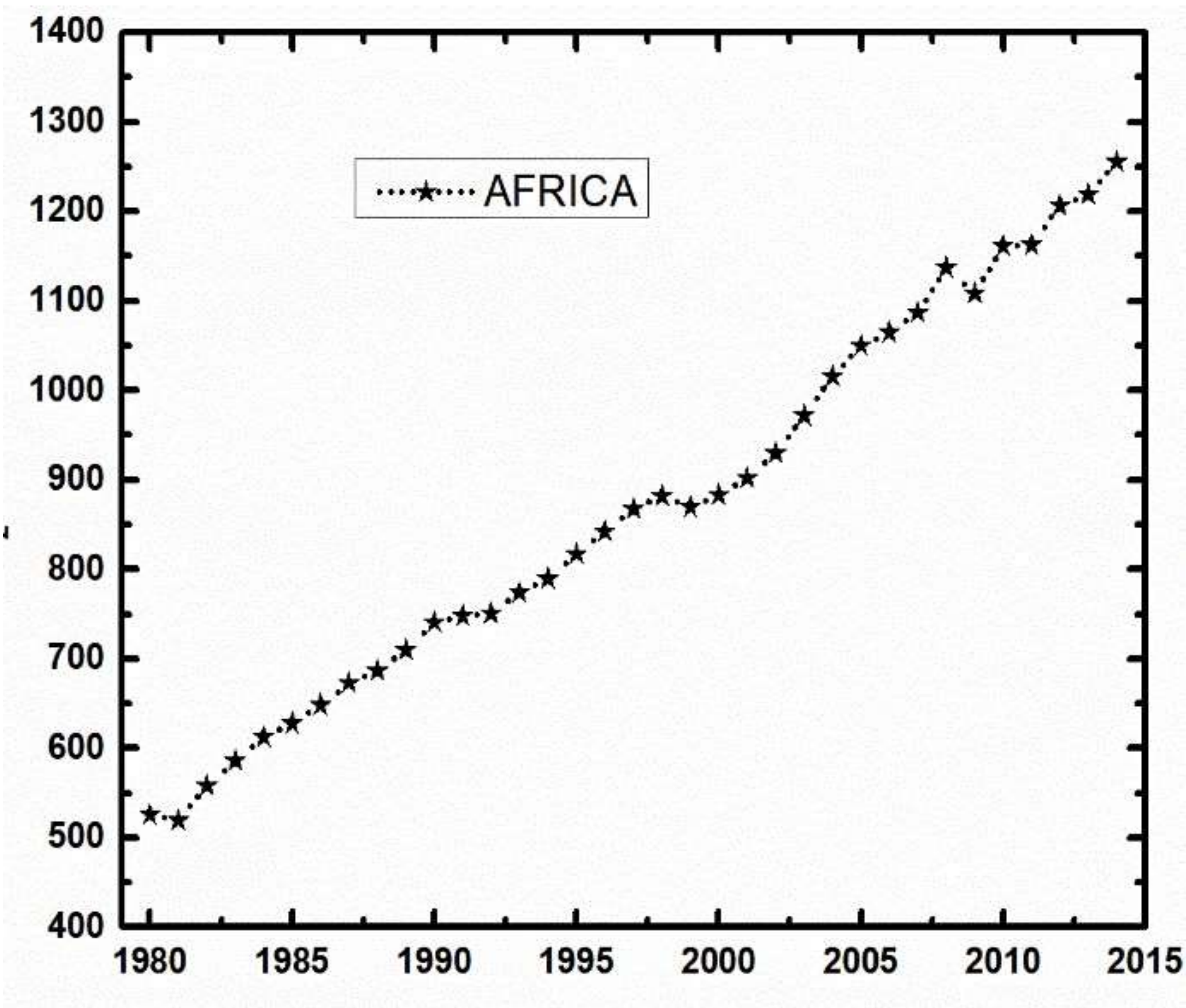


Fig 5: Total CO2 emissions in Africa (AmeyawID and Yao, 2018)

I.3.3. Global CO_2 emission by sector

The building, industrial and the transportation sectors are globally depicted as the major emission sectors. Global CO_2 emission by sectors is shown in figure 7, with the building sector being the highest emitter.

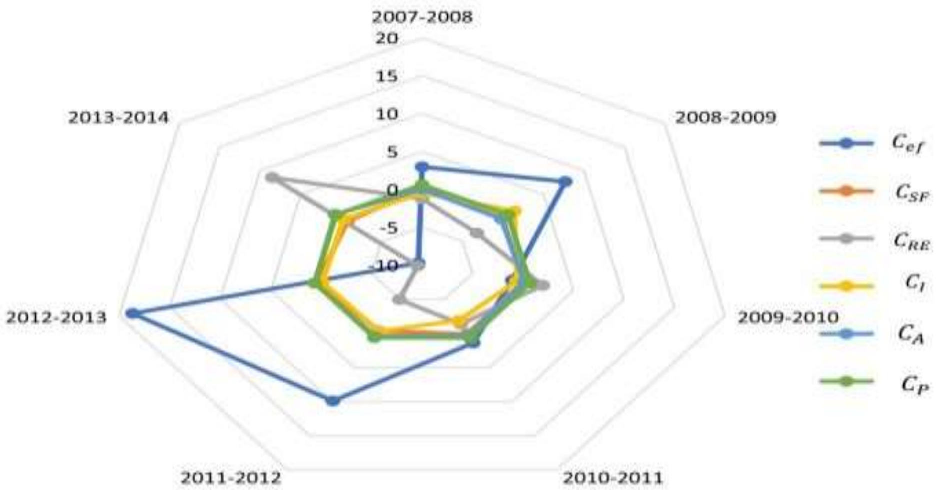


Fig 6: Change in Cameroon's CO2 emissions during the introduction of natural gas in the country energy package in percentage (2007-2014) (Hossain and Chen, 2020)

C_T CO_2 emission aggregating the determinants effects

Cp demographic factor or total population

C_A economic activity or affluence

C_{ef} CO_2 content per fossil fuel unit

C_{RE} Penetration of non-fossil energies or renewable energies including hydropower, solar, and wind

C_{FF} Switching fossil fuel types into total fossil fuel, including coal, oil, peat and gas

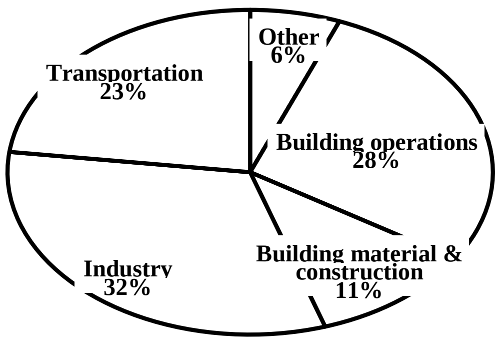


Fig 7: Global CO2 emission by sectors. (IEA, 2019)

I.3.4. Sources of CO_2 emission in buildings

A high rise building has contributed in increasing the amount of carbon dioxide (CO_2) emission. It can't be avoided because population growth has made numbers of high rise building increase in big cities. On the other hand, the population fulfillment demand will indirectly cause the increase of carbon dioxide (CO_2) emission. Carbon dioxide (CO_2) emissions source in construction can be divided into some parts, which are the upstream part (material construction industry), transportation, operational and construction implementation.

Ramesh et al. drew up an overview of 73 studies, including both residential and commercial buildings from 13 countries (Ramesh et al., 2010). They concluded that 80 to 90% of the effects are linked to the operating phase, whereas only 10 to 20% are embedded impacts. The review by Rossi et al. (Rossi et al.,2012) shows that the operation phase accounts for 62 to 98% of total life cycle impact, while the construction phase accounts for 1 to 20% and the dismantling phase for 0.2 to 5%. Lastly, according to Ooteeghem and Xu (2012), the operating energy and global warming potential (GWP) is responsible for 90% of the total energy and GWP after 50 years for retail buildings in Canada. Caldas et al (Caldas et al.,2017) in their study found that the operational phase was the most significant regarding the total CO_2eq emissions (50% to 70%), followed by the construction (20% to 30%), maintenance (11% to 20%) and end-of-life (lower than 1%) phases.

Other works have been done on the upstream, especially in a material manufacture construction industry, one of that is cement (Kim et al.,2013). Therefore, the early stage on reducing carbon dioxide (CO_2) emission in the upstream becomes important because carbon dioxide (CO_2) emissions that have been produced are very significant. There are many researches about carbon dioxide (CO_2) emission produced in the upstream (Rehan and dan Nehdi, 2005), however, other parts like construction implementation should not be ignored. Even though carbon dioxide emission produced from construction implementation is only about 0.4-12% (Caffrey, 2001), but its contribution to the greenhouse gas becomes important and significant. It is because construction implementation is also an inseparable part of life cycle. Carbon dioxide emission source in an on-site high rise building can be derived from a concreting work (Jeong et al.,2012). Onsite concreting work needs supporting equipment such as; tower crane, concrete pump and ready mix truck. A tower crane is one of important equipment on concreting work, especially in a high rise building. In practice, a tower crane needs huge energy and also very significant as carbon dioxide (CO_2) emission can also derived from other factor like site plan and others.)

According to ISO 14040, the system boundary is a set of criteria specifying which unit processes are part of a product system. It also describes the limits of what is included or not included in the assessment of the whole life cycle for a new building or any remaining cycle stages for the existing building. The Life cycle phases of a typical house building project is presented in Figure 8. The challenge in sustainably advancing the building sector is the increasingly large outflows of CO_2 due to the utilization of non-sustainable energy sources in the planning, construction, and operations of buildings *(Huang et al.,2018)*. CO_2 is also emitted from the broad utilization of land in the urbanization process *(Klufallah et al.,2014)*. The energy sourced from fossil fuels is non-sustainable, and yet it accounts for a large percentage of the energy used in the construction and operation processes. Sustainable or renewable energy sources only account for 6% of the total energy used in the sector, while fossil fuel used in construction activities accounts for 40% of worldwide greenhouse gas emissions. Although numerous novel methods have been proposed to lessen the CO_2 footprint of buildings, particularly in high-density urban communities, the challenge has yet to be solved appreciably *(Yim et al.,2018)*.

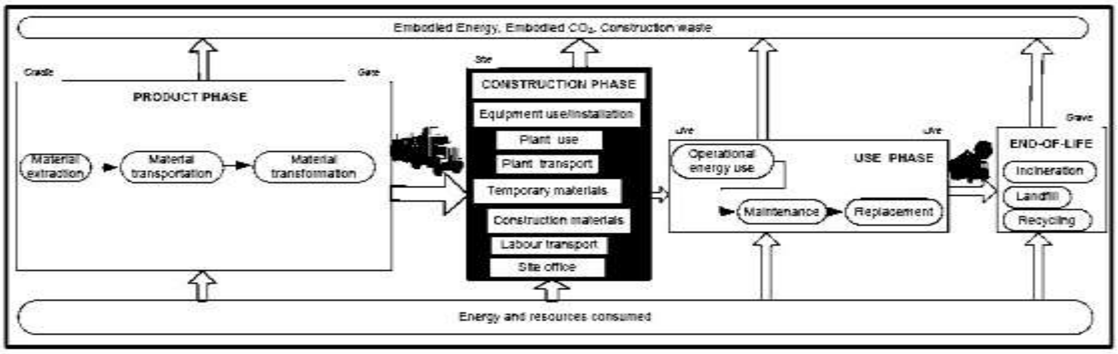


Fig 8: Life cycle phases of a typical house building project

Operational energy

Operational energy of buildings is the energy required to condition (heat, cool, ventilate, and light) the interior spaces and to power equipment and other services. The emissions associated with the repair of building materials is sometimes included in the operational stage (Chong et al.,2016). Life cycle assessments of conventional buildings indicate that the operation phase contributes largely to their total life cycle primary energy-use and GHG emissions (Sartori and

Hestnes, 2007; Asdrubali et al.,2013). For typical developed nations like the OECD countries, about 24 to 40% of anthropogenic greenhouse emissions will be related to buildings; 40 to 95% of these emissions will be caused by operational energy use with the remainder being caused by construction and demolition (Gustavsson et al.,2010). This has led to different attempts to reduce operation energy and related GHG emissions in buildings.

Over the life of a building operational energy may be much larger than the embodied energy in the materials. However, heating and cooling energy use is dropping because modern buildings of all materials are using more insulation for higher thermal efficiency, and new designs make use of "passive solar architecture" to entrain and store solar energy in parts of the building, which will make embodied energy more important in the future. The reinforced concrete industry is quick to promote the benefits of concrete as a good thermal storage material, and some timber buildings may have components such as ceramic tiles or concrete-timber composite floors designed to store energy. Thermal storage is not needed if buildings have sufficient thermal insulation, and new research is showing that buildings with exposed wood interiors may be much more thermally efficient than previously thought, because of moisture movement in and out of the wood surfaces during heating and cooling. Recent international studies into comparative building materials assume that the heating and cooling energy can be designed to be the same for all materials, over the life of the building (Gustavsson et al.,2006). More research is needed into innovative methods of reducing energy requirements for heating and cooling of all buildings, with thermal insulation, passive solar architecture and use of wood waste energy.

- **Embodied energy**

Embodied energy describes the amount of energy consumed in all processes associated with the production of a building, from mining and processing of natural resources/materials to manufacturing, transport and then the delivery of the product (Milne and Reardon, 2008), and is often assessed as part of a life cycle analysis, which includes the energy used throughout all phases of a building's life: manufacture and construction, operation, and demolition (Ramesh et al., 2010). Embodied energy can represent a substantial portion of the total energy used over the building's life cycle, usually somewhere between 10 and 20% (Munarim and Ghisi, 2016; Ramesh et al.,2010), although this share can increase for buildings with better operational effi ciency and decrease when a longer building lifespan is considered (Preservation Green Lab., 2011).

As a retrofit criterion, embodied energy can be viewed in two ways: first, as a novel criterion for comparing retrofit options to one another based on material-related resource consumption, and second, as an extension of conservation criteria, allowing for a quantitative assessment of retrofit impacts on the removal of building fabric. For all the emphasis on embodied energy within the historic preservation community it has received comparatively little treatment in most historic building retrofit studies. A few studies have evaluated both embodied energy and operational energy in order to determine whether retrofit and reuse of a traditional building is better than constructing a new one (Preservation Green Lab., 2011), and others examined this question on the basis of embodied energy only (Ding, 2013). Embodied energy in these studies acts as "sunk costs" (Munarim & Ghisi, 2016), and all of them conclude that it is better to reuse the existing building. In addition to comparing demolition and new construction options, Grytli et al. (2012) compared a variety of retrofit strategies in terms of embodied energy and operational energy, and Heath et al. (2010) assessed embodied energy in several slim-profile double-glazing units, a window retrofit strategy for historic buildings.

Abanda et al (2014) made a detailed study using process analysis approach supported by two popular housing types in Cameroon (mud-brick and cement-block houses) to assess the embodied energy and CO2 impacts from building materials. Embodied energy and CO_2 assessment of T4 cement-block and T3 mud-brick house are presented in table 4 and table 5 respectively. They used Building Information Modelling (BIM) tool to validate the computational results of the process analysis method. They found out that cement-block house expends at least 1.5 times more embodied energy and emits at least 1.7 times more embodied CO2 than mud-brick house. Although these findings cannot be generalized, they nonetheless indicate the importance of considering embodied energy and CO2 in making alternative choices for use in different building projects.

- **Building materials**

Different materials could be used to provide similar functions in buildings but the related energyuse and emissions could vary widely. Material inventory and ECO_2 emissions of some building materials are presented in table 6. This may be largely due to the required energy for material production and maintenance. A better understanding of the energetic and climatic implications of different materials substitution is needed to enable a choice of materials that give primary energy and GHG benefits over the full life cycle of buildings *(Tettey et al.,2014)*. About 24% of global raw material extractions go into buildings *(Bribián et al.,2011)*.

Construction is a sector which consumes various materials and comes from many sources. There are some materials which obtained from the nature such as, sand, wood, and water; however, there are some materials which are made/ produced by manufactures. Some of construction materials example which produced through manufacture process is cement, steel, bricks, etc. While materials based on implementation method can be divided into two; on site and off site. Implementation of construction materials needs energy for both on site and off site. The needs of energy mentioned above is the need of fuel used to process the construction material to be a component in a construction project.

Construction faces some challenges to answer global warming which occur in almost all countries. The challenge faced by construction is how to reduce greenhouse gas as the cause of global warming. Carbon dioxide (CO_2) produced by building/construction is the domino effect from the activity that occurred before, in the sections of industry which produce construction materials, transportation of materials to the location of the building and then to the process of construction implementation. Production of construction materials provide significant contribution to global warming in particular as the source of Carbon dioxide emission (CO_2). Cement and steel emit Carbon dioxide (CO_2) in significant quantities. The percentage of Carbon dioxide (CO_2) emission from some of construction materials can be seen in figure 9 (Bribián et al.,2011). Cement and steel have large percentage compared to other construction materials. While ceramics have lower percentage because there are some production processes that are similar to the cement production process. Both materials are the main material in providing various kinds of constructions like building and infrastructures (road, bridge, irrigation).

Tab 4: Material Inventory and ECO2 Emissions (Cui et al.,2011)

Materials	**Total Weight (kg)**	**ECO$_2$ Intensity (kg CO$_2$/t)**	**Total ECO$_2$ Emissions (x 10^6)**
Cement	2189565	820	1795
Reinforcement	1209685	1790	2165
Steel H-pile	475235	1640	779
Glass windows	65450	770	50
Timber	85030	1350	115

Besides water and aggregate, another material that is complementary to cement is steel. Steel is the main material after cement which is also used in most infrastructure and non-infrastructure projects. Steel production indicates an increasing growth globally. The total amount of crude steel production in 2007 is 1.3435 billion tons, and has increased as big as 5.6% in 2008. The crude steel distribution are China 34%, Japan 9.3%, Asia 10.5%, European Union 15.9%, non-European Union 2.9%, NAFTA (Argentina, Brazil, Venezuela and Latin America) 10.5%, CIS (Canada, Mexico and US) 9.6%, and others 7.2%. The use of steel in construction becomes an alternative method and increasingly trending after the outbreak of global warming issue.

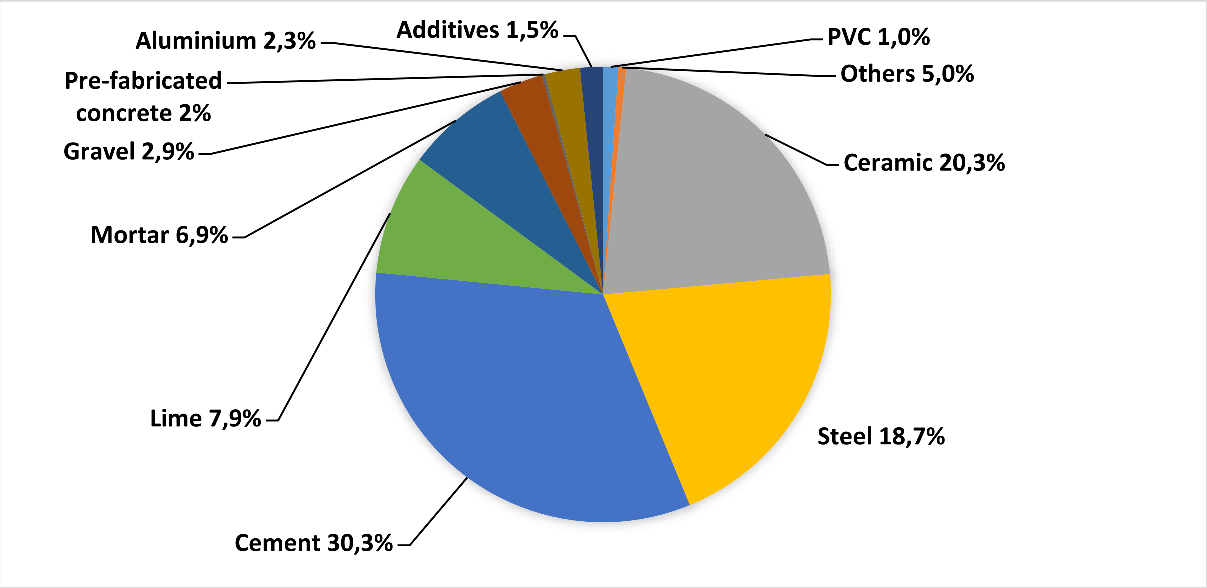


Fig 9: CO2 contribution from various construction materials (Bribián et al.,2011)

I.3.5. Impact of Greenhouse gas emission

It is well-known that CO_2 emissions contribute to global warming and climate change, which can significantly cause severe impacts and consequences for humans and the environment. CO_2 can significantly cause severe impacts and consequences for humans and the environment. These impacts and consequences of CO_2 emissions can be seen now. They extend well beyond the rising global temperatures, which is affecting ecological systems and communities across the world.

CO_2 emissions act like a blanket in the air, trapping heat in the atmosphere, and warming up the Earth (Klufallah et al.,2014). This layer prevents the Earth from cooling, and thus raises global temperatures. Global warming would affect environmental conditions, food and water supplies, weather pattern, and sea levels (Paoletti and Manes, 2003). Based on the National Oceanic and Atmospheric Administration (NOAA) Global Climate Summary, it stated that combined land and ocean temperature since 1880 has increased with an average rate of 0.07°C per decade. The temperature continues rising since 1981, with an average rate of 0.18°C, which is over twice as massive as previous times. Figure 10 illustrates the impact of CO_2 emissions as a result of rising global temperatures.

The Third Assessment Report (TAR) of the Intergovernmental Panel on Climate Change (IPCC) and other organizations indicated the following: an increase of even 1°C in global average surface temperature compared to pre-industrial level will have significant impacts on the fragile ecosystems, an increase of 2–3°C will have negative impacts on agriculture, water resources, and human health, and an increase of above 3°C will have serious risk of large scale and irreversible system disruption such as destabilization of ice sheets in the Antarctic area. The IPCC recommended in the Fourth Assessment Report (AR4) (IPCC, 2007) that a fair chance to limit the increasing of average global temperature is at 2°C as well as the concentration levels of GHG need to be stabilized at 450 parts per million (ppm) carbon dioxide equivalent.

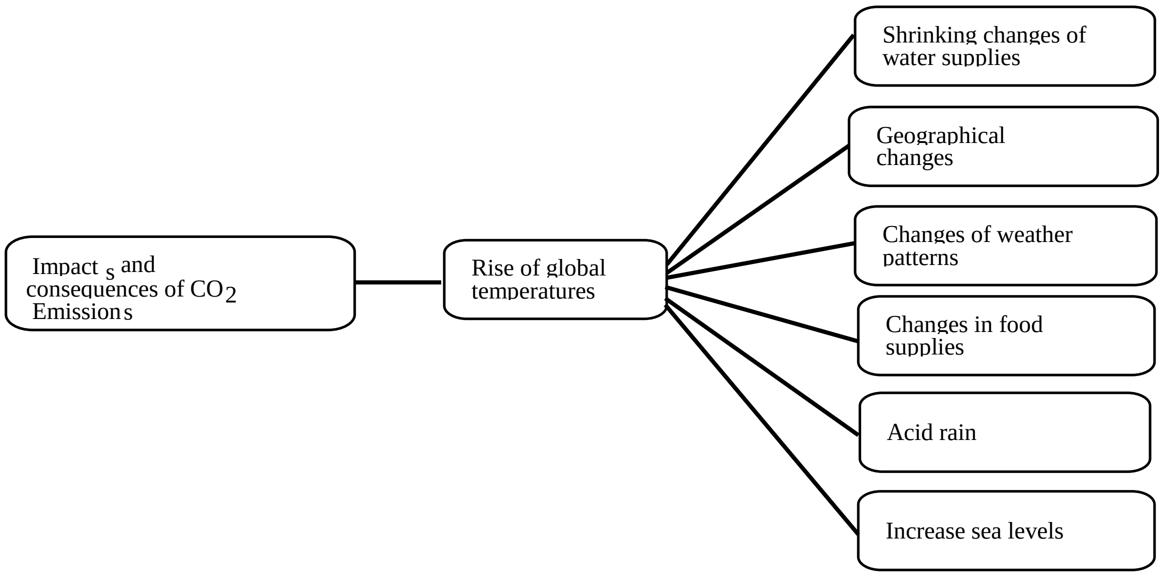


Fig 10: Impacts and consequences of CO2 emissions on the environment (Ali et al., 2020)

The performance of buildings depends on the climate they are exposed to. Their long lifetime (in the range of 50 to 100 plus years) corresponds to the timescale over which the climate is expected to show substantial change. This implies that buildings built today need to be designed to work successfully in both the current and future climate, and with the aim of reducing the greenhouse emission burden they place on this and future generations. Most climatic models point to a substantial future change in climate of approximately plus1.5°C in annual mean temperature by 2050 and 2-4 °C by 2080 when averaged over the planet's surface and under the conservative assumption that the atmospheric concentration of carbon dioxide (the main anthropogenic greenhouse gas) will have only increased to 600 ppm (Solomon, 2007).

