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On Comfort in Tropical Climates. The Design and Operation of Net Zero Energy Buildings.

Aurélie Lenoir

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THESE

Présentée pour obtenir le grade de

DOCTEUR DE L'UNIVERSITE DE LA REUNION

Spécialité: Mécanique et Environnement

Présentée par

AURELIE LENOIR

CONFORT EN CLIMAT TROPICAL

CONCEPTION ET EXPLOITATION DE BATIMENTS ZERO ENERGIE

Thèse dirigée par **François Garde**

Codirigée par **Etienne Wurtz**

Préparée au sein du laboratoire **PIMENT EA 4518**

En convention CIFRE avec le bureau d'étude **Imageen**

Soutenue publiquement le 24 mai 2013

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UNIVERSITY OF REUNION ISLAND

PHD THESIS

Presented to obtain the title of

DOCTOR OF PHILOSOPHY, UNIVERSITY OF REUNION
ISLAND

Speciality: Mechanics and the Environment

Presented by

AURÉLIE LENOIR

ON COMFORT IN TROPICAL CLIMATES

THE DESIGN AND OPERATION OF NET ZERO ENERGY BUILDINGS

Thesis directed by **François Garde**

Co-directed by **Etienne Wurtz**

Prepared in the **PIMENT Laboratory EA 4518**

Under a CIFRE agreement with the design office **Imageen**

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A mes trois étoiles,

- Les étoiles sont belles, à cause d'une fleur que l'on ne voit pas...

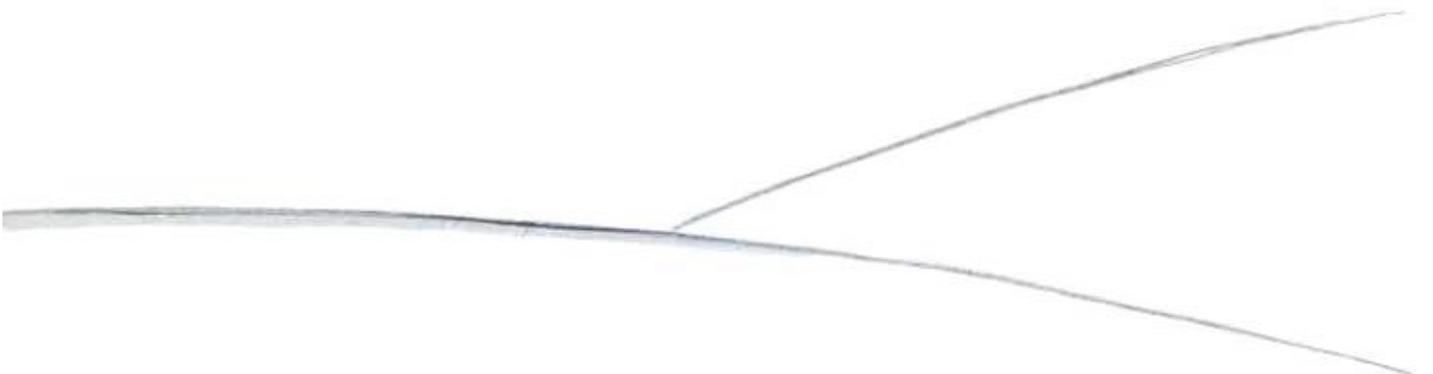
Je répondis "bien sûr" et je regardai, sans parler, les plis du sable sous la lune.

- Le désert est beau, ajouta-t-il...

Et c'était vrai. J'ai toujours aimé le désert. On s'assoit sur une dune de sable. On ne voit rien. On n'entend rien. Et cependant quelque chose rayonne en silence...

- Ce qui embellit le désert, dit le petit prince, c'est qu'il cache un puits quelque part...

ANTOINE DE SAINT-EXUPÉRY





ABSTRACT

This thesis investigates a comfort approach for the design and the operation of Net Zero Energy Buildings (Net ZEBs) in tropical climates. The work is part of an international research project, Task 40 / Annex 52 led by the International Energy Agency (IEA), that concerns net zero energy solar buildings. The case study of the ENERPOS building located in Reunion Island is one of the 30 Net ZEBs selected by the IEA to create a database of demonstration projects worldwide.

The point of departure of the study is the observation that one of the challenges facing the intertropical zone today is the growing energy demand. Passive design is suggested as a possible solution to reduce the energy demand of buildings. This approach leads to dealing with comfort issues rather than energy issues, as is usually the case. In spite of the inherent subjective nature of occupant comfort, there is an essential need for methods and tools to characterise comfort in relation to the physical parameters of the environment, for instance, temperature, humidity, air speed and illuminance. Different approaches to thermal and visual comfort are introduced, with the aim of proposing comfort evaluation criteria that are adapted to the design offices. A thermal comfort survey of the occupants of the ENERPOS building, based on over 2,000 feedbacks was conducted from 2008 to 2011. The results have led to the recommendation of modifications in the Givoni comfort zones, notably by extending the maximum humidity level, for passive buildings combining the use of natural ventilation and ceiling fans.

An innovative methodology using simulations and taking the passive behaviour of the building into account, as opposed to the conventional approach with regard to energy use, is proposed to facilitate the optimisation of the design of passive buildings. The study focuses on the design of solar shading, given the extensive role it plays in tropical climate, as well as the direct impact it has on both thermal and visual comfort of building occupants.