As less change is predicted over the oceans, because of their greater heat capacity and their ability to loose heat via evaporation (Rowan et al.,2007), a greater change is expected over land. The models also indicate that even over land the change will not be even, with areas such as Alaska and Canada experiencing a warming of 10 °C change due to a reduced period of snow cover (Solomon, 2007). It is therefore clear that the effect is not a minor one and that the implications for the built environment are likely to be large. These changing environmental effects then have an impact on building behaviour and performance.

Typical areas affected are energy use and emissions, inefficiency and malfunction caused by systems confronted with a shift in operation conditions, and problems caused by overloading. Furthermore, the environmental effects might cause issues in the urban context, like failures in the electrical grid, which can cause problems for buildings that in themselves are functioning properly. Many of these impacts need to be discussed in terms of risk, with recent work on flood insurance in the Netherlands providing a good example (Aerts and Botzen, 2011). The impact of climate change on buildings is deeply intertwined with consequences for the building occupants and key processes that take place in those buildings. As buildings have different functions, climate change impact assessment studies must be tailored towards the specific needs and requirements at hand.

Complex interactions exist: for instance, between the comfort as experienced by occupants, control settings in the building, and energy consumption of heating and cooling systems (Nicol and Humphreys, 2002). Note that many buildings are designed to only just meet national guidance on overheating and large change in external temperature is more than likely to take such building into problematic conditions, particularly as the bulk of the increase in mean annual temperature is expected to be during the summer months. Assuming the overheating criteria were set in a sensible manner, and given the lifetime of a building is such that the predictions are that it will experience substantial climate change, one can conclude that modelling for design and compliance should be completed using both current and future climates.

The impacts of climate engage, which is mostly felt in Africa, range from energy shortages, deteriorating food security, spreading infectious disease, increasing migratory burdens and incessant clashes over limited water and land resources (APF, 2008). The continent lost 65% of its arable land between 1950–1990 and likely to lose up to two thirds by 2025 due to land degradation (Aboubacar, 2006). The recurring drought-induced famine in Africa, frequency of heat waves, and heavy precipitation events, which have increased since the 1950s, are fallouts of global warming (Cogan, 2008).

The overall conclusions of these studies are well articulated by Crawley (Crawley, 2008) who states that the impact of climate change will result in a reduction in building energy use of about 10% for buildings in cold climates, an increase of energy use of up to 20% for buildings in the tropics, and a shift from heating energy to cooling energy for buildings in temperate climates.

I.3.6. CO_2 emission models

The amount of embodied CO_2 in construction materials is calculated using the expression in equation (2).

$$V \times D \times C = Amount\ of\ CO_2\ emission \quad (2)$$

Whereas: V = volume of building material used (m^3)
D =Density of the building material (kg/m^3)
C = Embodied carbon dioxide emission (kg CO_2/ ton)

To assess CO_2 emissions at the regional or national scale, the Kaya model whose form is expressed in Equation 3 is often used (Kaya, 1990).

$$C = \frac{C}{E} \times \frac{E}{GDP} \times \frac{GDP}{P} \times P = CI \times I \times A \times P \quad (3)$$

where **C** represents aggregate or total emissions of CO_2, *E* refers to total energy consumption, *P*, *A*, EI and CI denote population, GDP (gross domestic product) per capita, energy intensity per unit of GDP per capita and the carbon intensity, respectively. To further investigate these country's CO_2 emissions, an identity of Kaya, namely the carbon intensity (CI), has been extended.

CO_2 emission estimated based on the IPCC National Guidelines on Greenhouse Gas Inventory (IPCC, 2006) is estimated in equation

$$C_i^t = \sum_j^{n=7} FF_{ji}^t \times EF_j \quad (4)$$

Where C_i^t represents the total CO_2 emissions of the sector (i) for the year (t), FF_{ji}^t and EF_j are the total amount of j-type fossil fuel used by sector (i) in the year (t), and the amount of carbon contained in fossil fuel (j), respectively. (n) is the fuel number.

Simple on-site CO_2 calculations are performed using equation 5. In this equation, for each of the fuels burned onsite, $Fuel_i$, HC_i, and C_i represent the fuel mass, heat content, and carbon content respectively. FO_i Considers the amount of oxidation; and CO_2 and carbon molecular weight are used to calculate the mass of onsite CO_2 emission (USEPA, 2008).

$$Emission = \sum_{i=1}^{n} Fuel_i HC_i C_i FO_i \frac{CO2(m.w)}{C\ (m.w)} \quad (5)$$

I.4. Software tools

I.4.1. ESP-r (Energy Simulation Software tool)

The software tool ESP-r (Energy Simulation Software tool) is intended to support the construction project with regard to energy and environmental performance, in a realistic and accurate way. The software tool is mathematical software for a project manager that coordinates the data, simulation, CAD applications, different tools for evaluating performance, display and report generators, etc. The ESP-r uses several complex equations to deal with all aspects at the same Time (geometry, construction, operation, distribution, heat dissipation, etc.). These equations are integrated in successive time in response to the influences of the occupants, and climate Control systems. The geometry of the building can be set in CAD software tools or other similar tools to allow the specification of the geometry of buildings. The models created in this software can be exported to Energy Plus (Brenan et al.,1996).

The operating conditions are determined through database support. Shading, insulation, HVAC systems, areas of computational fluid dynamics (CFD), electricity, renewable energy embedded systems, lighting, natural ventilation, combined heat and power generation, facades photovoltaic systems for control of indoor air quality can also be included in the models pre-determined. The time simulation of the building with ESP-r simulation tool can vary in a range from one minute to one hour. The outputs of the simulations can be viewed by the interactions between the domains of assessment or exported to other graphics software. The ESP-r is extremely useful and is a powerful tool to simulate many innovative technologies. However, the program requires a great knowledge and expertise from its users, and requires a long learning process.

I.4.2. IDA ICE

The thermal simulation software tool IDA Indoor Climate Energy is based on a general system simulation platform with a modular system. The multi-domain physical systems are described in the IDA using symbolic equations starting with a simulation language Neutral Model Format (NMF - Neutral Model Format). The user defines the tolerances which control the accuracy of the solution, thus allowing the isolation of numerical modeling approaches. End-user has the following advantages:

- Extensions can be added to the initial model;
- The mathematical model can be inspected to investigate the variables, parameters and equations;
- The research models are easily performed.

I.4.3. IES VE (Integrated Environmental Solutions - Virtual Environment)

The simulation software tool IES provides the design professionals with a variety of variables in simulation analysis of buildings. The model works on the geometric representation that represents the building. The software tool allows interaction with other energy simulation software tools. The simulation software tool incorporates a tool for dynamic thermal simulation of heat transfer processes of buildings, which is the ApacheSim. The simulation software tool was tested using the IES ASHRAE 140 and is qualified as a dynamic model in CIBSE system of classification. The software tool provides an environment for the detailing of the building systems, allowing their optimization taking into account criteria such as comfort and energy. The dynamic tool ApacheSim can be dynamically linked to the Macro FLO dynamic tool for natural ventilation and HVAC Apache dynamic tool to perform analysis of air leaks and for analysis of natural lighting and shading. The results should be automatically exported.

I.4.4. TRNSYS

TRNSYS is a transient system simulation software tool with a modular structure that has been specially designed to develop complex systems related to energy, outlining the problem in a number of smaller components (Friedenthal et al., 2008). The components ("Types") may range from simple heat pump to a multi-zone of a building complex. The components are configured through the graphical user interface known as TRNSYS Simulation Studio. In the simulation software tool energy TRNSYS the construction of the building can be achieved by the introduction of data on dedicated Visual interface, known for TRNBuild. The software tool sets the time intervals which may vary from 15 minutes to an hour, but may be able to perform simulations in the time interval of 0.1 seconds. The library software tool in addition to a multi zone, allows the use of many commonly used components, including: solar panels, photovoltaic systems, HVAC systems, cogeneration systems, hydrogen, among others. It also allows the creation of routines to manipulate Weather data and other data by changing the simulation results.

The modular nature of this software tool facilitates the addition of mathematical models to the software tool. The components can be shared among multiple users without having to recompile the software tool due to the use of DLL technology. In addition, this energy simulation software tool allows the user to incorporate other components developed in software tools such as Matlab, Excel, VBA, etc... Moreover, the software tool includes the possibility of adding HTML views through a software tool called TRNSED, which enable non-users to view and do parametric studies of TRNSYS files, in a simplified representation of a web page.

I.4.5. OpenStudio

OpenStudio is a suite of free and open-source building-energy simulation tools for building design. OpenStudio supports the entire building energy simulation based on EnergyPlus and advanced lighting analysis based on Radiance, thermal comfort, air condition and lifecycle costs (LCC). OpenStudio includes graphical interfaces along with a software development kit (SDK) for constructing a building energy simulation. Its primary application is as a plugin for SketchUp. OpenStudio was designed to cooperate with SketchUp, allowing architects to simulate before construction. OpenStudio organizes a parametric energy simulation process based on its several tools. Macumber et al. (September 2014) illustrate this process using the Parametric Analysis Tool in detail, in which cloud computing helps to analyze parameters and energy simulation.

Picco et al. (2014) introduced a simplification methodology for commercial building models around the optimization of energy efficiency in early-stage design. They built a large multi-story office building with detailed information through the OpenStudio software. Then they analyzed the detailed model and progressively simplified it. At each simplification step, a comparison between the detailed model results and the simplified model results was given to ensure the quality of the results of the simplified model. Their research aims to meet the time requirements and to maintain a received level of correctness of results. OpenStudio usually needs many detailed parameters to build energy models. Therefore, it is more suitable to be used in the late design stages. They coupled OpenStudio with an uncertainty and sensitivity analysis method to quantify the parameter sensitivity for the most optimal sampling results, which can support decision making.

I.4.6. HTB2 (Heat Transfer in Building: version 2)

Jones et al. (2013) introduced a plugin—HTB2 (Heat Transfer in Building: version 2) based on SketchUp—aimed at building energy consumption at an early design stage. HTB2 was developed as two processes within an intensive computational framework. One process involves the modeling of multi-building scale development. The second involves a trade-off between multiparameter options for a single building type. For single-building modeling, HTB2 can perform a parametric analysis at the early design stage with millions of data items. The results can be referred to by A post-processing "sensitivity tool" to help designers make decisions. They (Jones et al.,2017) also present an energy-modeling framework based on this tool and its sub-models to simulate the SOLCER house. The sub-models are developed based on HTB2 for the thermal system, i.e., the Transpired Heat Recovery (TSC) and Mechanical Ventilation Heat Recovery System (MVHR). The authors compared simulated data by sub-models and measured data, which indicates the higher accuracy of sub-models for a thermal system. Variation exploration in the design of the SOLCER house can be realized with this modeling framework now. Alexander et al. (2005) modified and tested this HTB2 tool for the calculation of glazing and shading options. They developed and selected an algorithm to enhance the calculation accuracy of a glazing system, which can be provided for selection for multiple glazing options at different design stages.

I.4.7. Green Building Studio (GBS)

Green Building Studio (GBS) is a simulation tool for an entire building's energy built on Autodesk. It helps architects and designers to realize an entire building energy analysis, energy consumption optimization and carbon-neutral design in the early design stage based on a web energy-analysis source. GBS simulates building energy based on the DOE-2.2 engine and, at the same time, creates accurate input files for EnergyPlus for interoperability. GBS software creates a one-step simulation process in which GBS creates a complex and integrated energy model through reading from Revit and Vasari with minimum sets of inputs because GBS has stored default building model information. Based on the GBS tool, Lin and Gerber (2014) proposed a framework for evolutionary energy performance feedback for design (EEPFD), which supports early decision making and rapid design iteration through parametric analysis, automation, and multi-objective optimization. There are six steps in the EEPFD process for integrating design and energy simulation. The process uses Revit to design and model, GBS to analyze energy performance and H.D.S. Beagle to evaluate results. In this EEPFD process, an integrated, iterative and decision-supported design workflow can be realized.

I.4.8. Grasshopper

Grasshopper is a parametric design plugin for Rhino. Parametric design tools provide more alternatives for building design in the early design stage. Such parametric scripting tools overcome the obstacles of expertise with the simulation tool, simplifying or reducing tools' and interfaces' professional levels. An increasing number of parametric design tools are being utilized in building design and studies (Nembrini et al.,2014). Similar to Grasshopper, other parametric tools include Dynamo (Dynamo BIM, 2017), a plugin for Revit and stand-alone software Generative Components Plugins for grasshopper and plugins for Rhino, can help designers to complete performance simulations and to support decision making. Elbeltagi et al. (2017) raise a visualized strategy for building parametric analysis in the early design stage. The strategy is an energyoriented workflow aimed at the climate in Egypt. Through Rhino, Grasshopper and its plugins couple a parametric design tool and an energy simulation tool to construct a building energyconsumption database. These two types of tools' parallel cooperation can visualize the energy model database and help an operator to evaluate building performance in a more flexible manner.

Along with materials and construction techniques also energy simulation software tools of buildings have had developments over the years. Currently there are several energy simulation software tools with different levels of complexity and response to different variables. Among the most complete simulation software tools are the EnergyPlus, the ESP-r (Energy Simulation Software tool), the IDA ICE (Indoor Climate Energy), IES-VE (Integrated Environmental Solutions - Virtual Environment) and TRNSYS. Being the most complete software tools, these are also the most complex and therefore require greater expertise. From the analyzed energy simulation software tools, TRNSYS is the most complete, but depending on the user perspective and final purpose the other software tools could be more appropriated. The major limitation of TRNSYS is to not being able to connect with AutoCad Software tool for importation and exportation of files. In this aspect EnergyPlus, ESP-r and IDA ICE are more appropriate.

Conclusion

The existing body of literature mostly analyzed buildings located in cold and temperate climates. Hence, there is a research gap regarding GHG emissions across the life cycle of buildings located in warm and humid, subtropical and tropical climate regions. This gap in the literature is appalling, considering the geographic extent of these climate regions and the number of people inhabiting them. By 2060, more than half of new residential buildings are expected to be constructed, with remarkably rapid growth, in Africa, Asia and Latin America, regions that have humid subtropical and tropical climates (Abergel et al., 2017). The importance of studying buildings in these regions is further emphasized, as warm climates are nearly twice as sensitive to local temperature changes due to global heating and, hence, more affected by related harmful effects than cold or temperate climate regions. Consequently, there is an urgent need to address the impact of climate and buildings on each other in these regions, especially climate and the residential construction sector, by implementing building design strategies that enable significant reduction of GHG emissions.

Chapter II: Material and Methods

Introduction

The material and the methods used in the study are presented in this section. The buildings used for investigation are presented together with their characteristics. Equipment; their precision and the quantities collected are also presented. Followed in the section are the presentation of statistical methods like the "hat matrix", used in the treatment of collected data; the mean bias error and the coefficient of variation of the mean square error. The residual and the scatter plots, used to test how constant the simulation engine can best represent the real situation; the energy-related CO_2 emissions model is also presented. The procedure of how the research was carried out is also presented.

II.1. Description of the study site

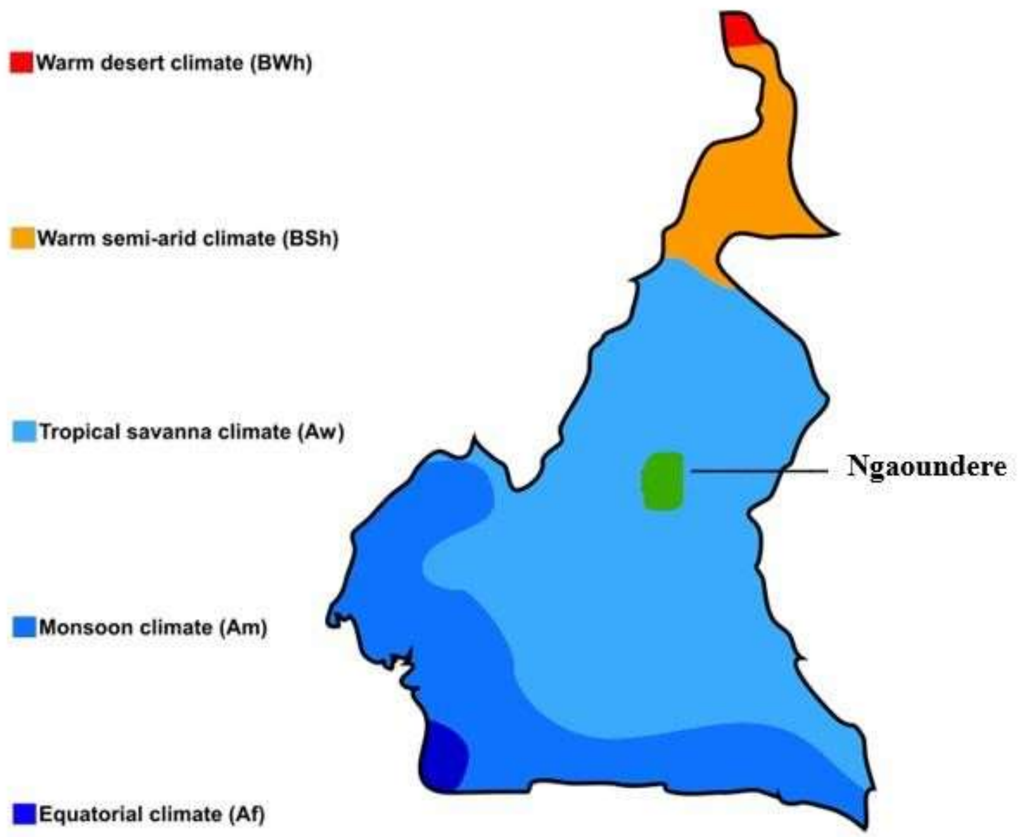


Fig 11: Cameroon map of KÖppen climate classification

Ngaoundere is the head quarter of the Adamawa region of Cameroon and is found on the Adamawa Plateau which is part of plateau in west-central Africa stretching from south-eastern Nigeria through north-central Cameroon (Adamawa and North regions) to the Central African Republic. It is situated on a plateau with an average altitude of 1 000 meters. Its geographical location is latitude 7.34°, longitude 13.57° and 1104.00m above sea level, with an area of 17,196km2. The data used was collected from the 2010 to 2018. According to Koppen climate classification Ngaoundere is found in the tropical savanna climate figure 11.

II.2. Material

II.2.1. Investigated laboratory building (LCTV)

Within the study period LCTV was equipped with two tables, a shelf, a printer, three desktop computers, a data logger and some office chairs. It is found on the first floor of UIT (university institute of technology). Its west wall has a large glass window. The characteristics of the block considered in the building energy model are shown in table 11 and are taken from (Tchuen and Cyrille, 2016)**,** while those of the roof are as defined in designbuilder. The plan of LCTV and the building energy model used for simulation are shown in *figure 12*. The building is built with light weight hollow concrete blocks, with cement plaster on both sides. The block and the plaster thickness were considered to be 15cm and 1.5cm respectively. The room was naturally ventilated. It was in this room that real measurements of internal temperatures were taken down by the temperature sensor. This room was therefore used to calibrate the calculation engine used in this study.

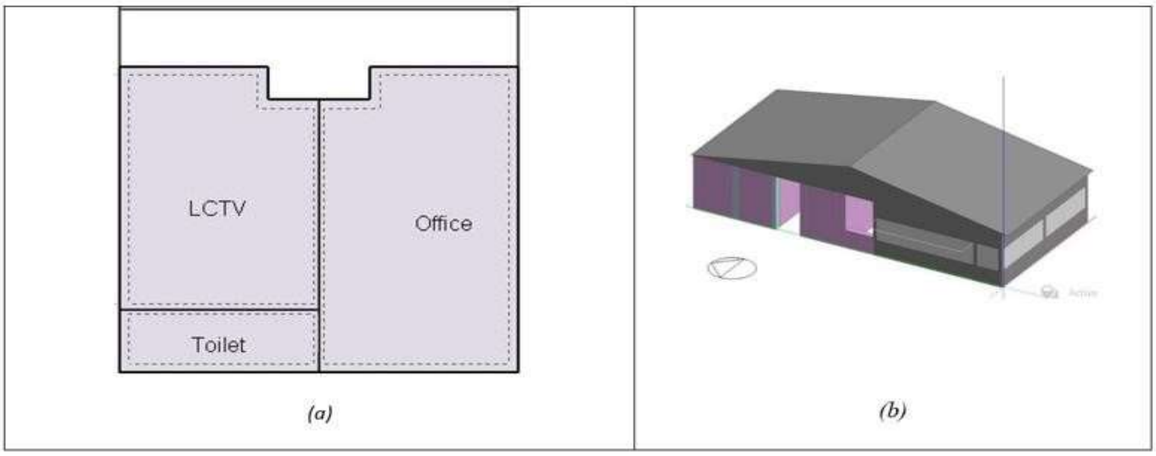


Fig 12: LCTV building; (a) plan; (b) structure designed in designbuilder

II.2.2. Investigated residential building

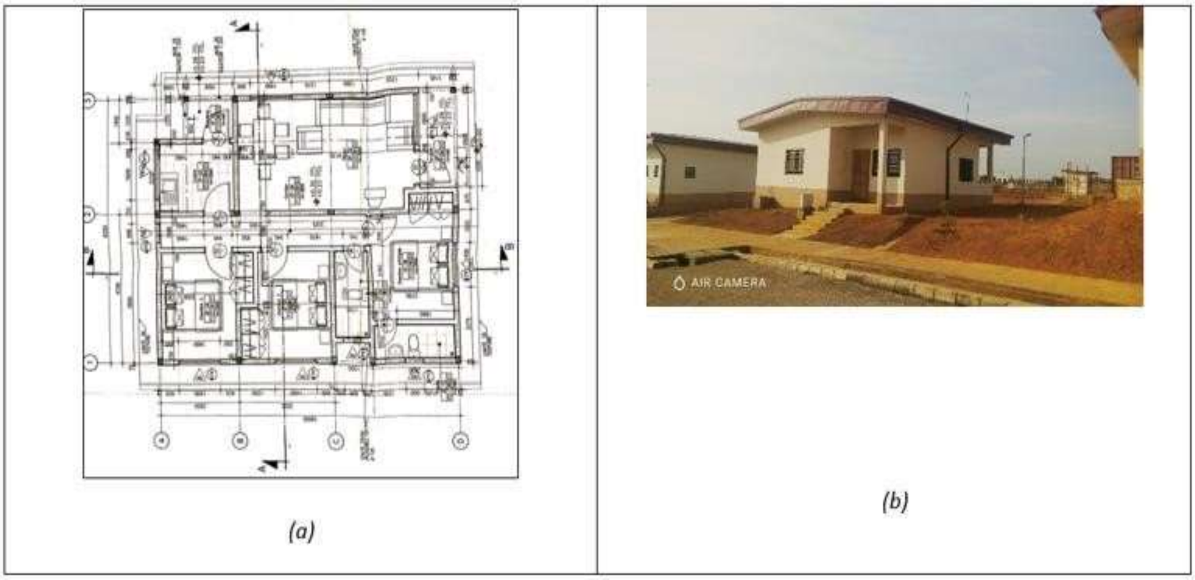


Fig 13: Case study residential building; (a) Plan; (b) Structure

The residential building studied here is one of the social buildings constructed by alliance construction for the government of Cameroon and is located in the town of Ngaoundere (latitude7.34°E and longitude 13.57°N and at 1104m above sea level), the headquarters of the Adamawa region of Cameroon. The building consisted of three sleeping rooms, a living room, two bathrooms, a corridor and a kitchen. The plan and the building are shown in Figure 13. The building is built with light weight hollow concrete blocks, with cement plaster on both sides. For the present study we considered that the block and plaster thickness were as those of LCTV. The characteristics of the building material under investigation in the present studies are summarized in Table 7. Table 8 gives a detailed summary of the building zones.

Tab 5: Properties of building materials

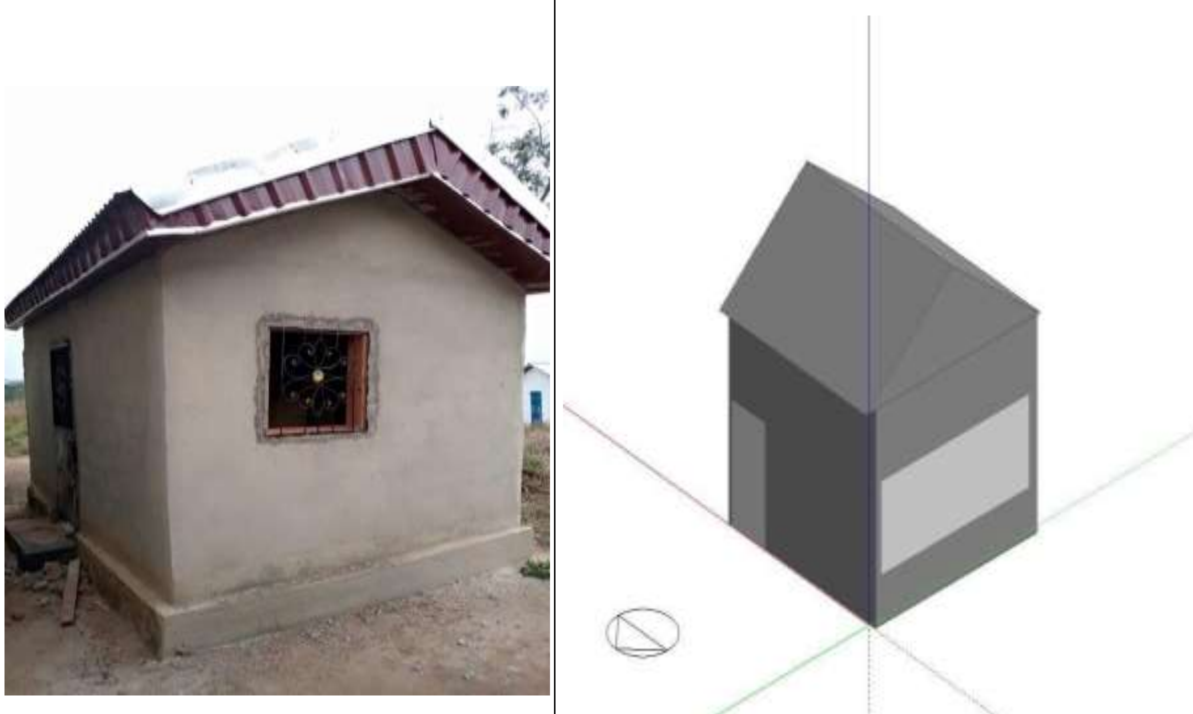
Building material	**Thermal conductivity(W/m.K)**	**Specific heat capacity(J/kg.K)**	**Density (kg/m^3)**	**Thickness (m)**
Burnt block	0.85	880	1500	0.15
Mud bricks	0.44	1200	880	0.15
Compressed block	1.15	900	1800	0.15
Hardwood	0.17	1880	700	0.15
Hollow concrete block	0.67	1250	880	0.15
Softwood	0.12	180	510	0.15
Roofing sheet	45.28	500	7824	

Tab 6: Details of the case study building

Partitioning	Area [m^2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [m^3]	Multipliers	Above Ground Gross Wall Area [m^2]	Window Glass Area [m^2]	Opening Area [m^2]	Lighting [W/m^2]	People [m^2 per person]	Plug and Process [W/m^2]
Living room	21.03	No	Yes	52.99	1.00	29.65	2.41	2.79	7.5000	53.19	0.0000
Bedroom 3	9.80	No	Yes	24.71	1.00	15.01	1.12	1.30	5.0000	43.67	0.0000
Bathroom 7	2.56	No	Yes	6.45	1.00	14.06	0.27	0.36	7.5000	53.48	1.6700
Common circulation area	6.03	No	Yes	15.20	1.00	2.86	0.27	0.36	5.0000	64.52	0.0000
Bedroom 2	9.07	No	Yes	22.87	1.00	11.80	1.12	1.30	5.0000	43.67	0.0000
Kitchen	5.30	No	Yes	13.36	1.00	14.15	1.29	1.49	15.0000	42.19	0.0000
Bedroom 1	9.79	No	Yes	24.68	1.00	17.57	1.12	1.30	5.0000	43.67	0.0000
Bathroom 6	3.14	No	Yes	7.90	1.00	3.83	0.27	0.36	7.5000	53.48	0.0000
Roof	77.27	No	No	27.13	1.00	7.30	0.00	0.00			
Total (without roof)	66.73			168.15		108.92	7.88	9.26	6.7956	48.44	0.0641
Conditioned space Total	0.00			0.00		0.00	0.00	0.00			
Unconditioned space Total	144.00			195.29		116.22	7.88	9.26	3.1491	104.53	0.0297

II.2.3. The building model used for the study of WOA

In order to study the effect of WOA on CO_2 emission, a third building model was designed (figure 14). Its characteristics were the same like that of the laboratory. The main door of the building was located on the north wall while its single window was located on the west wall. The sill height of the window was 0.8m while the window height and width were 1.5m and 4.8m respectively. The zone summary is presented in table 9.



A	B

Fig 14: 3D building designed by DesignBuilder

Tab 7: Zone summary

	Area [m^2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [m^3]	Multipliers	Above Ground Gross Wall Area [m^2]	Underground Gross Wall Area [m^2]	Window Glass Area [m^2]	Opening Area [m^2]	Lighting [W/m^2]	People [m^2 per person]	Plug and Process [W/m^2]
BLOCK1:ZONE 1	25.00	No	Yes	87.50	1.00	70.00	0.00	6.42	6.90	20.00 0 0	9.01	11.770 0
ROOF1:ZONE 1	23.09	No	No	15.40	1.00	8.42	0.00	0.00	0.00			
Total	25.00			87.50		70.00	0.00	6.42	6.90	20.00 0 0	9.01	11.770 0
Conditioned Total	0.00			0.00		0.00	0.00	0.00	0.00			
Unconditioned Total	48.09			102.9 0		78.42	0.00	6.42	6.90	10.39 6 2	17.33	6.1181
Not Part of Total	23.09			15.40		8.42	0.00	0.00	0.00	0.000 0		0.0000

II.3. Numerical tools

II.3.1. Data logger

Fig 15: Vantage Pro Data logger

Tab 8: Characteristics of the weather station Vantage Pro 2

Physical quantity	Function	Instrument	Resolution*	Range	Precision**
Pressure	Barometric pressure -460 - 3650m	Barometer	0.1 hPa	880 - 1080 hPa	1.7 hPa
Temperature	External temperature	Temperature sensor	0.1 °C	-40 °C - +60 °C	0.5 °C
Wind	Direction Wind speed	Wind vane Animometer	1° 0.5 m/s	0° - 360° 1 - 54 m/s	7° 5 %

The data logger device installed in LCTV, and connected to a weather station, is shown in figure *15*. Characteristics of the weather station Vantage Pro 2 is presented on Table *8*. Simulated values were got from energyplus simulations using energyplus weather files for the locality. The weather file was compiled from passed weather data registered in a computer, connected to the data logger device, within the period of 2010 and 2018.

Nowadays, there are several simulation software for building performance analysis. Each software tool of the mentioned energy simulation software tools has certain characteristics, and specific applications (Modelica Association, 2005). Whether for energetic or structural analysis, these programs work as a powerful development and support tool for the design, concept, and execution of a project. With these tools one can determine indoor comfort levels and building energy consumptions, supporting test, and development solutions for better shading, building orientation, glazing areas, and ventilation. This provides a more conscious and passive design, which is crucial for sustainable projects that look toward comfort and energy such as areas with extreme climate conditions, third world countries with low GDP that are not able to facilitate construction technologies, or even large-scale temporary housing for catastrophe victims.

II.3.2. EnergyPlus

Energy Plus is one of the most known energy simulation software tools. The internal elements of the program are shown in Figure *16*. Its development began in 1996, sponsored by the Department of Energy (DOE) from United States of America (USA) *(Willms, 2008)*. The EnergyPlus aims to develop and organize software tools in modules that can easily work together or separately. It is important to outline that in EnergyPlus does not exist a visual interface that allow users to see and concept the building. In this case third-party software tools, i.e., Design Builder need to be used. EnergyPlus has its roots in both the BLAST and DOE–2 programs. BLAST (Building Loads Analysis and System Thermodynamics) and DOE–2 were both developed and released in the late 1970s and early 1980s as energy and load simulation tools. Their intended audience is a design engineer or architect that wishes to size appropriate HVAC equipment, develop retrofit studies for life cycling cost analyses, optimize energy performance, etc.

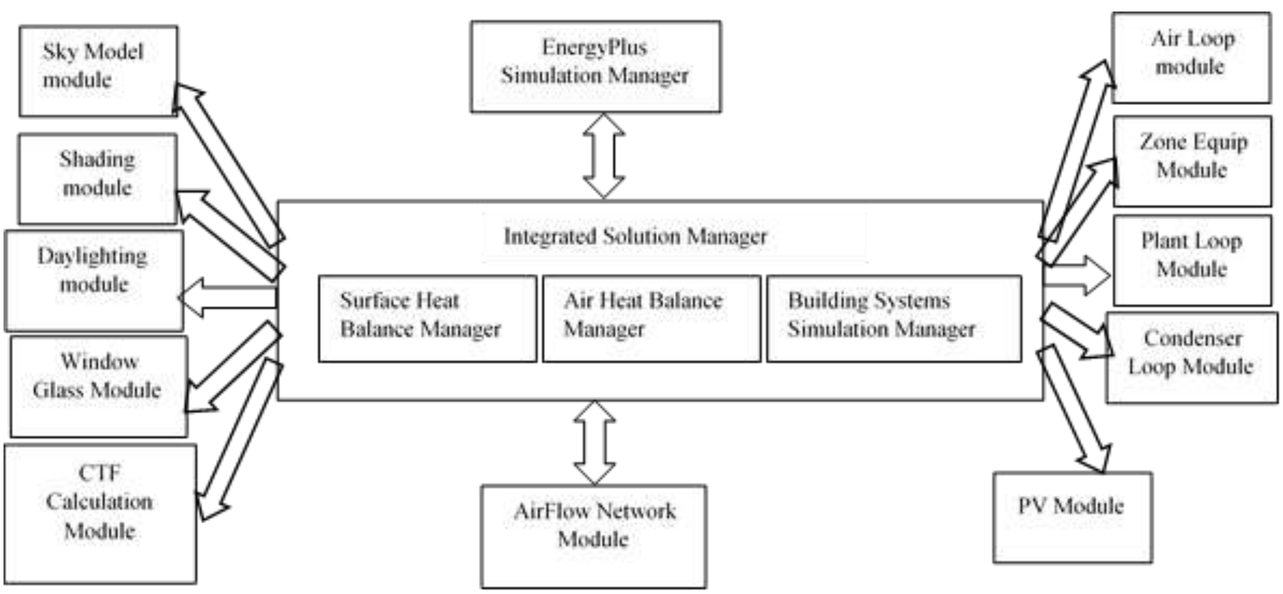


Fig 16: The internal elements of energyplus

Born out of concerns driven by the energy crisis of the early 1970s and recognition that building energy consumption is a major component of the American energy usage statistics, the two programs attempted to solve the same problem from two slightly different perspectives. Both programs had their merits and shortcomings, their supporters and detractors, and solid user bases both nationally and internationally. Like its parent programs, EnergyPlus is an energy analysis and thermal load simulation program. Based on a user's description of a building from the perspective of the building's physical make-up, associated mechanical systems, etc., EnergyPlus will calculate the heating and cooling loads necessary to maintain thermal control setpoints, conditions throughout secondary HVAC system and coil loads, and the energy consumption of primary plant equipment as well as many other simulation details that are necessary to verify that the simulation is performing as the actual building would.

Many of the simulation characteristics have been inherited from the legacy programs of BLAST and DOE–2. (EnergyPlus , 2010) the simulation of a building is divided into two stages (Tanenbaum, 2003):

- Construction of the building;
- Introduction of data, such as environmental aspects, effects of shading, cooling system, internal gains, etc.

Below is list of some of the features of the first release of EnergyPlus. While this list is not exhaustive, it is intended to give the reader an idea of the rigor and applicability of EnergyPlus to various simulation situations.

- Integrated, simultaneous solution where the building response and the primary and secondary systems are tightly coupled (iteration performed when necessary)
- Sub-hourly, user-definable time steps for the interaction between the thermal zones and the environment; variable time steps for interactions between the thermal zones and the HVAC systems (automatically varied to ensure solution stability)
- ASCII text based weather, input, and output files that include hourly or sub-hourly environmental conditions, and standard and user definable reports, respectively
- Heat balance based solution technique for building thermal loads that allows for simultaneous calculation of radiant and convective effects at both in the interior and exterior surface during each time step
- Transient heat conduction through building elements such as walls, roofs, floors, etc. using conduction transfer functions
- Improved ground heat transfer modeling through links to three-dimensional finite difference ground models and simplified analytical techniques

- Combined heat and mass transfer model that accounts for moisture adsorption/desorption either as a layer-by-layer integration into the conduction transfer functions or as an effective moisture penetration depth model (EMPD)
- Thermal comfort models based on activity, inside dry bulb, humidity, etc.
- Anisotropic sky model for improved calculation of diffuse solar on tilted surfaces

II.3.3. Designbuilder

DesignBuilder is a visual modeling tool for overall building performance-simulation software based on the EnergyPlus engine. DesignBuilder has its own modeling window and permits model image visualization. In addition, a geometry model can also be imported from SketchUp or Revit through specific plugins or files. DesignBuilder has a large amount of building model information data. When the building type is selected, the corresponding default settings will be extracted to construct an energy model to allow architects to analyze factors that influence energy consumption such as spatial form, plane layout, and window-to-wall ratio. This software remains under development; two blocks on Parametric Analysis and Optimization have been used for real design.

Fig 17: Logos of designbuilder and energyplus

The Logos of designbuilder and energyplus are presented in figure 17. Designbuilder version5.5.1.015 is a visual modeling tool for overall building performance-simulation software based on the EnergyPlus engine. It permitted us in the realization and visualization of the model image, as well as to study the factors that affects the building carbon dioxide emission in the building. The main input to this software was the weather file compatible with energy plus calculation engine which was constructed using past weather data for the locality. Other input included the building characteristics and the occupancy rate. Heating and cooling systems could be installed and uninstalled as need was found. This software remains under development.

II.4. Methods

II.4.1. Statistical Methods

II.4.1.1. Errors of measurement and the normal distribution function

Here, various means were used to ascertain the validity of the instrument as well as to improve and validate the predictive models. The validation of the numerical tool was based on quantities like the NMBE (equation 6), CV (RMSE) (equation 7), MAPE (equation 8), and statistical diagrams like the frequency chats. Equations 6- 10 depicts the various instrument employed in the process.

$$NMBE = \frac{\sum_{i=1}^{N}(M_i - S_i)}{\sum_{i}^{N} M_i} \tag{6}$$

$$CV(RMSE) = \frac{\sum_{i=1}^{N}\left[\frac{(M_i - S_i)^2}{N_i}\right]}{\frac{1}{N_i}\sum_{i}^{N} M_i} \tag{7}$$

$$MAPE = \frac{1}{N}\sum_{i=1}^{n}\left|\frac{(M_i - S_i)}{M_i}\right| \times\ 100\% \tag{8}$$

Where M_i and S_i are measured and simulated data at instance i respectively while N_i is the count of the number of values used in the calculations. MBE and CV indices were constructed over monthly intervals in order to study monthly variation. The diagonals of the hat matrix are given in equation 9.

$$\mathrm{Hii} = \frac{\partial \hat{y}_i}{\partial y_i} \tag{9}$$

h_{ii}, the i^th^ element on the diagonal of the hat matrix expresses the sensitivity of the prediction $\hat{y}_i$ to any change in variable y_i. The value of hii, for each data point, was used to check on outliers. That is data points that could possibly not be meaningful for used but that possibly could distort information.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad (10)$$

Where μ is the mean and σ is the standard deviation x. the normal distribution function (equation 10) was used to test the binomial nature of the residuals. The studendized residuals is given in equation 11.

$$studentized\ residual\ r_i = \frac{\hat{e}_i}{\hat{\sigma}_e\sqrt{1-h_{ii}}} \quad (11)$$

$\hat{e}_i$ is the "residual," the difference between the predicted and the observed value, $\hat{\sigma}_e$ is the standard deviation observed in the residuals,

II.4.1.2. Scatterplots and correlation coefficient

Scatterplots

The mandatory first step in all data analysis is to make a plot of the data in the most illustrative way possible. A two-dimensional representation of n pairs of measurements (x_i , y_i) made on two random variables x and y, is known as a scatter-plot. The first bivariate scatterplot (Rodgers and Nicewander, 1998) showing a correlation was given by Galton in 1885. Such plots are particularly useful tools in exploratory analysis conveying information about the association between x and y (Weihs, 1993), the dependence of y on x where y is a response variable, the clustering of the points, the presence of outliers, etc. Scatterplots are much more informative (Cook and Weisberg, 1994) than the correlation coefficient. This should be clear (Tomassone et al.,1983) from Figure 1. Each of the four data yields the same standard output from a typical regression program. Scatterplots can also be combined in multiple plots per page to help understanding higher-level structure in data set with more than two variables. Thus, a scatterplot matrix can be a better summary of data than a correlation matrix, since the latter gives only a single number summary of the linear relationship between variables, while each scatterplot gives a visual summary of linearity, nonlinearity, and separated points (Weihs, 1993)

Covariance and correlation

The covariance between two random variables x and y, with a joint normal distribution, is a measure of correlation of the fluctuation of two quantities and is defined as (Asuero et al., 1988) the expected value of the product of the deviations of x and y from their expected values (true or population means). The sample covariance is given in equation (12).

$$cov(x, y) = \frac{1}{n-1}\sum(x_i - \overline{x})(y_i - \overline{y}) \tag{12}$$

It satisfies the so-called Schwartz inequality (equation 13)

$$\text{cov}(x, y) \leq SxSy \tag{13}$$

which implies immediately that $r \leq 1$

The covariance is a measure of the correlation between x and y. If two variables are related in a linear way, then the covariance will be positive or negative depending on whether the relationship has a positive or negative slope. If x and y are independent, i.e., not correlated, the covariance is zero. However, the converse is not necessarily true (Brownlee, 1984), for it is possible to construct examples of highly dependent random variables, often in a nonlinear way, whose covariance (correlation) is zero. Although the covariance is often ignored in introductory textbooks, the variance is the special case of the covariance of a random variable with itself. The square root of the variance is called the standard deviation (denoted by σ for the population and by s for the sample) and is always positive. Covariance have to be taken into account at least in cases where realistic uncertainty budgets have to be calculated or traceability chains have to be built up (Bremser and H¨asselbarth, 1998). Standard addition method, for example, inevitably leads to correlated data. Here, covariances must be taken into account (Salter, 2000). The determination of the boiling point of water from measurements of its vapour pressure constitutes (Levie, 2004) a dramatic example of the need to consider the covariance.

The covariance is often not a useful descriptive measure of association, because its value depends on the scales of measurements for x and y, and then it must be standardized before it can be used as a generally applicable measure of association. By dividing the sample covariance by the product of the sample standard deviation of x and y, S_x and S_y , respectively, we obtain (Asuero et al.,1988) the sample correlation coefficient r_{xy} equation (14). A simpler formula can be used: r_{xy} is the covariance between two standardized variables z_x and z_y , and is independent of the scales chosen

$$r_y = \frac{cov(x,y)}{s_x s_y} = \frac{1}{n-1}\sum\left(\frac{x_i-\overline{x}}{s_x}\right)\left(\frac{y_i-\overline{y}}{s_y}\right)$$

$$= \frac{1}{n-1}\sum z_x z_y \qquad (14)$$

Also we get

$$r_{xy} = \sum\frac{(x_i-\overline{x})(y_i-\overline{y})}{\sqrt{\sum(x_i-\overline{x})^2(y_i-\overline{y})^2}} = \frac{S_{XY}}{\sqrt{S_{XY}S_{XY}}} \qquad (15)$$

The part above the line in this equation is a measure of the degree to which x and y, vary together (using the deviations of each from the mean). The part below the line is a measure of the degree to which x and y varies separately. Eq. (15) describes r_{xy} as the centered and standardized sum of cross product of two variables and allows the direct computational formula for r_{xy}, which automatically furnishes the proper sign.

The assumption $(x_i - \overline{x})(y_i - \overline{y}) \neq 0$eliminates vertical and horizontal lines. Notice that r_{xy} has the same value whether n or n − 1 is chosen as the common divisor for $cov(x, y)$, $S^2{}_X$ and $S^2{}_Y$

II.4.2 CO_2 emission model

The energy-related CO_2 emissions from buildings can be estimated using equation (16):

$$I = \sum_{ij} E_{ij} \times K_j \times \frac{44}{12} \qquad (16)$$

Where I represents the total CO_2 emissions from buildings, i refers to the sources of building energy consumption including transportation, warehousing and postal service, wholesale, retail, catering and accommodation, living consumption and others. j is the fossil fuel, j= coal, liquefied petroleum gas, natural gas, heat and electricity, E is the building energy consumption, and K is the carbon emission coefficient of fossil fuel.

II.4.3. Strategies to reduce the emission of GHG

Over the past two decades, governments and policymakers have been urged to take action to mitigate CO_2 emissions in various sectors (Langevin et al.,2019). This section discusses several strategies to reduce CO_2 emissions in response to concerns on the global warming challenge in the building sector (Figure *18*). These strategies can be applied at various scales towards CO_2 emissions reduction.

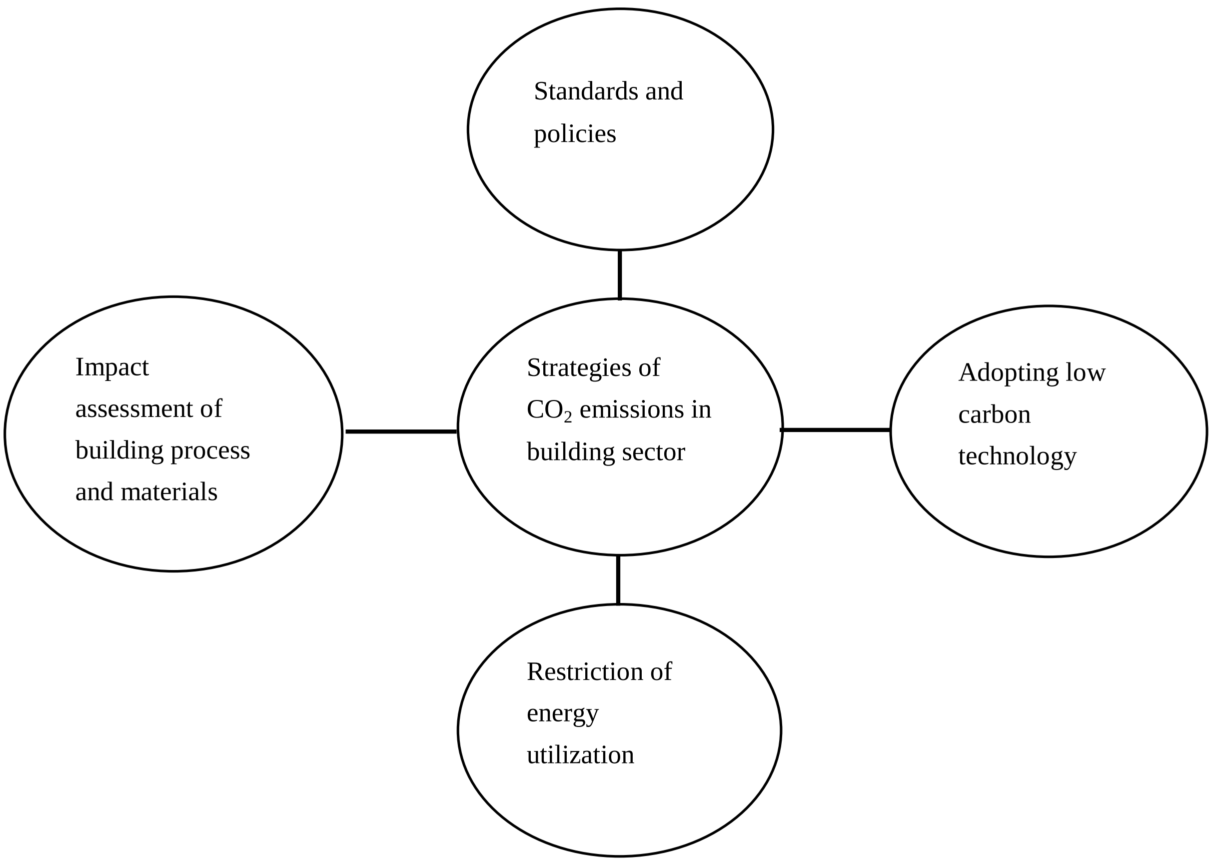


Fig 18: Strategies in reducing CO2 emissions in the building sector. Emissions in the building sector.

Standards and policies

Many sustainable building standards, codes, policies, and guidelines packages have been introduced in many countries across the world, which aim to improve building energy performance and reduce CO_2 emissions. Under the Paris Agreement commitment and the United Nations Sustainable Development Goals, Nationally Determined Contribution (NDC) was set up in 2015 for the decarbonization of the building sector. A total of 184 countries participated in the NDC. Governments have taken initiatives in the decarbonization of the building sector through the establishment of policies and standards. These packages set minimum requirements for energy performance and efficiency in buildings towards zero or low carbon buildings. There are more than 60 countries worldwide that initiated plans to implement these either mandatorily or voluntarily (Abergel et al.,2017).

First, the existence of fiscal policy instruments (environmental tax) asserts that taxes should be leveraged on activities that cause harm to the environment. Based on environmental tax models, African countries have been urged to start national carbon tax systems in readiness for carbon taxing Regimes**.** Low Carbon Building technologies can be classified into three key areas: building materials, renewable energy for buildings and building design. These technologies are relevant for all residential, commercial and industrial buildings. They are relevant for new as well as retrofitted existing buildings (Ahmed et al., 2013).

Adopting Low Carbon Technology

Low carbon technology is one of the technical strategies that can be adopted in buildings to reduce carbon dioxide emissions. Low carbon technology refers to the technology that has a minimal output of GHG emissions into the environment, specifically for CO_2 emissions (Tan et al.,2016). Examples of renewable and sustainable energy technologies are evaporative cooling, passive ventilation and cooling, solar photovoltaic, dehumidification, and energy recovery systems. These technologies have been proven to significantly help to decrease emissions and promote energy savings in buildings. Through low carbon technology, the development of basic strategy requirements of innovation-driven development in the building can also be achieved (IPCC, 2007).

However, the downside of the low carbon technology implementation is it might increase the operation cost of buildings. Therefore, systematic consideration should be addressed carefully to ensure the balance between the reduction of CO_2 emissions and investment of the technology.

Restriction Strategy

Closing down the operation in particular areas and shutting down associated devices is a straightforward approach to minimizing the CO_2 emissions and energy utilization in buildings. The most accessible practice is to keep the doors closed and switching of the lights and electrical appliances of vacant rooms. It is defined as the restriction strategy when this is practiced in public buildings. Most of the public buildings, such as teaching blocks, libraries, and fitness centers, have been grouped into several sections according to the usage rate. In these public buildings, restriction strategy is achievable if unused areas are closed, and users have to gather in certain permitted areas to share the services. Hence, energy consumption is reduced. A study reported the linkage between building occupant rate and energy consumption in their study (Chen et al.,2018). A significant decline in lighting and heating energy consumption per capita with the increase of occupant rate has been displayed.

Nevertheless, when the occupant rate increases, it might lead to the dissatisfaction of occupants. In general, high occupant rates usually reduce air quality, ultimately affecting the operational effectiveness of the occupants. Therefore, the major obstacle of the restriction strategy is energy conservation refuting the occupants' satisfaction.

Impact Assessment of Building Process and Materials

Understanding the entire building process is very important in mitigating CO_2 emissions. These processes include extraction, manufacturing, transportation, construction, maintenance, and disposal. Wide ranges of material are utilized in buildings that use energy and release CO_2 through its life cycle, which is regarded as embodied energy and embodied carbon. As part of mitigation measures, assessment of embodied carbon of building materials is one of the fundamental approaches that can have a positive impact on carbon footprint. The selection of appropriate sustainable building materials can reduce about 30% of embodied CO_2 emissions over a lifespan of the building (González and Navarro, 2006; Chastas et al.,2018).

Through this assessment, it has been reported that reinforced concrete and clay bricks are the most carbon-emitting materials leading to approximately 60% to 70% of the total embodied carbon (Kumanayake et al.,2018; Robati et al.,2019). Detailed inventories on building materials and embodied carbon are presented in Hammond and Jones (Hammond and Jones, 2008). Besides, to reduce CO_2 emissions or meet the emissions targets, sustainable or low carbon materials can be considered in the manufacturing process. Low carbon cement, timber, straw, and compressed Earth, which has lower carbon footprints are some excellent alternatives. II.3.4. Thermal comfort models

The predicted mean vote (PMV)

In this study winter and summer clothes had values of 1clo and 0.5clo respectively. The PMV index suggested by Fanger predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale. Subjects exposed to the climate chambers are asked to give their opinions according to the ASHRAE seven-point scale of thermal sensation. A mean vote (MV) is obtained for a given condition by finding the mean value of the feeling given by all the subjects for that condition. Fanger related PMV to the imbalance between the actual heat flow from a human body in a given environment and the heat flow required for optimum comfort at a specified activity is stated in equation (17) (Lin and Deng, 2008; Fanger, 1972):

$$PMV = [0.303 \exp(-0.036M) + 0.028]L = \alpha L \quad (17)$$

Where L is the thermal load on the body, defined as the difference between internal heat production and heat loss to the environment for a person hypothetically kept at comfort values of Tsk and Ersw at the activity level, and the sensitivity coefficient. The Institute for Environmental Research of the State University of Kansas, under ASHRAE contract, has conducted extensive research on the subject of thermal comfort in sedentary regime. The purpose of this investigation was to obtain a model to express the PMV in terms of parameters easily sampled in an environment. The results have yielded to equation 18. (Fundamentals, 1993)

$$PMV = aT + bP_V - c \quad (18)$$

Where P_v is the pressure of water vapour in ambient air and T the temperature. α, b and c are the coefficients for indoor environments, taking into account the exposure time and sex. Coefficients a, b and c are given in Table *11*.

In some studies, the thermal conditions were chosen, and participants recorded how hot or cold they felt, using the seven point ASHRAE thermal sensation scale (table *12*) ranging from cold (-3) to hot (+3) with neutral (0) in the middle as follows: (i) 1: slightly warm (+) or cool (-); (ii) 2: warm

(+) or cool (-); (iii) 3: hot (+) or cold (-); (iv) 0: neutral (neither cool nor warm) (Han et al., 2007). These conditions were assumed for a relative humidity of 50%, a mean relative velocity lower than 0.15 m/s, a mean radiant temperature equal to air temperature and a metabolic rate of 1.2 met.

Clothing insulation was defined as 0.9clo in winter and 0.5clo in summer. In other studies, participants controlled the thermal environment themselves, adjusting the temperature until they felt thermally 'neutral' (KE, 2003).

Tab 9: Values of the coefficients a, b and c as a function of spent time and the sex of the subject

Time/SEX	A	b	C
1 h/man	*0.220*	0.233	6.673
Woman	0.272	0.248	7.245
Both	0.245	0.248	6.475
2 h/man	0.221	0.270	6.024
Woman	0.283	0.210	7.694
Both	0.252	0.240	6.859
3 h/man	*0.212*	0.293	5.949
Woman	0.275	0.255	8.620
Both	0.243	0.278	8.802

Three different levels of acceptability (category A for 90%, B for 80% and C for 70%) are defined around the temperature of neutrality and are introduced in the standards ISO 7730 and ASHRAE Standard 55 (European, 2007). The upper/lower temperature bandwidth (Tal) of the comfort zone is shown in Table *13* while the indoor thermal classification is given in table *14*.

Tab 10: Occupant evaluated parameters and rating scale

Rating scale value	Thermal comfort evaluation	Thermal comfort satisfaction
+3	Hot	Very satisfied
+2	warm	Satisfied
+1	Slightly warm	Moderately satisfied
0	Neutral	-
-1	Slightly cool	Moderately unsatisfied
-2	Cool	Unsatisfied
-3	Cold	Very unsatisfied

Tab 11: The comfort zone upper/lower temperature bandwidth for each acceptability limit

Acceptability (%)	Upper/lower temperature bandwidth	source
90	2.5	ASHRAE Standard 55-2013
80	3.5	ASHRAE Standard 55-2013
70	4.0	European Standard 15251

Il.5 Data acquisition and analysis

In order to validate the energy plus calculation software, measured and simulated values of internal temperatures were compared and errors calculated. Without conditioning the residential building model, the temperature variation of the hottest and the coldest months were traced and compared with the comfort temperature band of the locality. The heating and the cooling systems were then installed at separate instances of time. The heating set point was at 19 while the cooling set point was at 24. In each case the simulation was carried out and the amount of CO_2 produced for the various months were evaluated. The evolution of CO_2 with temperature was then evaluated in both cases. The influence of building orientation, building material, insulation, window opening area and wall thickness on CO_2 emission was then evaluated.

Tab 12: Indoor temperature classification

Range	Description	Notation
<=5	*Extremely cold*	EC
5-10	Very cold	VC
10-15	Cold	CD
15-20	Cool	CL
20-25	Temperate	TE
25-30	Warm	WM
30-35	Hot	HT
35-40	*Very Hot*	VHT
>40	Extremely Hot	EHT

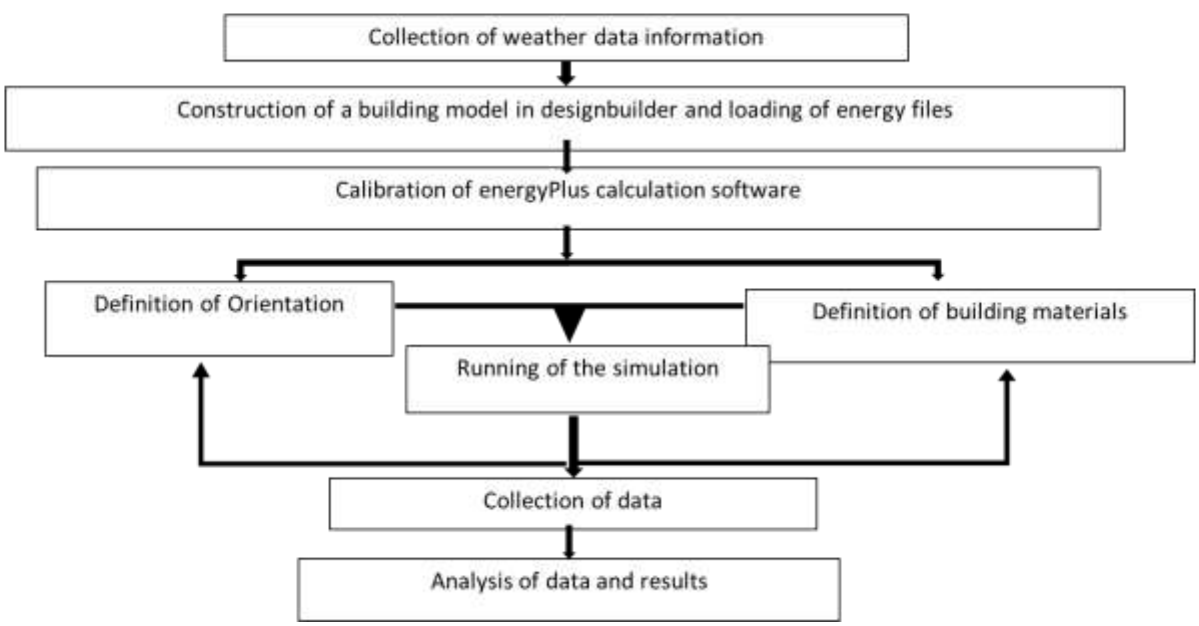


Fig 19: Research protocol

For simplicity of study, a third model (consisting of a single room) was used to study the influence of window opening area on CO_2 emission. In order for that to be accomplished, the model was designed without a door on it. This was to do away with the influence of the door in the investigations carried. One of the walls (north, east, south and west walls) was in turn chosen and a single window was installed on it. The window opening area was then varied from 0 to 15.87m^2 and data was collected on discomfort hour, solar intake, external infiltration and sensible heat addition. Data collected for solar intake, infiltration, and sensible heat were later on correlated with discomfort hours and their influence on CO_2 production was checked. The prediction models proposed in the study were first generated in an excel program. These models were then improved upon through when outliers were sorted out. The main criteria for the validation of these models were based on coefficient of correlation and on the distribution of points around the line of the prediction model. The research protocol that was used is given in figure 19.

Conclusion

It was the central goal of this section to present the methods and material used in the study. The buildings models for the study was presented together with their zone summaries. Statistical methods are for the validation of the calculation engine while the other models like the thermal comfort and the Carbon dioxide models are used by the engine in order generate results linked to thermal comfort and carbon dioxide emission.

Chapter III: Results and Discussion

Introduction

Site data are presented in this section. Results of the calibration procedure are also presented. These results are then followed with results of the evaluation of CO_2 emitted. The quantity of CO_2 emitted due to low temperatures and high temperatures are the evaluation metrics. The results of the evolution of CO_2 with temperature are also presented. Results of the strategies for the reduction of the CO_2 due to operational energy used are also presented.

III.1. study area

The World Bank (2007) classified Cameroon among one of the middle-low and low income countries for which all explanatory factors considered play a role; especially income and population but also energy efficiency, the percentage of industrial activity and urbanization.

Site data

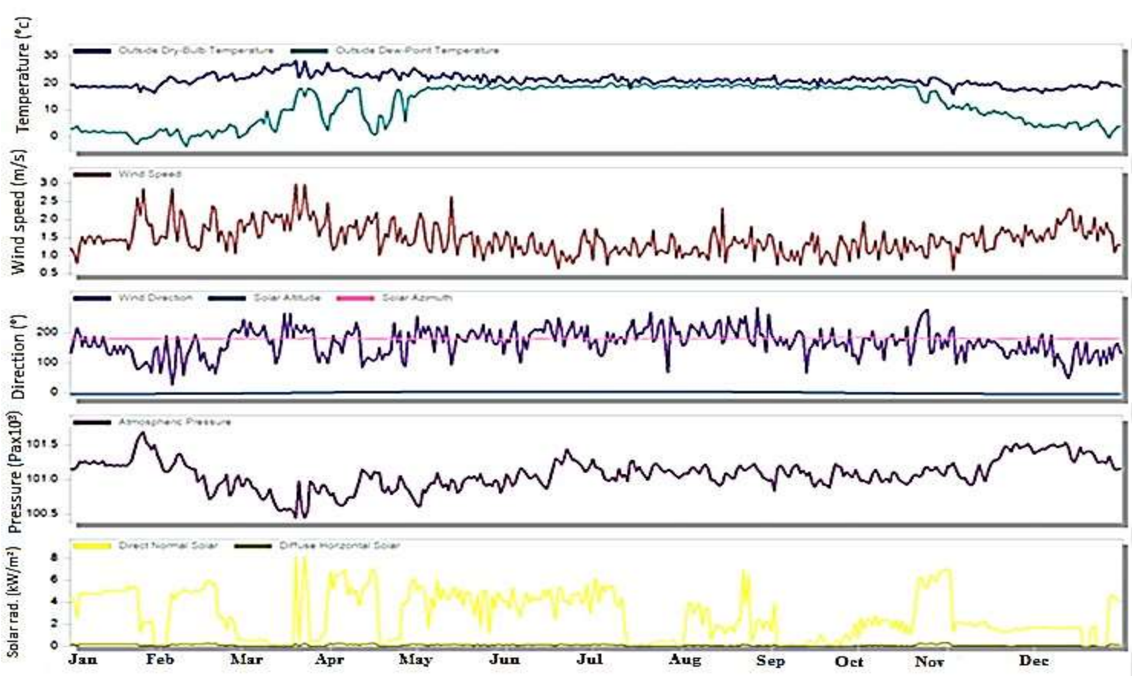


Fig 20: Data of the study site

The annual average outside dry bulb temperature of the site is 21.15°C. Quantities like dew point, direct normal solar, diffuse horizontal solar, wind speed and atmospheric pressure have annual average values of 12.19°C, 1031.75kWh, 36.38 kWh, 1.467603 m/s, 101080.9Pa, respectively. These quantities are presented in figure *20*. Cameroon's average solar irradiation is estimated at 5.8 kWh/day/m2 in the northern part of the country and 4.9 kWh/day/m2 in the south of the country. The average wind speed in Cameroon is estimated at about 2 to 4 m per second, at a height of 100 m (RECP, 2018). Unfortunately, the promotion of solar and wind energy remains less effective in Cameroon, because of technological and financial barriers related to their implementation (Engo, 2019a). Over the 2009–2010 and 2013–2014 periods, the penetration of renewable energies contributed to increasing the carbon intensity by 1.96% and 8.51%, respectively. These increases are attributable to the increased consumption of biofuels and waste. Hydropower and biofuels are the most currently exploited sources of renewable energy in Cameroon. Biofuels often contribute to increasing the country's carbon intensity because of their intense consumption during periods when hydropower production is less efficient.

III.2. Calibration of Tools

It has been the goal in this research to study and predict how climate change affects building designs. Among the numerical tools that exists, we chose to use energy plus. This section is then dedicated on calibrating this tool in order to test its accuracy in prediction. The validation of the numerical tool was based on quantities like the CV (RMSE), MAPE, NMBE and statistical diagrams like the frequency chats.

In Figure *21*, that follows, are presented measured and simulated values of internal temperature of the laboratory considered. The measurement was done for the month of March. A CV (RMSE) of 11% and an NMBE of 2% was obtained. An MAPE of 9.2% was also achieved. ASHRAE guideline 14 report and FEMP (Federal Energy Management program) report (Ruiz and Bandera, 2017) give acceptable monthly criteria of NMBE less than ±5% and a CV (RMSE) index less than ±15%. MAPE (mean absolute percentage error) obtained in this study is within an interval of high accurate forecasting (Lewis, 1982). It is the most useful measure to compare the accuracy of forecasts between different items or products since it measures relative performance (Makridakis et al.,1998).

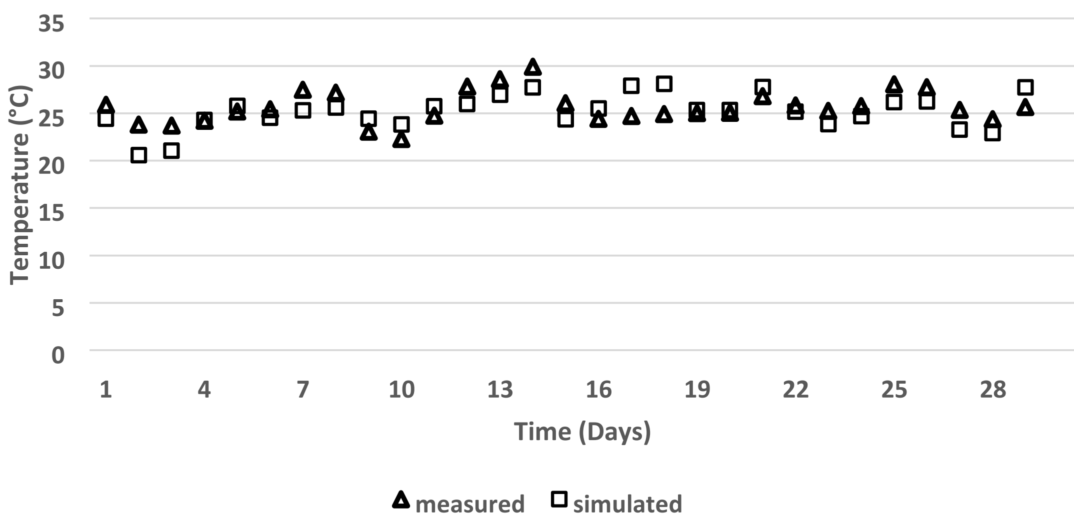


Fig 21: Variation of simulated and measured internal temperature with time

The plot of the residuals and their frequencies of occurrence are presented in Figure *22*. The normal density function has been superimposed with plotted points. The mean of the residuals is 0.25. 67.6% of the residuals are within one standard deviations of the mean, (above and below), which proves the distribution is normal according to Chebyshev's theorem.

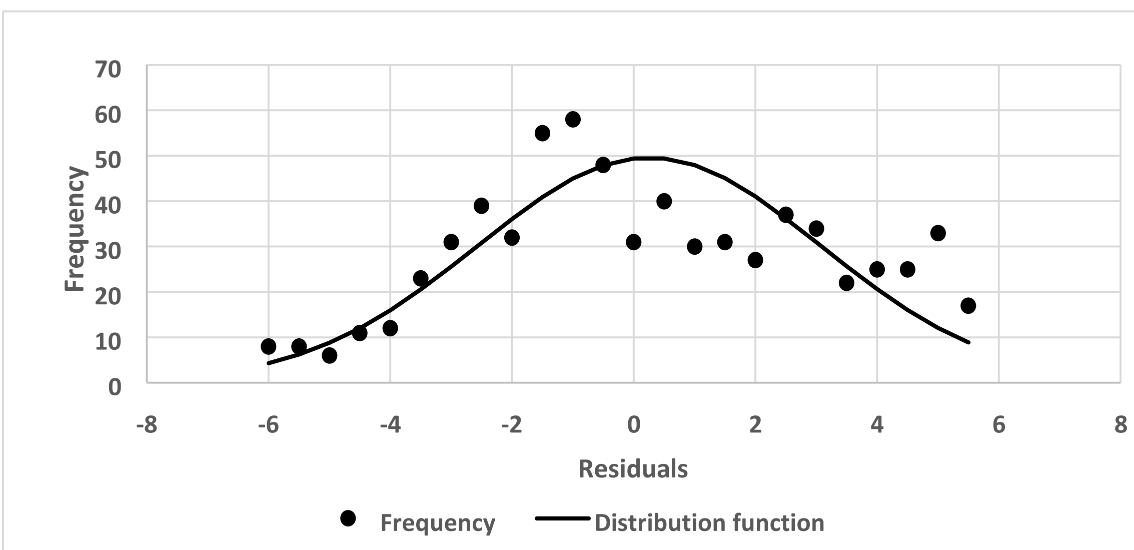


Fig 22: Plot of the residuals and its frequency of occurrence

A clearly S-shaped curve in *Figure 23* further suggest that the distribution of residuals is bimodal.

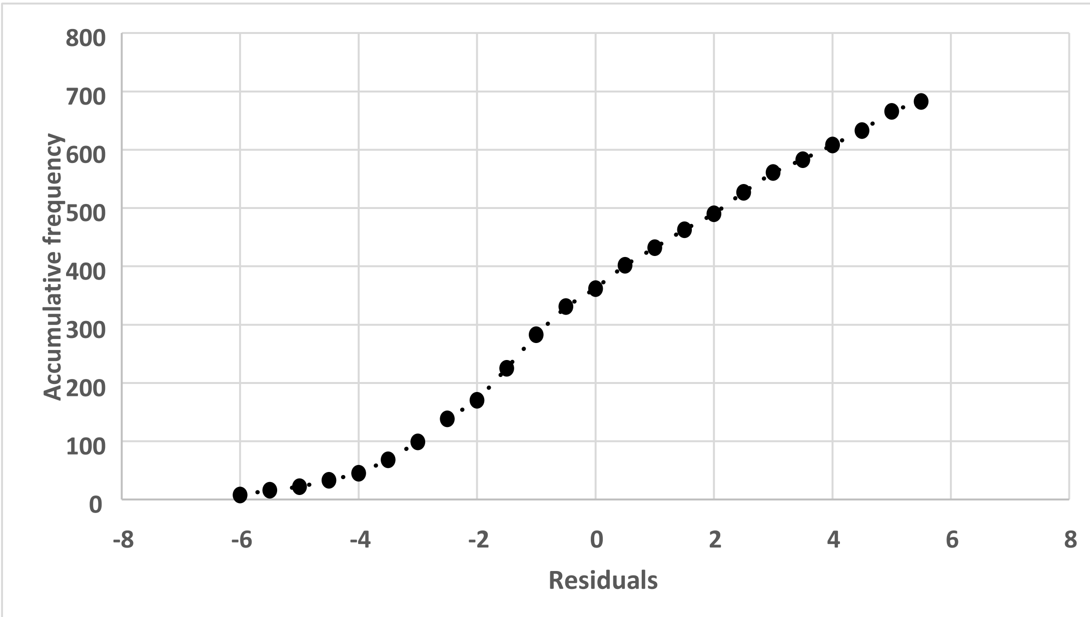


Fig 23: Accumulative frequency plot

Calibration was conducted in order to test the numerical tool fitness to do the task described in this piece of work. The MBE index however has a drawback of cancellation making it possible for the magnitude of seasonal errors to be under-reported. Monthly intervals of MBE index can then be instrumental in the case the analyst focuses on instances of under or over prediction. MAPE and the accumulated frequency distribution curve however indicate that the numerical tool is good for forecasting and can produce reliable distributions.

III.3. Referential building

In this study, especially this section, two cases are considered. The hot moments and the cold moments are taken into consideration in order to better understand the present and the future emission trend. This is done through evaluation of the amount of CO_2 emitted in the building, followed by a study of its evolution. ‘The hot moment’ is considered here as the period when the temperature of the environment is above 24°C, the upper limit for temperature band considered in this study, while 'the cold moment' is considered as the period when the temperature of the environment is below 19°C, the lower limit of the temperature band considered in the present study.

III.3.1. Comfort band for the locality of study

The first and famous work done before the installation of heating and cooling systems was the determination of the temperature of neutrality of the locality of study. In figure 24 are presented the variation of the operative temperature with the PMV values observed in the building. The PMV values are negative. This is a clear indication that most temperature values are below the comfort temperature value, and that the environment under study is generally cold. The PMV values increases with an increase in the operative temperatures. The linear relation linking these two quantities proves that more than 90% of the variation in PMV is explained by temperature variations. The neutrality temperature is 21.5°C, giving a comfort temperature band of 19-24°C for 90% acceptable limit.

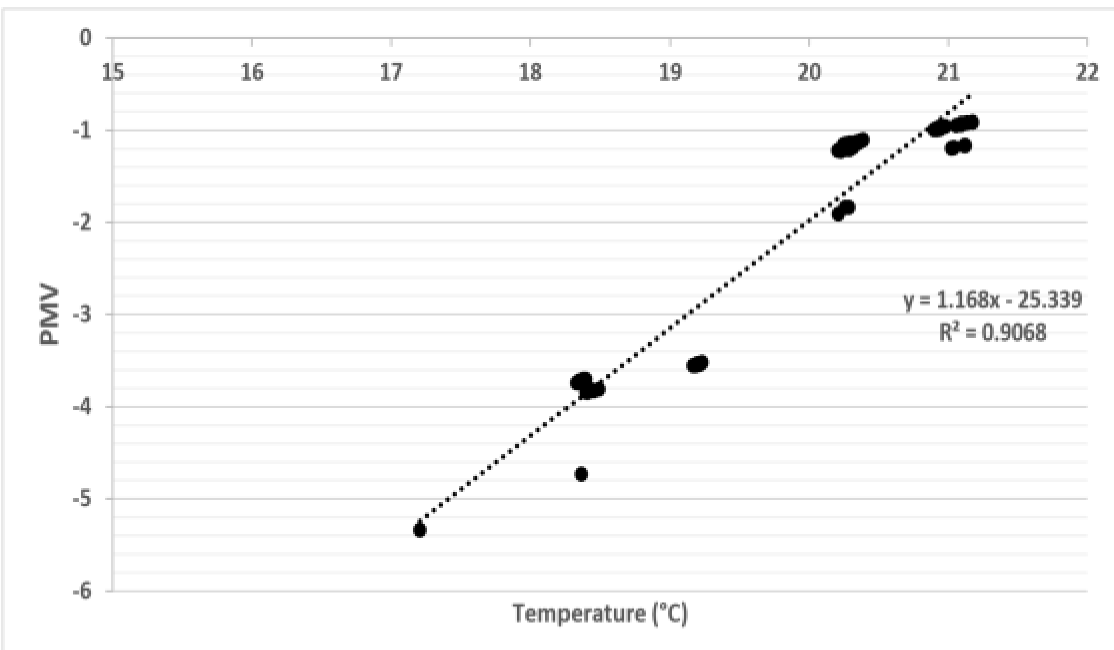


Fig 24: Neutral temperature parametric curve

III.3.2. Evaluation of CO_2 emitted

CO_2 emission emerging from the building is studied by installing cooling and heating devices one after the other. Though an annual simulation is made, there was no ignorance of the fact that within the year some periods are hotter than the others.

Hot and cold moments

The operative temperature of one of the hottest days of the year and one of the coldest day of the year, together with the comfort band is shown in figure *25*.

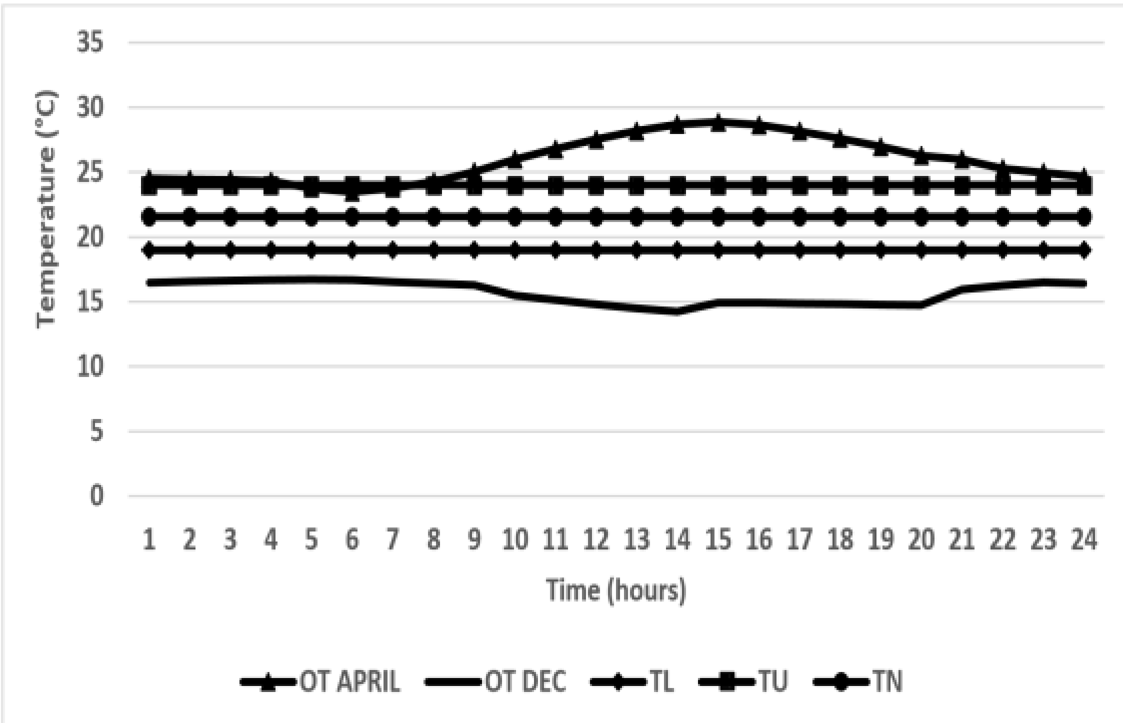


Fig 25: A hot and a cold day of the year behaviour around the comfort temperature band

TN is the temperature of neutrality while TL and TU are the lower and the upper limits of the comfort temperature band. Most of the temperatures are out of the temperature band and can be brought back by either cooling or heating the building. The use of cooling and heating systems will lead to the release of greenhouse gasses especially CO_2.

Quantity of CO_2 emitted due to low temperatures

Low temperatures demands heating. 325.8282kg of CO_2 was emitted throughout the whole year. More than 90% of this emission was done in the month of January, November and December. Emissions from the month of April to the month of October were so minimal. Temperatures within those months were within the comfort band and thus little heating was needed, leading to less emission during those months. The variation in CO_2 emission, due to low temperatures, within the year is presented in Figure *26*. Emission from cooling systems was also studied.

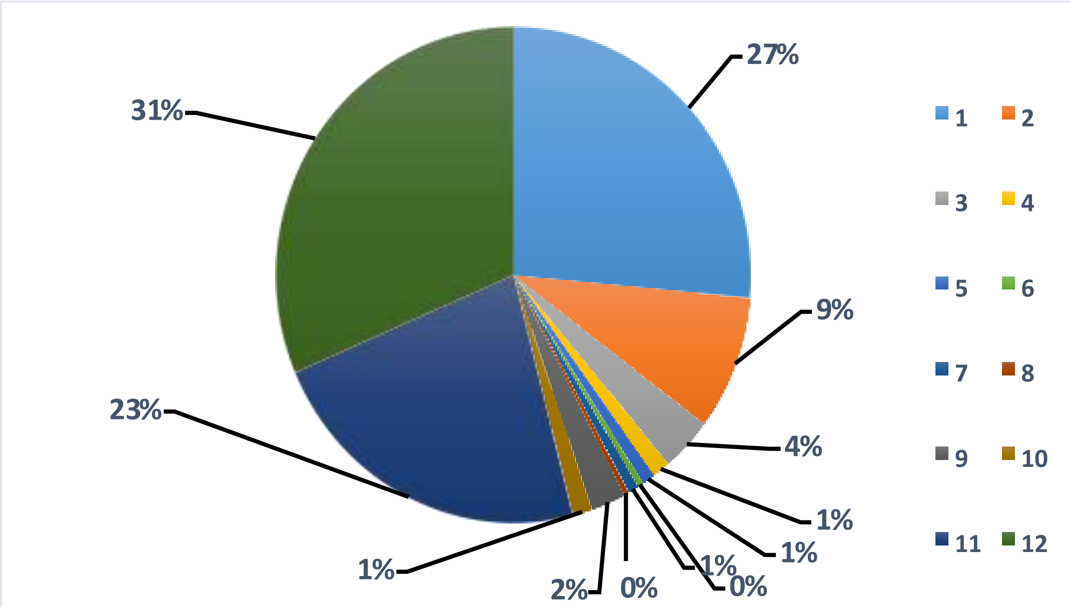


Fig 26: Monthly values of CO2 emission from the operation of heating systems

The quantity of CO_2 emitted due to high temperatures

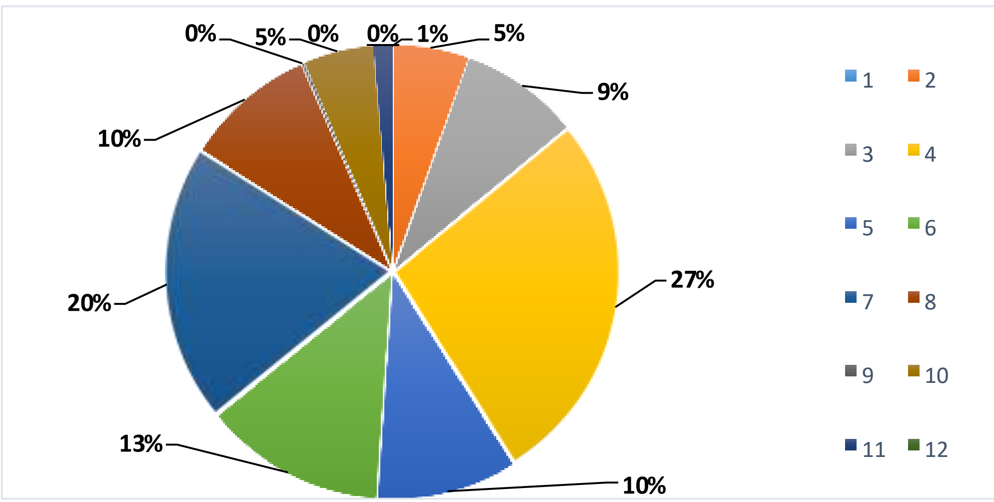


Fig 27: Monthly values of CO2 emitted from the operation of cooling systems

Within the year the emission of CO_2 due to cooling is presented in Figure *27*. There was no emission in the month of January, and December. That of September is just the same as for

January and December. Consequently, there was no need for cooling systems during those months.

The total CO_2 emitted due to cooling for the year was 17.48511kg. The emission peak was in the month of April. It was then necessary for the study to be made on how temperature variations affect the quantity of emitted CO_2 in the two cases, so as to be able to predict what the future emission trend may look like other factors kept constant.

III.3.3. Evolution of CO_2 with temperature

Climate change brings about increasing global average temperature. In Figure *28* is presented the linear relationship between the monthly average temperatures and the monthly CO_2 emissions. This emission originated from cooling systems. CO_2 emission was seen to increase with an increase in average temperatures. 90% of the emission in CO_2 was explained by the rise in temperature.

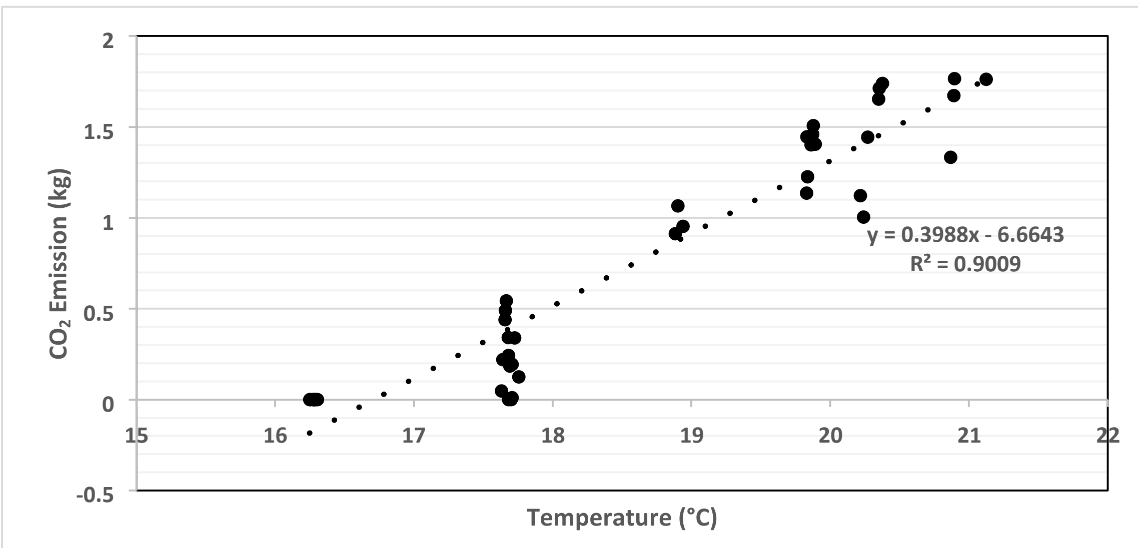


Fig 28: Variation of CO2 emitted from cooling systems with operative temperature

On the contrary, it was noticed that increasing monthly average temperatures led to a reduction in the quantity of CO_2 emission that originated from heating systems. A polynomial of the fourth order was used to predict this (Figure *29*).

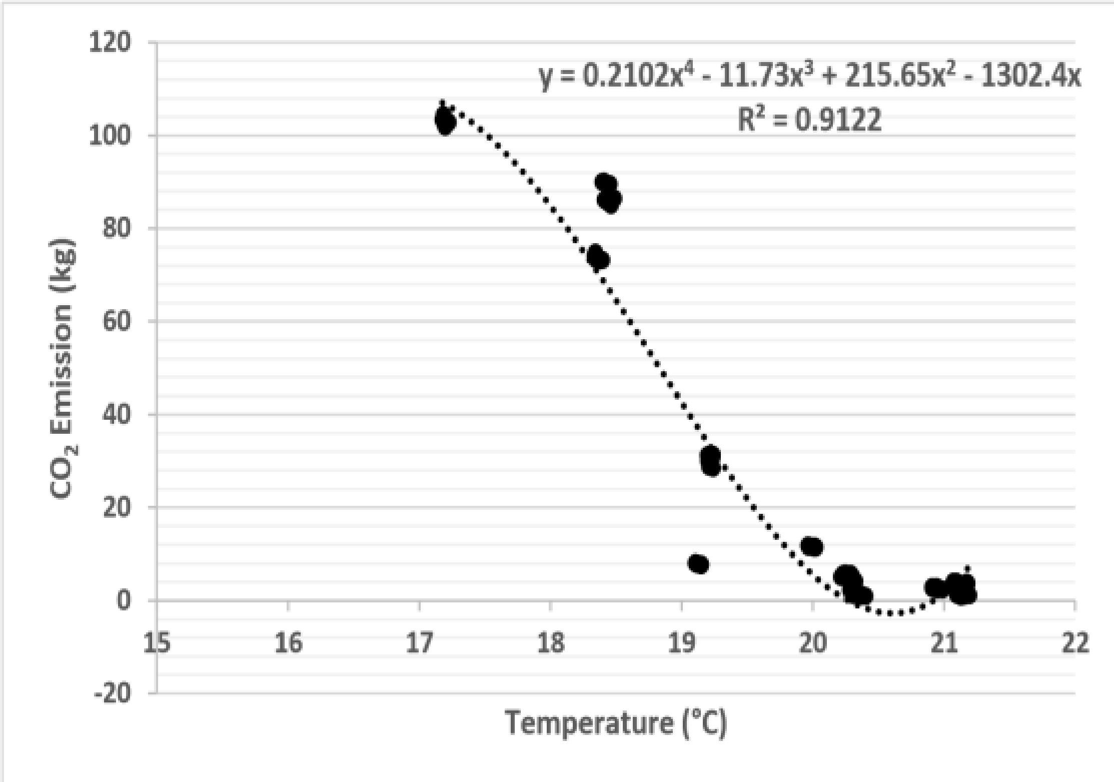


Fig 29: Variation of CO2 emitted from heating systems with operative temperature

Considering that lighting, water heating and other household appliances are insensitive to global warming, researching the climate change impact on heating/cooling energy use and carbon emission is important for the development of proper adaptation pathways for residential houses (Song and Ye, 2017). Emission studied here was due to the use of cooling and heating systems installed in the building considered. Emission from heating system was much indicating that much energy was used during heating than during cooling. The results however showed that there will be a reduction of CO_2 emitted from heating systems installed in the house as average temperature increases. There will also be an increase in the quantity of CO_2 emitted from cooling systems as the average temperature increases. Dino and Akgül (2019) found that overheating will be experienced in the future, which will have a strong effect on cooling energy use and/or occupant comfort. There will surely be a shift in the future from heating to cooling energy needs. Studies have shown that the global temperature is going to increase on an average temperature of 2–5.6 °C by 2100 (IEA, 2017), which would make life difficult on our planet. There will therefore be an increase in emission due to cooling energy. On the other hand heating will reduce leading to a reduction in CO_2 produce by this effect. To combat this global warming, humanity decided to keep the temperature below 2 degrees (UNFCCC, 2015), and the achievement of this goal requires a significant reduction in the CO_2 content in the atmosphere.

To effectively combat global warming and above all to maintain temperatures below 2°, mitigation of greenhouse gas (GHG) emissions is required.

III.3.4. Reduction of emitted CO_2

Reduction of CO_2 emission was also one of the main objective of the present study. Reduction strategies were focused around construction materials, the choice of insulating material, the building orientation, the wall thickness and on window opening area.

Contribution of direction

The building was orientated in eight different directions. Emissions from cooling systems are presented in figure *30* while emissions from the heating systems are presented in figure *31*. It resulted that the direction that minimized CO_2 emission during heating and cooling was the southeast (the main entrance facing the southeast direction). There was therefore less fluctuation in this direction than in the other directions. There was a reduction in emission from cooling systems of 35.3% when the building was rotated from the northwest direction to the southeast direction. On the other case rotating the building from the northwest direction to the southeast direction leads to a reduction of 3.3% in CO_2 emitted from heating systems.

The difference in percentage reduction in emission generated by rotating the building from the worst direction to the best direction between cooling and heating moments is high. Direction therefore plays a vital role during cooling compared to heating. The northeast, northwest and the north are therefore presented as the worst directions in the case of cooling while the southwest, west and northwest are presented as the worst cases in the case of heating. The northwest thus appeared as the worst directions in the two cases. For the rest of the study, all comparison in emission are made to a building oriented in the northwest direction. It is good to note that none of the directions has maintained its position in any of the cases except the southeast direction.

It was observed that CO_2 emission was minimized during cooling and heating when the building was oriented towards the southeast direction. No other direction was seen to maintain its position in the two cases. A clear indication that if not for the southeast direction then with time the building orientation would need to be changed. Many research works reveal that buildings will suffer from a heating effect in the coming century. Thus cooling will replace heating. CO_2 emission from cooling will therefore surpasses that from heating. Therefore, the SE orientation saves both the present and the future scenarios.

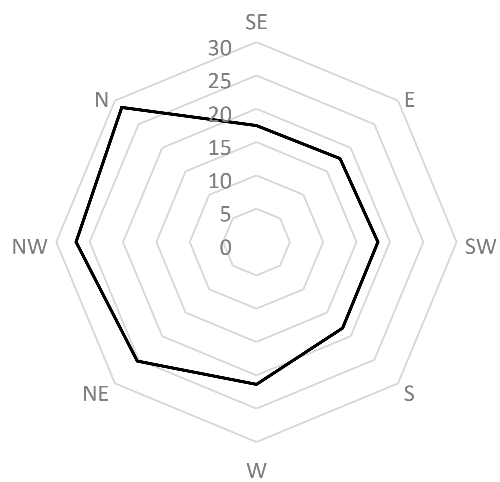


Fig 30: CO2 emitted from cooling systems when the building is oriented in different directions

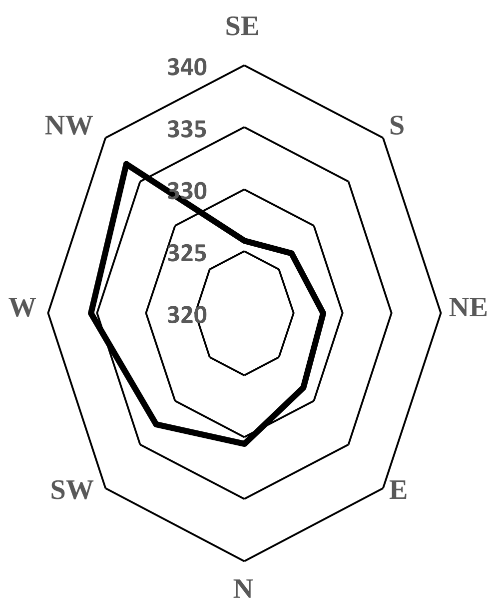


Fig 31: CO2 emitted from heating systems when the building is oriented in different directions

Building material and CO_2 emission

In this section, building materials used in the area were studied. In Figure *32* emission from cooling systems is presented and in Figure *33* emission from the heating system. Hollow concrete block was seen to emit more CO_2 during cooling than others. In the heating case it was compressed earth blocks that emitted more than the others. In the heating and cooling cases sundry earth brick was seen to emit less when compared to others. It was then clear that sundry earth block limited temperature fluctuations in the building. A study carried out in Maroua, one of cities of Cameroon, on three building materials shows that earth block houses are the best as far as maintaining thermal comfort is concerned (Cyrille et al.,2017)**.**

Results of the present study indicate that the use of the best block lead to a reduction of 9% during cooling hours and 3.2% during heating moments. Preferring hollow concrete bricks to sundry earth bricks would lead to a 9% increase in CO_2 emission during cooling moments. Hashemi et al. (2015) in their study of low income tropical houses found that bare hollow concrete walls provide the worst thermal comfort conditions compared with traditional and other common walling materials. On the other hand, a choice of compressed earth bricks over sundry earth bricks would lead to an increase of only 0.7% in CO_2 emitted during heating moments.

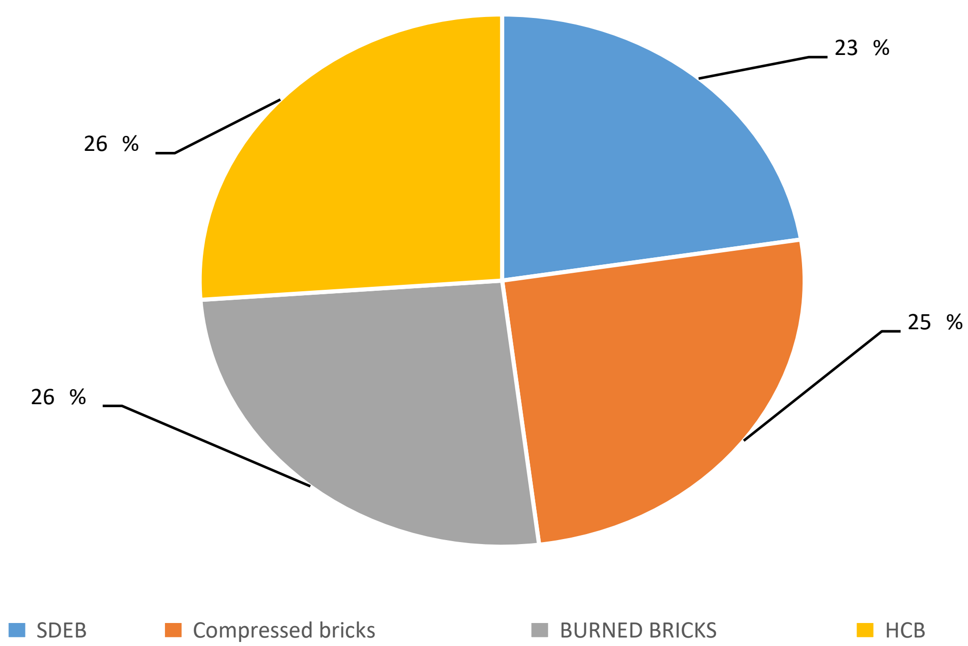


Fig 32: CO2 emitted from cooling systems when different building materials are used

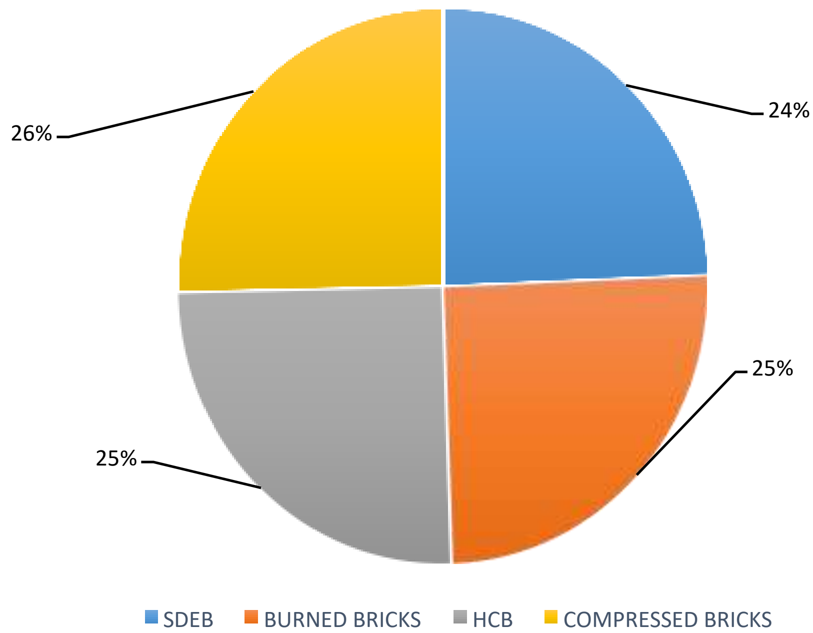


Fig 33: CO2 emitted from heating systems when different building materials are used

The main building materials used in the study area were sundry earth bricks, burned bricks, compressed bricks and hollow concrete bricks. Among those materials sundry earth bricks emerged to be the best choice within the two cases: heating and cooling. Abanda et al. (2014) in a study on embodied carbon emitted from houses built with mud bricks and cement blocks found that mud bricks emit less than cement block. Compressed brick which was the worst building material during heating moment turned out to be the second best during cooling moments. This indicates directly that if not for sundry earth brick then none of the bricks would maintain its position in the two cases. This therefore shows that buildings that are not built with sundry bricks materials may not be able to respond positively to both the present and future climate. This will then put pressure on building designers who work to reduce the effect buildings exert on the environment.

Insulating materials

In order to reduce the environmental impact of buildings, one approach is to reduce fluxes. From a thermal point of view, this can be achieved by increasing insulation, leading to very low or zero energy buildings. Considering the building oriented in the northwest direction as mentioned above, it was seen from this study that the application of an insulating material on the external wall led to an emission reduction of 7.1% in the case of heating and 24.3% in the case of cooling. Zahra and

Amanda (2016) also found a reduction of CO_2 emission with insulation retrofit for large and small office buildings. Emmanuel and Baker (2012) also did studies on Carbon Management in the Built Environment in cool/temperate climates and found that heat losses can be prevented by adding thermal barriers (insulation) to roof, walls and/or floors of buildings. The insulators used in this present study had their origins from biomass. In the figures below the various insulators and their emission in the two cases are presented. In the case of cooling (Figure *34*), results showed that if wood wool was replaced by wood cellulose as an insulating material then there would had been a decrease of 2.4% in CO_2 emission. On the other hand, if during heating moment there happened to have been any replacement of wood cellulose with wood wool then there would had been a decrease of 1.3% in CO_2 emission (Figure *35*). Uniben et al. (2014) found a reduction of about 6–7% in primary energy use and 6–8% in CO_2 emission when the insulation material in the reference buildings was changed from rock wool to cellulose fiber in the optimum versions.

The insulator that emits less during cooling was seen doing the contrary during heating. Wood cellulose emitted less during cooling and more during heating. This signified that wood cellulose minimized the temperature inside the building than other insulators. On the other hand, wood wool emitted more than others during cooling and less than others during heating. It therefore did the contrary to wood cellulose.

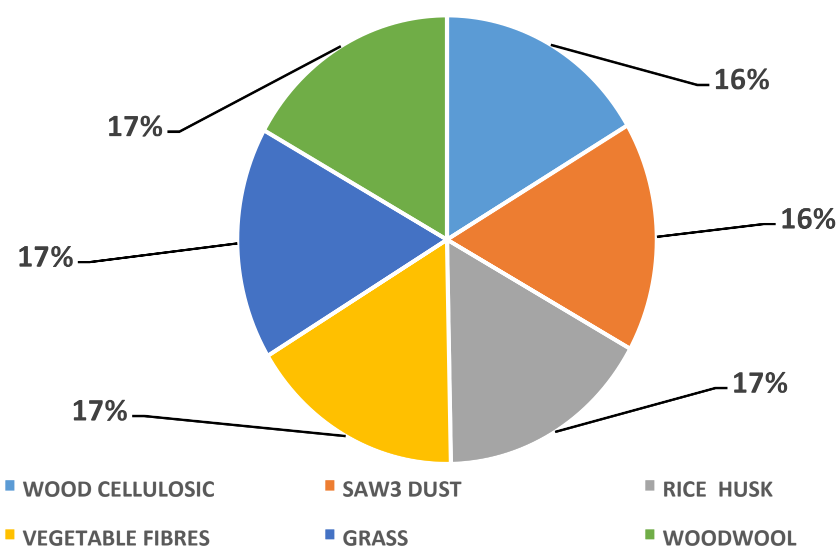


Fig 34: CO2 emitted from cooling systems when different insulating materials are used

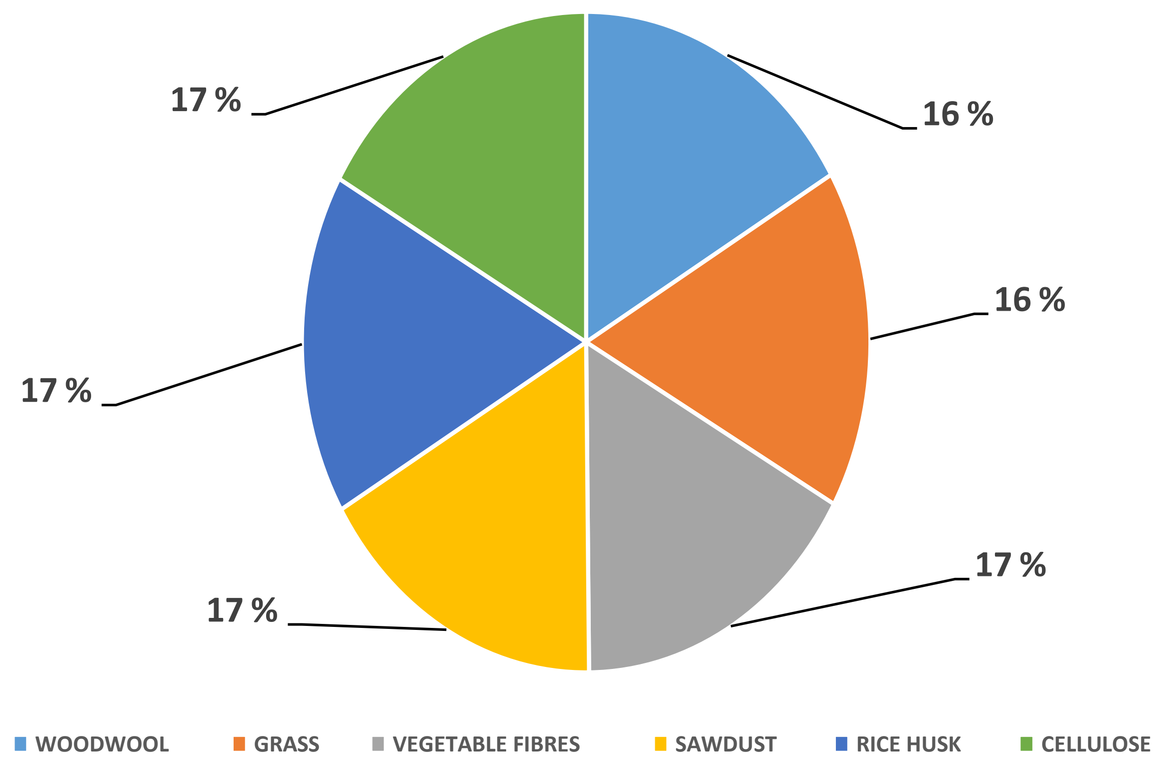


Fig 35: CO2 emitted from heating systems when different insulating materials are used

None of the insulators was seen to be stable in both studied cases. The best insulator during heating moments was seen as the worst during cooling moments. The percentage of emitted CO_2 was 5% and 95% for cooling and heating respectively. Wood wool was seen to reduce CO_2 emission originating from heating system better than other materials used in this study. For the future climate wood cellulose would be preferable.

Window opening area

The effect of window opening area on CO_2 emission was studied by first of all studying the effect discomfort hour has on CO_2 emission. The effect of window opening area on discomfort hours was then studied. From Figure *36*, emission in CO_2 is seen to increase with an increase in hours of discomfort. Emission in CO_2 is seen to be explained by 86% change in discomfort hours.

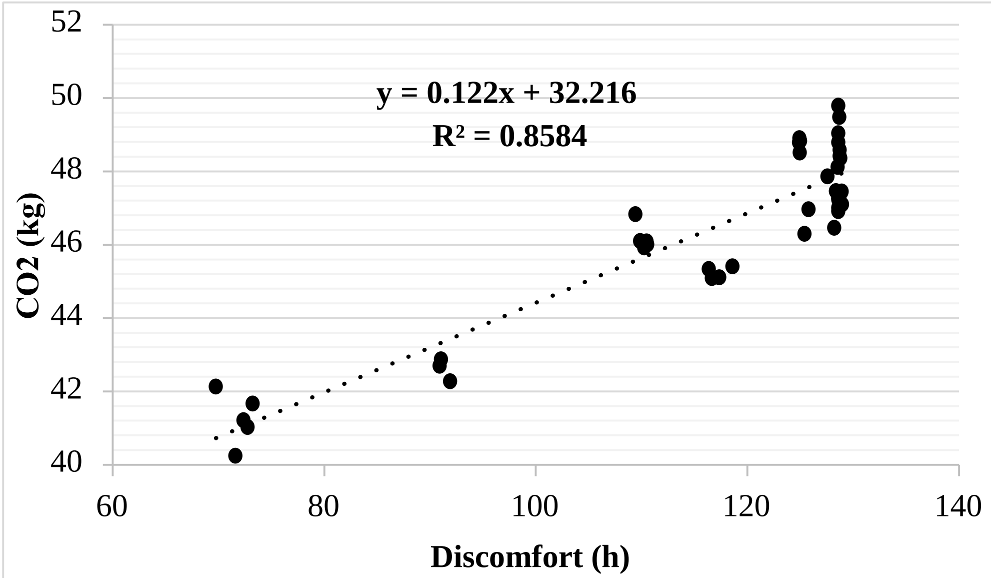


Fig 36: Variation of CO2 emission with discomfort hours

In the study a linear relationship was obtained between CO_2 emission and solar intake (Figure *37*). Results show that an increase in solar intake reduces the production of CO_2 in the building. 99% of a decrease in CO_2 emission is seen to be caused by an increase in solar intake.

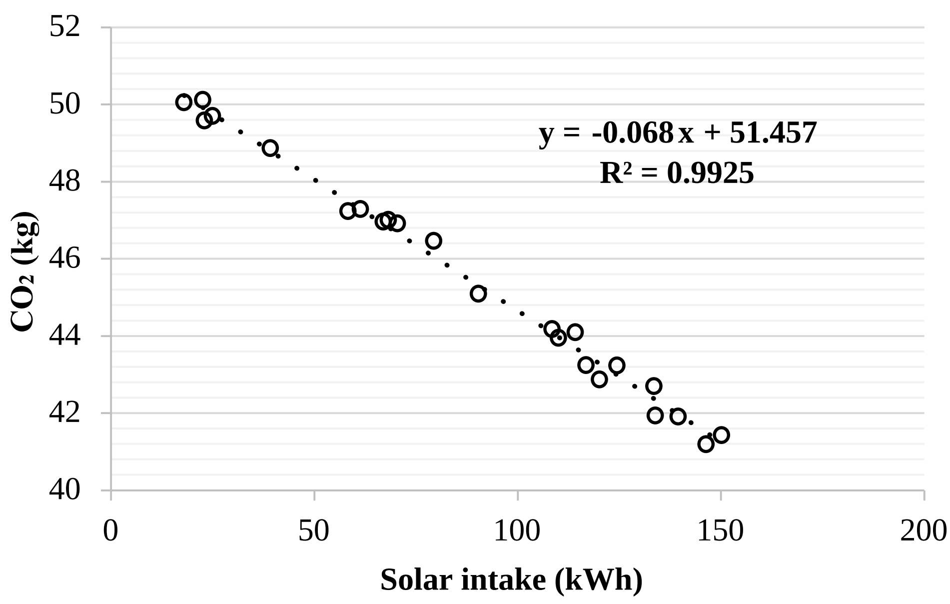


Fig 37: Variation of CO2 emission with solar intake

Effect of window opening area on the number of discomfort hours, solar intake and sensible heat addition

This section presents the results of the variation of window opening area with discomfort hours, solar intake and sensible heat addition.

An increase in the window opening area was seen to reduce the number of discomfort hours and infiltration (figure 38 (a) and (b)). On the other hand, its increase was noticed to increase solar intake and sensible heat addition (figure 38 (c) and (d)). When results from the various walls were compared it was discovered that the window opening area on the east wall could better reduce the number of discomfort hours and increase better the solar intake and the sensible heat addition (figure 38 (a) (c) and (d)). The window opening area on the east wall was also seen to reduce infiltration better though it capacity to do so was comparable to that of the window opening area on the west wall figure 38 (b).

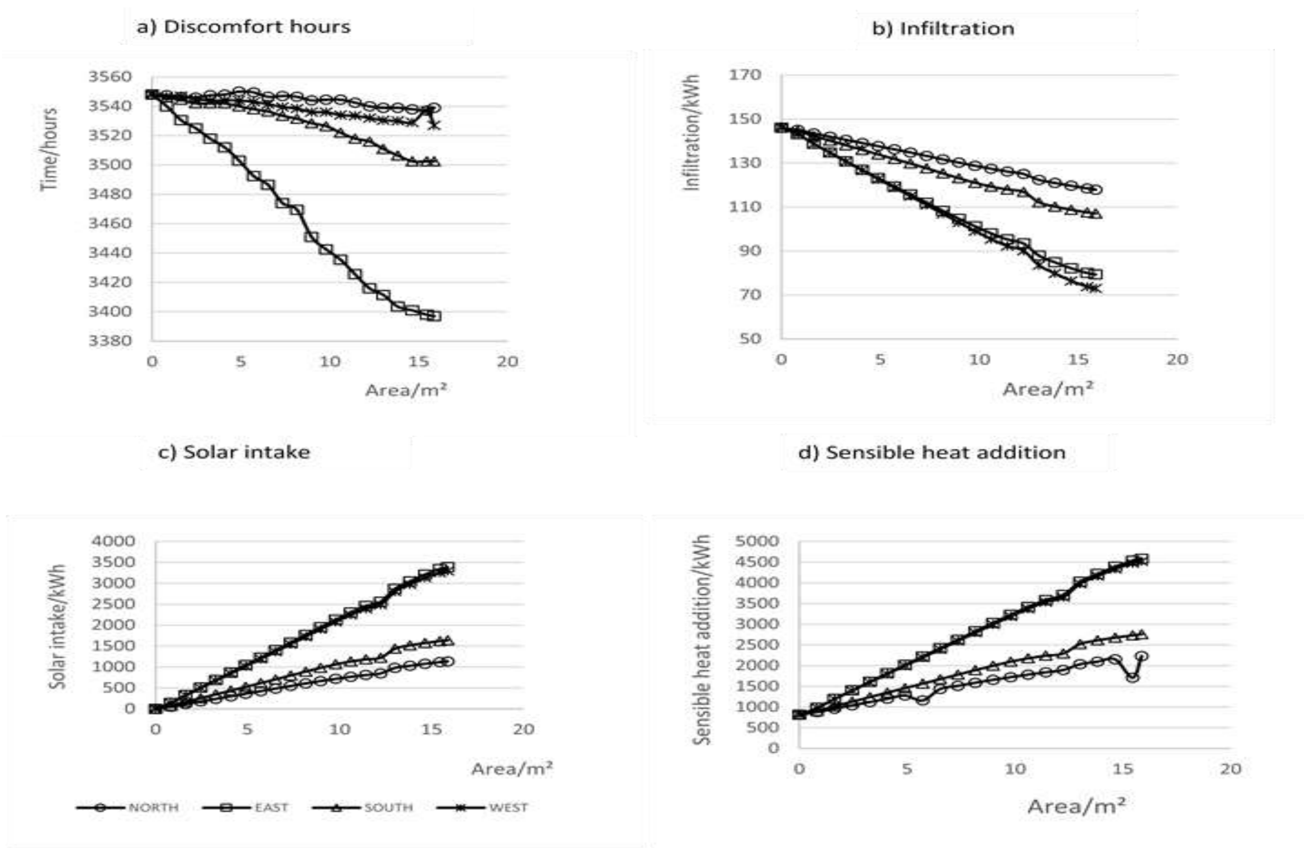


Fig 38: Impact of window opening area on studied parameters

Effect of solar intake, external infiltration and sensible heat addition on discomfort hours

The aim of this section was to investigate how other factors like solar intake, sensible heat addition and infiltration could be related to the number of discomfort hours. A negative gradient was obtained in the graph of discomfort hours with solar intake and sensible heat addition. On the other hand, a positive gradient was obtained in the graph of infiltration and discomfort hours (figure 39)

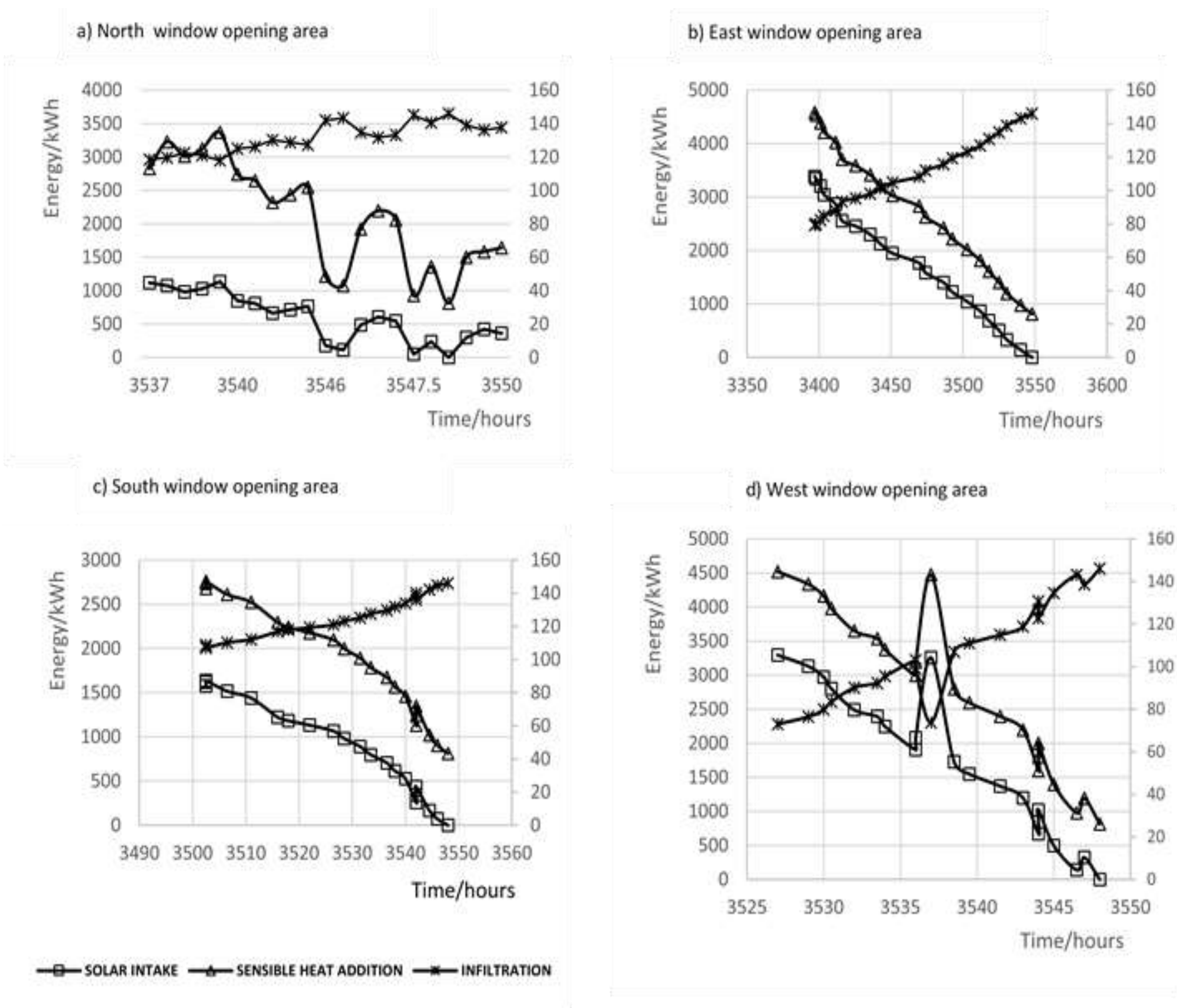


Fig 39: Energy and discomfort hours for the window opening area on various walls

The general result obtained was that an increase in the window opening area in buildings was seen to increase solar intake and sensible heat, and at the same time reduce external infiltration. An increase in solar intake, an increase in sensible heat and a reduction in external infiltration put together would therefore led to a reduction in the number of discomfort hours.

Increase in window opening area could reduce the number of discomfort hours and hence emission in CO_2. Aiman et al. (2018) confirmed that appropriate orientation helped to minimize heat losses in winter months by at least three times compared to the module when window facing south which impressively improve the overall thermal performance. Their work, based in a cold and temperate climate, found the best location for windows while this work, done in the humid tropical region, finds good location of windows which could improve on thermal comfort from a module whose windows faces the northern direction.

In the locality where the research was conducted many were seen struggling to keep themselves comfortable in their homes as a result of overheating or cold. The comfort problems in the locality was being addressed with the use of energy consuming devices which in one way or the other could be avoided and passive means applied. The study interest was therefore to investigate and find out the possible means through which the building design could be used to reduce discomfort.

Window opening area was seen as one of the means through which discomfort could be reduced. Increasing the window opening area led to a reduction in the number of discomfort hours. Energy consumption, thermal comfort and indoor air quality have been proven to be under the influence of building's window opening (Andersen et al. 2013; Rodrigues et al. 2019). Xiao et al. (2018) found out that indoor particles concentration is high with closed windows. There is therefore a need for living spaces in this locality of study to be built with provisions made for opening of windows as the means will provide. The high negative gradient of the graph of window opening area on the east wall and discomfort hours compared to others showed that in case a single window was to be designed it would be preferable to do so on the east wall.

There was also a correlation between solar intake, external infiltration, sensible heat addition and the number of discomfort hours. Increase in solar intake and sensible heat addition was observed to reduce the number of discomfort hours. This showed that improving on the operative temperature of the building generally led to thermal comfort improvement. This was achieved in the present work by increasing window opening area. That was in line with works of others which showed that increasing the proportion of opened windows leads to an increase in operational temperature (Stazi et al. 2017). Also components that could emit sensible heat within the building like equipment, the number of persons living in a building could also improve on the thermal comfort situation. External infiltration on the other hand was seen doing the opposite so buildings should be designed so as to reduce it as much as possible.

In the study locality, like many parts of Cameroon, it was observed by the authors that many building occupants used many ways to address their need to live in a thermally comfortable environment. During cool moments many made fire or burnt charcoal in closet which was very detrimental to their health. Others used electric means like cooling and heating systems. This research therefore provides a better way of seeking and achieving thermal comfort without putting the lives of users at risks from gases like CO_2, emitted from heating and cooling systems. It may also go a long way to reduce cost in electric bills and so on and so forth. Reliance on energy systems for the maintenance of thermal comfort can be avoided through window openings.

The research conducted revealed that adding heat into the building improves on the thermal comfort, it is therefore left for the home users to be able to eliminate these heat sources during hot seasons and to bring them back during cool seasons. Based on the study results, we therefore recommend the use of window openings to capture solar energy in other to improve on the building's thermal comfort.

Thickness of building material on CO_2 emission

A parametric study was carried out to study the effect of wall thickness on CO_2 emission. The brick thickness was varied from 12cm to 30cm. The increase in thickness induces higher thermal resistance that reduces the thermal requirements of buildings. An increase in the wall thickness was seen to reduce CO_2 emission as shown in figure 40 below. The same result was obtained in the two cases. That is for heating and for cooling. The slope is small and close to zero at a thickness of 23.1cm. The thickness of the brick used in the reference building was 15cm. It was seen that by increasing the thickness from 15cm to 23.1cm there would be a reduction in CO_2 emission by 8 percent. Ioannis et al () found that increasing the insulation thickness in residential buildings leads to the reduction of operational CO_2 emissions. By using different building materials, Asan (1998) showed that the thickness and thermo physical properties of building material have very profound effect on the decrement factor and the time lag of building envelope. Sylvie et al. (2014) carried out a sensitivity analysis on hemp concrete and found that an increase in thickness improves the climate change indicator but also increases the other environmental indicators at the wall level. However, this also improves the thermal resistance of the wall and may reduce the energy needs of the building during the use phase. This would lead to a reduction in the building's global impacts. However, as recent studies have shown, the success in reducing operational energy demand and related GHG emissions through increased energy efficiency of building envelopes and building systems has been accompanied by an increase in embodied GHG emissions in both relative and absolute terms (Röck, et al., 2020)

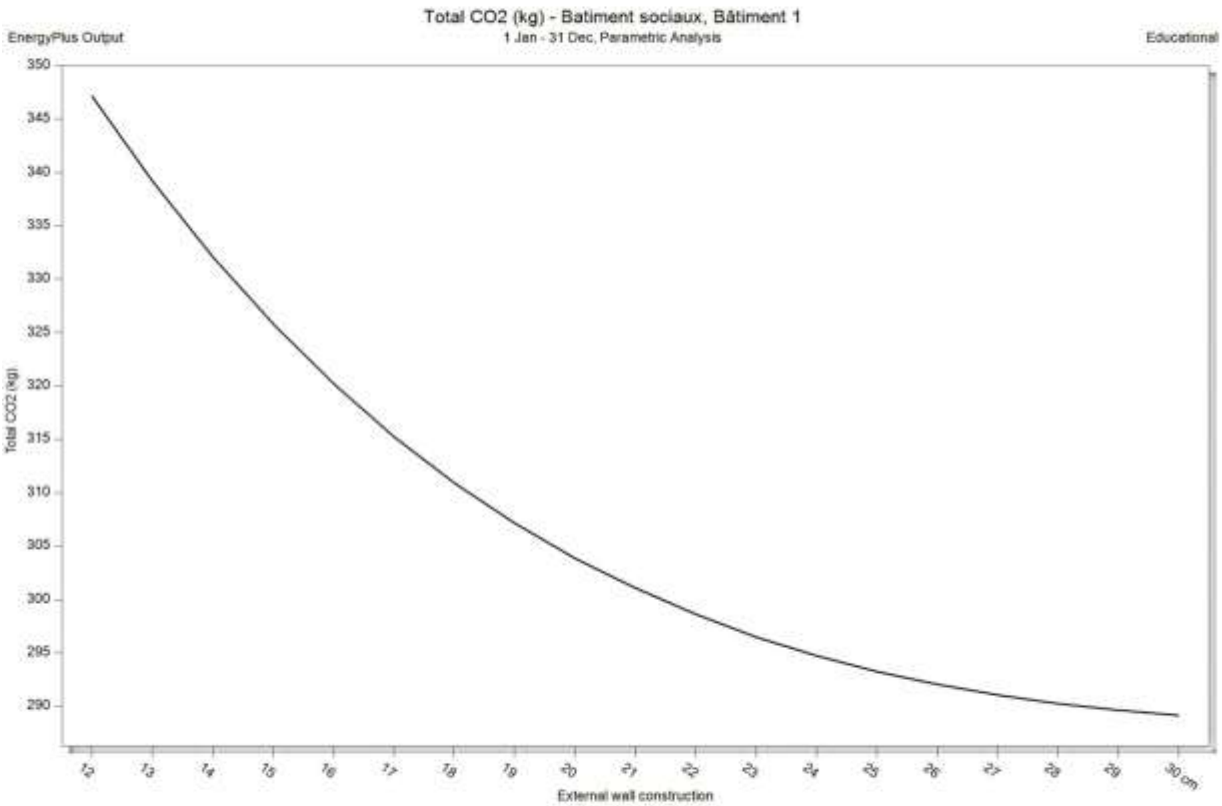


Fig 40: Change in CO2 emission as wall thickness increases

Conclusion

In this section it has been our goal to study the means of reducing CO_2 emission in residential building of reference in order to reduce emission of greenhouse gasses from the building sector. We considered emission from the various type of building material, building orientation, insulator type, material thickness and window opening area. The southeast direction is the only direction that keeps emission to a minimum during heating and cooling. From among the materials studied sundry brick seems to be the best while wood cellulose stands the best chance for the future climate scenarios. On the other hand, there will be need for a larger thickness of building material to be chosen for both hot and cold environments. A wall thickness of 23.1cm can reduce emission at the operational phase by 8%. For the optimum thickness to be obtained there is however a need to consider other factors like embedded emission and cost. A house built with mud bricks, insulated outside with wood cellulose and oriented in the southeast direction will reduce emission by 68.6% during cooling moments and by 13.6% during heating moments. Replacing wood cellulose with wood wool in the same building would instead lead to a 67.8% reduction in emission during cooling and a 14.7% emission during heating. The building blocks, insulators, and direction is a clear indication that building design only for today climate won't be able to answer future demands as far as combating climate change is concerned. On the other hand this is a clear indication that climate change will impose changes to be made on building designs. Building designers would need to consider dynamism when designing building plans in order to meet up with the needs of occupants.

General Conclusion

The search for the design of the building in the humid tropical region of Cameroon that minimizes the release of greenhouse gasses into the atmosphere was the central theme of the present study. This particular design that minimizes the release of greenhouse gases into the atmosphere is assumed in this study to minimize the impact of climate change into the building as well. CO_2 emissions due to space conditioning as well as occupant’s thermal comfort are the investigated building performance metrics. These performance metrics, especially CO_2, are evaluated in the following cases: building orientation, building materials, insulating materials, wall thickness and window opening area. It is clear from the study that residential buildings in the study region will have to undergo some changes as a result of climate change. The following key points are outstanding from the study.

- Results proved that energy plus calculation software can be used in the region of study. A CV (RMSE) of 11%, a NMBE of 2% and an MAPE of 9.2% was obtained. Also, 67.6% of the residuals are within one standard deviations of the mean, (above and below). The draw back seen with the simulation tool was that it under predict results. There is therefore the need for standards of calculation to be redefined in order to account for the error in the wet tropical regions.
- Thermal discomfort in the wet tropical region of Cameroon is seen to be the result of low temperatures. There is therefore a need of a heating source to heat the building to desired temperature for the occupants of the building.
- Building orientation, with the principal axis laying along the southeast and most windows facing the east and west, improves upon the buildings thermal comfort and hence reduces the release of greenhouse gasses into the environment;
- The use of local building materials like sundry earth bricks and wood products like cellulose improves thermal comfort in the building and minimizes greenhouse gas emission.

- There is an optimum thickness of building material that improves the building's thermal performance.

The following recommendations are therefore made for building designers in this particular region:

- The principal axis of the buildings and the door should face the southeast direction, with windows positioned in the east side of the building to make provision for much solar energy from the rising sun to be captured into the building
- The use of local materials like the fabrication and use of sundry earth bricks should be considered in construction of buildings, with a brick thickness of about 23cm
- The use of insulation materials should be encouraged, especially wood cellulose
- Building designs should improve on the intake of solar energy into the building; this can be done through the increase of window opening area especially the one on the east wall.
- Building designs should also strive to limit infiltration as much as possible; this can be done through the increase of window opening area especially the one on the west and the east wall.

If these recommendations are taken into consideration, then the buildings constructed will stand a better chance in combating the present effect imposed on it by the prevailing climate change. It will also go a long way to reduce the harm to the prevailing climate which will intend slow down the risk of overheating in the building sector, which is causing the changes being made. The study however is limited in scope as it has not considered embodied emission for optimal decisions. A combined study is envisaged for the next project study.

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Window opening area for thermal comfort performance in the wet tropical region of Cameroon

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ABSTRACT

The present study investigates how building design, particularly window opening design, can be used to better improve the thermal comfort of occupants of a building found in the wet tropical region of Cameroon. Window opening area positioning was done and the criteria for their operation were established. Simulation techniques using the energyplus calculation engine were employed. For each wall, the window opening area varied from 0 to 15.87 m^2; in steps of 0.75 m^2, and information linked to thermal comfort was collected. The calculation engine was validated with Coefficient of Variation of the Root Mean Square Error of 11%, a Normalised Mean Bias Error of 2% and a Mean Absolute Percentage Error of 9.2%. Simulated values were, however, under-predicted by the software. The final results indicate that thermal comfort can be improved in buildings within the wet tropical region of Cameroon by increasing the window opening area to capture solar energy when the thermal sensation of occupants is 'cool' inside the building. Window opening area should, therefore, be situated on the east, west and south-facing walls of the building to capture the sun's rays when the building occupants feel cold.

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Passive design; thermal comfort; window opening area; solar intake; infiltration

1. Introduction

The body system of human beings is sensitive to the degree of coldness or hotness and desires a neutral sensitivity for greater productivity and performance. Thermal comfort is a subjective parameter which uses the mind to express satisfaction with the thermal environment (Enescu 2017). According to Al-Horr et al. (2016), people's mode and satisfaction with the building are influenced by it. It also affects their health (Nicol, Humphreys, and Roaf 2012), and their work (Freire, Oliveira, and Mendes 2008). The energy consumed to sustain it cannot be forgotten (Yang, Yan, and Lam 2014) as it indirectly increases CO_2 emission (Elaiab 2014). A deep insight into what thermal comfort is all about intensified its research, especially during the introduction of air-conditioning systems in the twentieth century (Nicol and Roaf 2017).

Thermal comfort limits around the world have been the subject of research in this new developing field of study, with both national and international standards already established, such as ISO Standard (7730), ASHRAE Standard 55 and CEN Standard EN15251 (Humphreys et al. 2015b). Thermal comfort in air-conditional spaces is mostly studied using two Fanger's predictive models (PMV and PPD) (Fanger 1970). Nevertheless, a certain percentage of researchers feel that these two models do not fit in warm and hot climates as they observe them to overestimate the number of discomfort hours building dwellers perceive when exposed to natural ventilation (Nguyen, Singh, and Reiter 2012). The model that considers the human adaptation mechanism, known as the adaptive thermal comfort model, is proven through experiments to predict the thermal comfort in free-running and mixed-mode environments better (Humphreys, Nicol, and Raja 2007). Thermal comfort can be achieved in the built environment through various building design strategies, one of which is window openings. Factors that affect thermal comfort are influenced by window design parameters (Albatayneh 2021). Some studies focused on the analysis of factors influencing window-opening behaviour. These factors include physiological and psychological aspects (Li et al. 2015); as well as indoor CO_2 concentration and outdoor temperature (Yang et al. 2022).

To validate the energy plus calculation software, measured and simulated values of internal temperatures were compared and errors were calculated. The internal temperature values were captured by a temperature sensor device installed in the laboratory. This device was connected to a computer for data saving. Already registered values such as pressure, wind speed, wind direction, solar radiation, dew and dry bulb temperatures were extracted from the machine. These extracted values, for the past years (2010–2018), helped in the compilation of a weather data file compatible with the energy plus calculation engine. A model was then built and defined in the design builder and the window opening area then varied from 0 to 15.87m^2 based on the thermal sensation experienced by the users. Data were then collected on discomfort hour, solar intake, external infiltration and sensible heat addition. Data collected for solar intake,

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infiltration, and sensible heat were later correlated with discomfort hours.

A literature search indicates that window opening has been studied in relation to ventilation, temperature regulation, energy use, thermal comfort, solar gain and infiltration. Occupants of buildings respond to thermal stress by keeping their windows either open or closed (Kunle et al. 2021). Improved indoor air speed and airflow pattern can be obtained by a small operable window rather than a larger size window even under single-sided ventilation conditions. A recommendation is, however, made in the study for specific window design to be positioned at a particular location of the building to ensure a good and equally distributed ventilation performance (Trihamdani and Nurjannah 2022). There is a significant decrease in temperature just by fully opening the window or modifying its size (Deng et al. 2022; Liaw et al. 2023). Research work points out clearly that windows are opened for longer period in warm climates than in cold climates (Lai et al. 2004). The highest probability of window opening occurred between 7 a.m. and 9 am, while the highest probability of window closing occurred between 8 and 12 pm (Yang et al. 2022). There is an improvement in energy dispersion and human comfort when windows are opened (Prem Kumar, Thirumurugan, and Satyanarayanan 2023; Wang et al. 2023). Another study shows that window opening size does not affect the solar gain and that infiltration ventilation gain (heat gain or loss by airflow) decreases with an increase in Window Opening Area (WOA), for all sizes of glass (Alibaba 2022).

The literature search shows that most of the works done have not investigated the effect of window opening areas on solar intake as a means through which thermal comfort can be achieved in wet tropical regions. The present work, the first piece in the locality of study, therefore seeks to find out how window openings could be used to influence the amount of solar intake, infiltration and sensible heat addition in buildings to help fight thermal discomfort in the area of study. The rest of the paper presents the material and methods; the results obtained from the manipulations; discussions and finally the conclusion and recommendations.

2. Materials and methods

2.1. Materials

The Laboratory of Combustion and Green Technology (LCTV), of the University of Ngaoundere, was used to calibrate the calculation engine (EnergyPlus). To meet the objectives of the present study a simple model was then constructed in design builder.

2.1.1. Description of LCTV

Within the study period, LCTV was equipped with two tables, a shelf, a printer, three desktop computers, a data logger and some office chairs. It served as the laboratory for students of combustion and green technology. It is found on the first floor of the University Institute of Technology (UIT). Its west wall has a large glass window. The characteristics of the block considered in the building energy model are shown in Table 1 and are taken from (Ghislain and Vincelas 2016), while those of the roof are as defined in design builder. The plan of LCTV and the building energy model used for simulation are shown in Figure 1. The building is built with lightweight hollow concrete blocks, with cement plaster on both sides. The block and the plaster thickness were 15 and 1.5 cm, respectively. The room was naturally ventilated.

Table 1. Properties of building materials (Ghislain and Vincelas 2016, Design builder software).

Thermal properties	Hollow concrete block	Roofing sheet
Thermal conductivity (W.m^{-1}.K^{-1})	0.67	45.28
Specific heat (kJ.kg^{-1}.K^{-1})	1.25	0.50
Density (kg.m^{-3})	880	7824

2.1.2. The building model used for the study

The building model used in this study is presented in Figure 2 and its characteristics were the same as that of the laboratory. It served as a sleeping room. The main door of the building was located on the north wall while its single window was located on the west wall. The sill height of the window was 0.8 m while the window height and width were 1.5 and 4.8 m, respectively. The zone summary is presented in Table 2.

2.2. Data acquisition and analysis

To validate the energy plus calculation software, measured and simulated values of internal temperatures were compared and errors were calculated. The internal temperature values were captured by a temperature sensor device (Vantage Pro 2) installed in the laboratory. This device was connected to a computer for data saving. Already registered values such as pressure, wind speed, wind direction, solar radiation, dew and dry bulb temperatures were extracted from the machine. These extracted values, for the past years (2010–2018), helped in the compilation of a weather data file compatible with the energy plus calculation engine. For the main part of this work, the model in Figure 2 was used. To study the influence of the window opening area on the chosen parameters, the model was designed without a door on it. One of the walls (north, east, south and west walls) was in turn chosen and a single window was installed on it. Based on Fanger's predictive model, the window opening area was varied from 0 to 15.87 m^2 and data were collected on discomfort hours, solar intake, external infiltration and sensible heat addition. For each chosen wall, the window opening area was increased in steps of 0.75 m^2. The limit of this process was the size of the wall where the window was designed to be. Data collected for solar intake, infiltration, and sensible heat were later correlated with discomfort hours.

3. Results

3.1. Calibration of the research tool

The goal of this research was to study how building designs affect people's thermal comfort in the tropical regions of Cameroon. Among the numerical tools, we chose to use Energy Plus. This section presents the results of the calibration of this tool as a test of its accuracy in prediction. The validation of the numerical tool was based on quantities such as the Coefficient

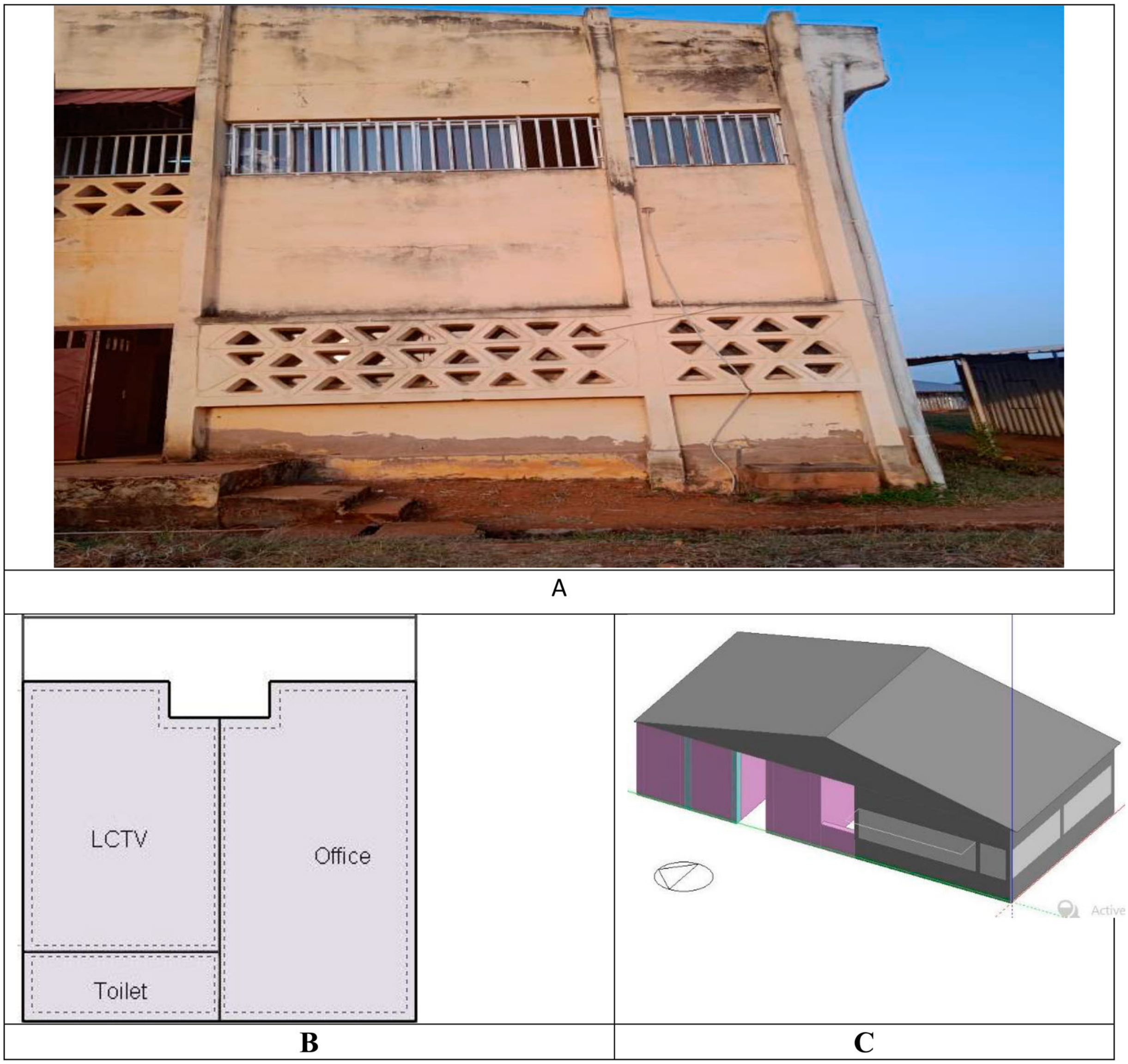

Figure 1. (A) University Institute of Technology building (B) 2D and (C) 3D Plan of the LCTV building designed by design builder.

of Variation of the Root Mean Square Error (CV (RMSE)), Mean Absolute Percentage Error (MAPE), Normalised Mean Bias Error (NMBE) and statistical diagrams like the frequency chats. Measured and simulated values of the internal temperature of the laboratory, considered, are represented in Figure 3.

These internal temperature values were captured by a temperature sensor device installed in the laboratory. This device was connected to a computer for data saving. The measurements were collected for March. A CV (RMSE) of 11% and an NMBE of 2% were obtained. A MAPE of 9.2% was also achieved. ASHRAE guideline 14 report and FEMP (Federal Energy Management Program) report (Ruiz and Bandera 2017), give an acceptable monthly criteria of NMBE less than ±5% and a CV (RMSE) index of less than ±15%. MAPE obtained in this study is within an interval of highly accurate forecasting (Lewis 1982). MAPE is the most useful measure to compare the accuracy of forecasts between different items or products since it measures relative performance (Makridakis, Wheelwright, and Hyndman 1998).

The plot of the residuals and their frequencies of occurrence are presented in Figure 4. The normal density function has been superimposed with plotted points. The mean of the residuals is 0.25. 67.6% of the residuals are within one standard deviation of the mean, (above and below), which proves the distribution is normal according to Chebyshev's theorem.

A S-shaped curve on this graph further suggests that the distribution of residuals is bimodal (Figure 5).

Calibration was conducted to test the numerical tool's fitness to do the task described in this piece of work. The MBE index, however, has a drawback of cancellation making it possible for the magnitude of seasonal errors to be under-reported. Monthly intervals of the MBE index can then be instrumental in the case the analyst focuses on instances of under- or over-prediction. MAPE and the accumulated frequency distribution curve, however, indicate that the numerical tool is good for forecasting and can produce reliable distributions.

Table 2. Zone summary.

	Area [m^2]	Conditioned (Y/N)	Part of Total Floor Area (Y/N)	Volume [m^3]	Multipliers	Above Ground Gross Wall Area [m^2]	Underground Gross Wall Area [m^2]	Window Glass Area [m^2]	Opening Area [m^2]	Lighting [W/m^2]	People [m^2 per person]	Plug and Process [W/m^2]
BLOCK1:ZONE1	25.00	N	Y	87.50	1.00	70.00	0.00	6.42	6.90	20.0000	9.01	11.7700
ROOF1:ZONE1	23.09	N	N	15.40	1.00	8.42	0.00	0.00	0.00			
Total	25.00			87.50		70.00	0.00	6.42	6.90	20.0000	9.01	11.7700
Conditioned Total	0.00			0.00		0.00	0.00	0.00	0.00			
Unconditioned Total	48.09			102.90		78.42	0.00	6.42	6.90	10.3962	17.33	6.1181
Not Part of Total	23.09			15.40		8.42	0.00	0.00	0.00	0.0000		0.0000

3.2. Effect of window opening area on the number of discomfort hours, solar intake and sensible heat addition

This section presents the results of the variation of window opening area with discomfort hours, solar intake and sensible heat addition.

An increase in the window opening area reduces the number of discomfort hours and infiltration (Figure 6(a) and (b)). On the other hand, its increase was noticed to increase solar intake and sensible heat addition (Figure 6(c) and (d)). When results from the various walls were compared, the window opening area on the east wall could better reduce the number of discomfort hours and increase the solar intake and the sensible heat addition (Figure 6(a) (c) and (d)). The window opening area on the east wall was also seen to reduce infiltration better though its capacity to do so was comparable to that of the window opening area on the west wall Figure 6(b).

3.3. Effect of solar intake, external infiltration and sensible heat addition on discomfort hours

The aim of this section was to investigate how other factors such as solar intake, sensible heat addition and infiltration could be related to the number of discomfort hours. A negative gradient was obtained in the graph of discomfort hours with solar intake and sensible heat addition. On the other hand, a positive gradient was obtained in the graph of infiltration and discomfort hours (Figure 7). The nature of these results is similar for all the walls though the graph indicates some degree of change.

From Figure 6, an increase in the window opening area in the building under investigation was seen to increase solar intake and sensible heat, and at the same time reduced external infiltration. Also, from Figure 7 an increase in solar intake and sensible heat addition as well as a reduction in infiltration reduces the number of discomfort hours.

4. Discussion of results

The study's interest is to investigate and find out the possible means through which the window design could be used to reduce discomfort. The study first calibrated the software tool and then used it to find out how the window opening area affects thermal comfort.

The residual plot when compared with the normal density function indicates that 67.6% of the residuals are within one standard deviation of the mean, (above and below), which proves the distribution is normal according to Chebyshev's theorem. The accumulative frequency curve has an S-shape, further proving that the distribution is normal. More so, the various errors considered in the study are within acceptable limits and further prove the software can be used. The mean of the residuals and the NMBE are, however, positive pointing to the fact that simulated values are under-predicted. This contradicts the results for tropical regions (Nguyen, Singh, and Reiter 2012). This may be a result of the use of ASHRAE guidelines in other studies which reverses the formula used in the present study. On the other hand, the wet tropical region may have some particularities different from other tropical regions. There is, therefore, the

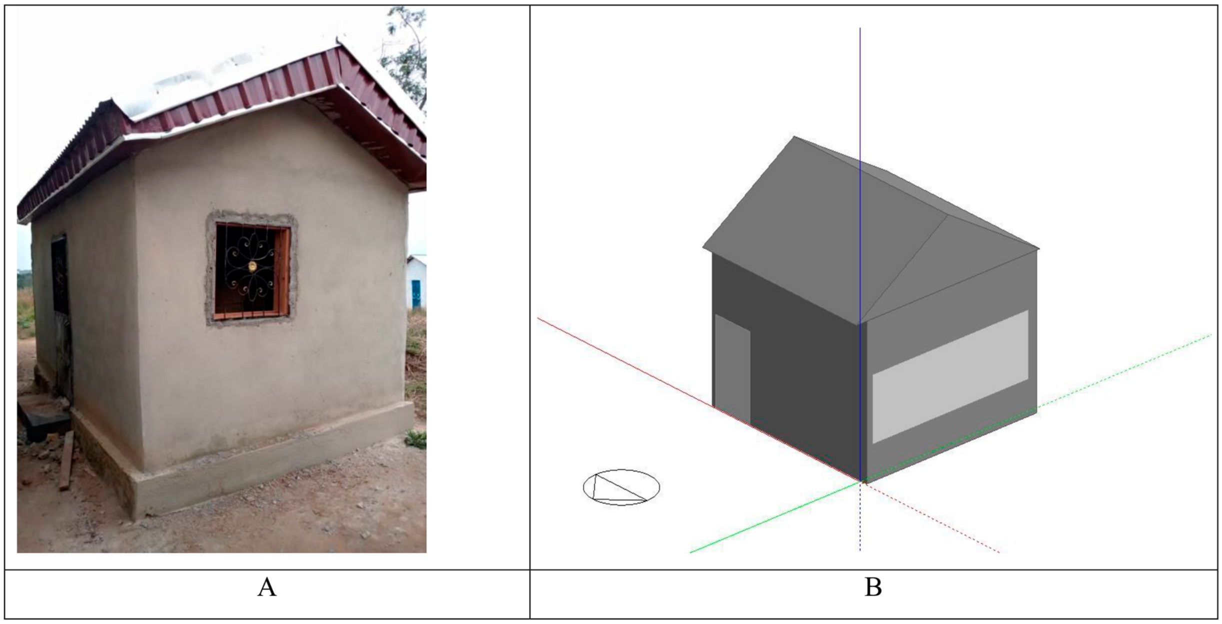

Figure 2. (A) A single-room building in north Cameroon (B) 3D building in design builder.

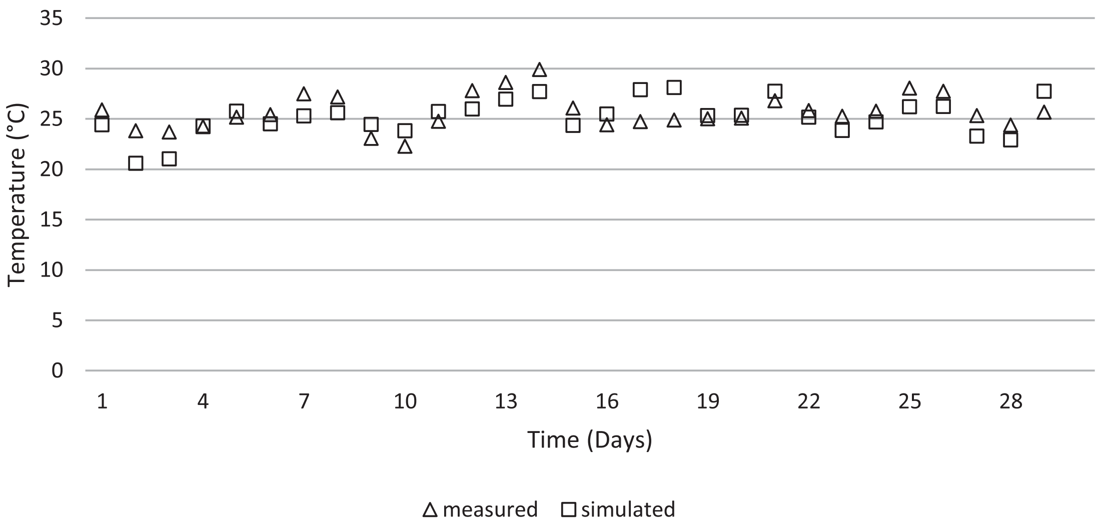

Figure 3. Temporal variation of simulated and measured internal temperature of LCTV.

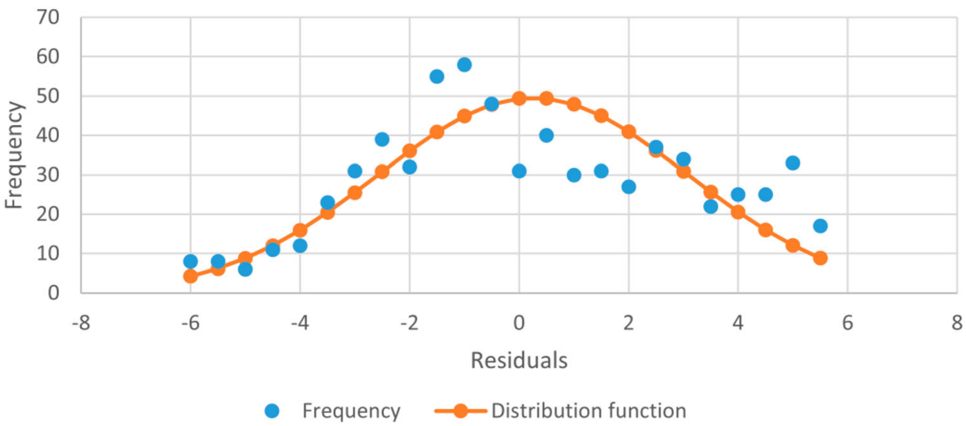

Figure 4. Plot of the residuals and their frequency of occurrence.

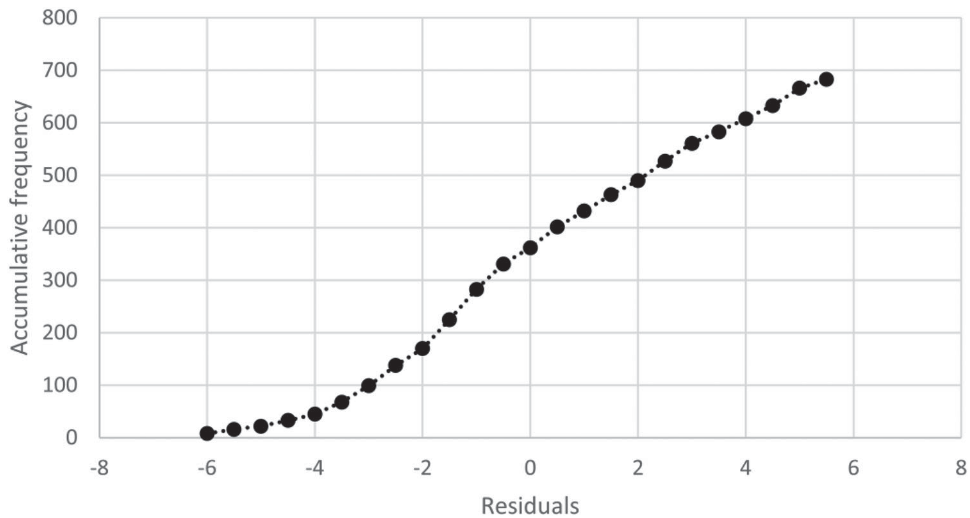

Figure 5. Accumulative frequency plot.

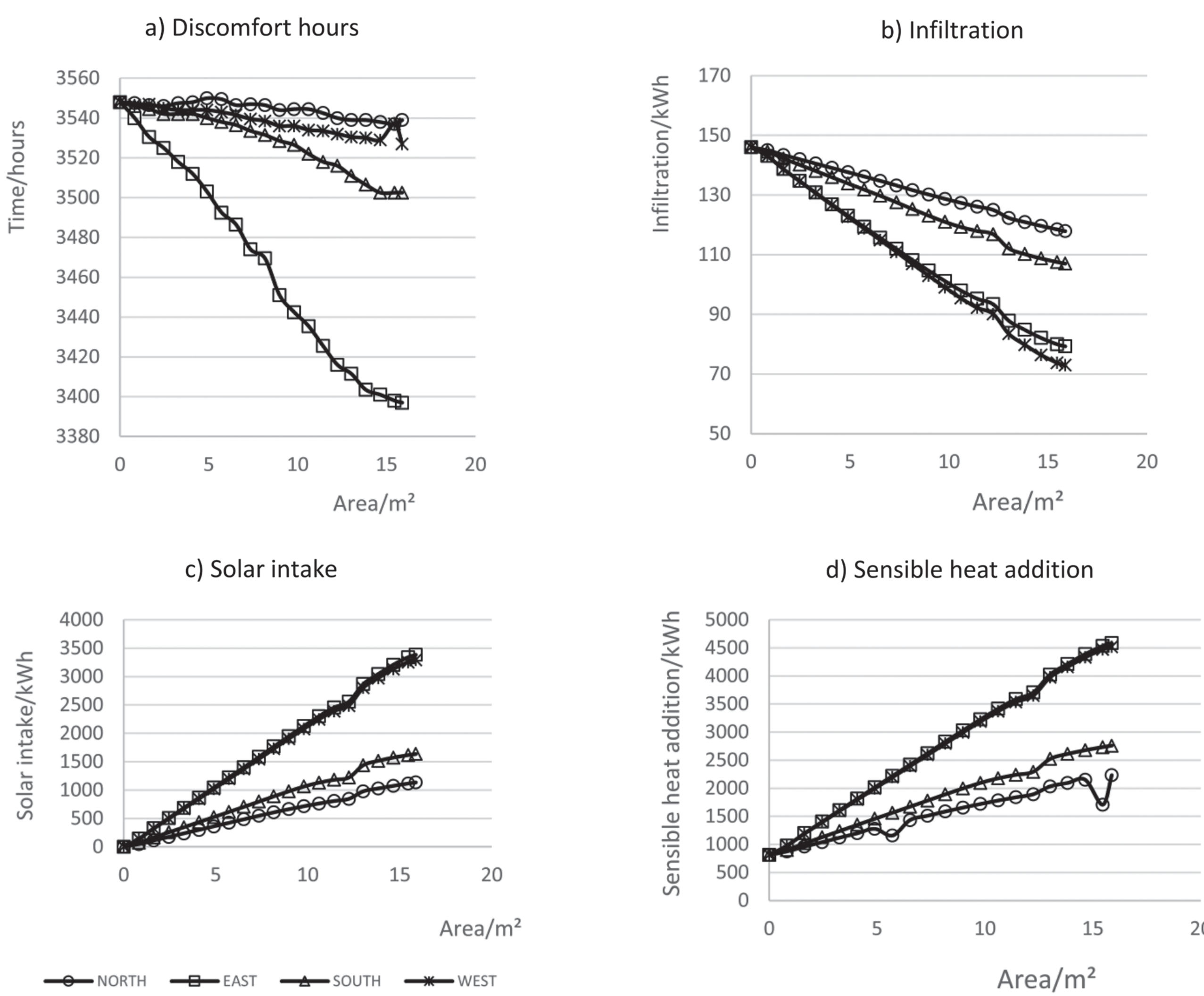

Figure 6. Impact of the window opening area on studied parameters.

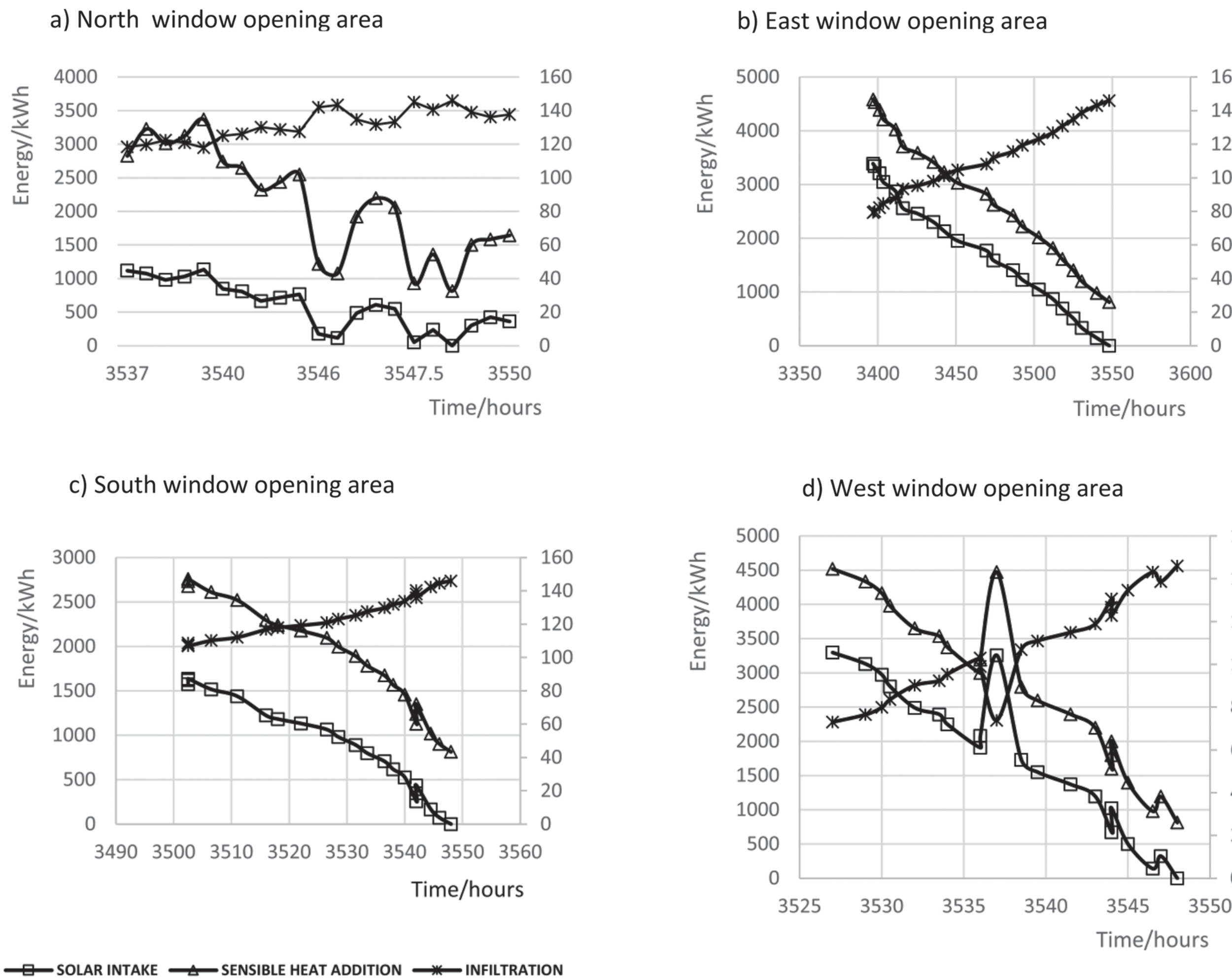

Figure 7. Energy and discomfort hours for the window opening area on various walls.

need for improvement in standards of calculation in wet tropical regions to account for this error.

An increase in window opening area has a positive effect on the thermal comfort of the occupants of the locality where the research is conducted. Other researchers found that thermal comfort is under the influence of window openings (Andersen et al. 2013). This is in line with another study in which occupants of a building responded to thermal stress by either opening or closing windows (Kunle et al. 2021). In the present study, it is observed that open windows lead to heat addition sources like solar intake and sensible heat addition. This seems to be in support of researchers who observed that increasing the proportion of opened windows leads to an increase in operational temperature (Stazi et al. 2017). These results point to the fact that the studied building needed to be heated for thermal comfort to be achieved. This alone, therefore, suggests that thermal discomfort, in the studied building, was generally a result of low temperatures. This is true because the locality under study is found in the western high-lands of the country which is high above sea level.

There is, therefore, a need for a heating source to heat the building to the desired temperature for the occupants of the building. The present study, however, reveals that solar radiation can play the role of a heating source for residents of the said locality if proper orientation is given to the window opening area. This seems to be contrary to another study carried out by Alibaba (2022) who found that window opening size does not affect the solar gain. His study indicates an increase in internal temperature when window openings are increased, for all sizes of glass. Although it is clearly stated in the study that office air is heated by energy transferred from the internal surface, it still does not explain clearly how opening windows will lead to an increase in internal temperature. According to our study, an increase in solar intake and sensible heat gain together with a decrease in infiltration explain this better. The difference here may, therefore, be at the level of data analysis and interpretation. In our study, we have graphed the information for easy and clear interpretation.

The present study revealed a maximum solar intake in the east, then followed by west directions. These are directions of the rising and the setting sun respectively for the locality studied. The low values on the south and the north surely reflect the absence of sun ray penetration through windows. This is surely because the sun is overhead and most windows are shaded by the building itself. Following the analysis of this piece of work, which indicates that low temperatures are the cause of discomfort in the present locality, we then recommend that the occupants of buildings in this locality should base the opening of windows on the thermal sensation they feel. If they feel cool, they should open windows. East-facing windows should be opened during the morning hours to capture the rising sun, south windows should be opened to capture the sun rays during the day while the west windows should be opened to capture the setting sun's rays. Another study had made recommendations for a particular window design to be located at particular locations in the building's envelope though their main goal was to ensure good and quality ventilation performance (Trihamdani and Nurjannah 2022). In yet another study a call is made for architects to ensure good positioning and orientation of windows for effective thermal stress (Kunle et al. 2021). The present study has gone beyond these recommendations and has proposed where windows should be located and when they should be opened to improve the building' thermal comfort.

Infiltration occurs through gaps, cracks and through poorly sealed windows. Infiltration is observed in this study to decrease as the window opening area increases. This is in line with another study (Liaw et al. 2023). This suggests that infiltration leads to the introduction of a cold sensation on the side of the occupants since an increase in window opening area leads to a reduction in discomfort hours. Increasing the WOA, therefore, reduces the pressure difference between the exterior and the interior of the building, thereby restricting air movement to a good degree.

Making good use of window design is a strategy which if policy-makers adopt they can ensure thermal comfort in buildings with a reduced use of heating and cooling systems, thereby reducing CO_2 emission into the atmosphere and electric bills for home users. The authors will be looking forth to make a study on the distance and the height of obstacles in the environment of the building, especially those that are located around window openings.

Thermal discomfort in the present study is seen to be the result of low temperatures. There is, therefore, a need for a heating source to heat the building to desired temperatures for the occupants of the building. An increase in solar intake and sensible heat addition can be a means of heating buildings when it feels cool inside. The present study reveals that these heat sources can be increased by increasing the window opening area. An increase in window opening area, therefore, improves the thermal comfort situation of buildings in the wet tropical region of Cameroon during winter periods.

5. Conclusion

The study's interest is to investigate and find out the possible means through which the building design, especially the window opening area, could be used to reduce the discomfort of occupants of residential buildings of the study locality. The study first calibrates the software tool before using it to achieve the central purpose of the study.

- Results proved that the software can be used in the region of study. A CV (RMSE) of 11%, an NMBE of 2% and a MAPE of 9.2% were obtained. Also, 67.6% of the residuals are within one standard deviation of the mean, (above and below). The drawback seen with the simulation tool was that it under predicted results. There is, therefore, the need for standards of calculation to be redefined to account for the error in the wet tropical regions.
- Thermal discomfort in the wet tropical region of Cameroon is seen to be the result of low temperatures. There is, therefore, a need for a heating source to heat the building to the desired temperature for the occupants of the building.
- Solar intake and sensible heat addition can act as heat sources for the studied building.
- The amount of solar intake and sensible heat addition can be increased in the building by increasing the window opening area.
- An increase in window opening area, therefore, improves the thermal comfort situation of buildings in the wet tropical region of Cameroon during winter periods by increasing the amount of solar intake.

The following recommendations are made based on these results.

- There should be provisions for adjustable window opening areas to manage any given situation (cold or hot).
- The provisions for window openings should be made available in the direction of the rising sun (east), in the south and north to capture rays from the overhead sun and in the direction of the setting sun (west).

If these recommendations are not put in place there will surely be an increased use of heating and cooling systems to achieve thermal comfort, thereby increasing the release of greenhouse gasses into the atmosphere. They will even be an increase in electric bills on the side of home users as a result of the use of these systems.

An increase in window opening area improves the thermal comfort situation of buildings in the wet tropical region of Cameroon during winter periods as it leads to an increase in solar intake and sensible heat addition and a reduction in infiltration. This will surely reduce the high dependency on electrical energy or use of other costly means of heating the building. It is, however, important to note that the results of the present study are based on an annual simulation and so they present an average situation for the locality in question. Each day, like each month, has its particularities. Window opening area, how the building directly connects to the external environment, is, therefore, an option to consider when seeking to improve the thermal comfort performance of a building.

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