Although the design phase aims to optimise the building to limit both discomfort and energy consumption, the operation of the building remains the critical phase that is often neglected or overlooked by design teams. A broad examination of the operation phase of the ENERPOS building, since its construction, from both energy and users' point of view, illustrates that a building can reduce its energy consumption significantly, and thus, its environmental impact while maintaining an acceptable level of comfort for its users.

Key words: *net zero energy buildings, tropical climates, thermal comfort, daylighting, passive design, experimental feedback.*



RÉSUMÉ

Cette thèse propose une approche originale axée sur l'étude du confort pour la conception et l'exploitation de bâtiments « zéro énergie » en climat tropical. Elle fait partie d'un projet international porté par l'Agence Internationale de l'Energie (AIE), la Tâche 40 / Annexe 52 qui concerne les bâtiments « zéro énergie ». Le bâtiment ENERPOS, situé à La Réunion et utilisé comme étude de cas dans cette thèse, est l'un des trente bâtiments sélectionnés par l'AIE pour créer une base de données internationale de projets pilotes.

L'étude part du constat que l'un des défis auxquels fait aujourd'hui face la zone intertropicale est la demande croissante en énergie. La conception passive des bâtiments est proposée comme une alternative intéressante pour réduire leurs besoins en énergie. Dans ce cas, une étude approfondie du bâtiment dans son ensemble est indispensable pour garantir l'équilibre entre le confort des occupants et la réduction des consommations énergétiques. Bien que la notion de confort soit profondément subjective, il est nécessaire d'affiner les méthodes et outils existants pour le caractériser en fonction des paramètres physiques de l'environnement (température, humidité, vitesse d'air, éclairage). Différentes approches du confort thermique et visuel sont introduites dans le but de proposer des critères d'évaluation adaptés aux bureaux d'études. Une enquête sur le confort thermique des occupants du bâtiment ENERPOS, incluant plus de 2000 questionnaires, a été menée entre 2008 et 2011. Les résultats obtenus conduisent à recommander des modifications de la zone de confort de Givoni, en augmentant en particulier la limite supérieure de l'humidité, dans le cas d'un bâtiment passif naturellement ventilé et muni de brasseurs d'air.

Une méthodologie de simulation innovante, prenant en compte le comportement passif des bâtiments, grâce à une étude couplée du confort thermique et visuel, par opposition à l'approche traditionnelle centrée sur la consommation d'énergie, est proposée pour aider à optimiser la conception des bâtiments passifs. L'étude se concentre sur le choix et le dimensionnement des protections solaires qui jouent un rôle essentiel en climat tropical et qui ont un impact direct sur le confort des usagers des bâtiments.

Bien que la phase de conception vise à optimiser le bâtiment pour limiter à la fois l'inconfort et la consommation d'énergie, son exploitation reste la phase critique qui est souvent négligée ou oubliée par les équipes de conception. Un retour expérimental global du bâtiment ENERPOS depuis sa construction, tant au niveau énergétique que du point de vue de ses utilisateurs permet de montrer qu'il est possible de réduire considérablement la consommation d'énergie d'un bâtiment, et donc son impact environnemental, tout en maintenant un confort acceptable pour ses occupants.

Mots clés : *bâtiments à zéro énergie, climat tropical, confort thermique, éclairage naturel, conception passive, retour d'expérience.*



NOMENCLATURE

α	Angle of visible sky from the midpoint of the window
ρ_m	Average reflection of the factor for all internal surfaces
A	Surface Area
E	Illuminance
f_{load}	Load Match Index
f_{grid}	Grid Interaction Index
h_c	Convective heat transfer coefficient
h_r	Radiant heat transfer coefficient
L	Thermal Load
M	Maintenance factor of the window
Mr	Metabolic rate
$R - value$	Thermal resistance
RH	Relative humidity
$S - value$	Solar factor
$SHGC$	Solar heat gain coefficient
t	Transmission factor of the glazing
T_a	Air temperature
T_g	Globe temperature
T_{mrt}	Mean radiant temperature
T_{op}	Operative temperature
$U - value$	Thermal transmittance
v_a	Air velocity



ABBREVIATIONS

AC	Air conditioning
ACH	Air Change per Hour
ASHRAE	American Society of Heating, Refrigerating and Air Conditioning Engineers
ATU	Air treatment unit
BBCC	Building Bioclimatic Chart
BIPV	Building integrated photovoltaic
BMS	Building management system
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CO₂	Carbon Dioxide
DA	Daylight Autonomy
DC	Daylight Coefficient
DF	Daylight Factor
DHW	Domestic Hot Water
DOE	Department of Energy
ECBCS	Energy Conservation in Buildings and Community Systems
EPBD	Energy Performance Building Directive
HQE	<i>Haute Qualité Environnementale</i> , French for “high environmental quality”
HVAC	Heating Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IEA	International Energy Agency
IESNA	Illuminating Engineering Society of North America
ISO	International Organization for Standardization
LEED	Leadership in Energy and Environmental Design

Net ZEB	Net Zero Energy Building
NMV	Natural and Mechanical Ventilation
NREL	National Renewable Energy Laboratory
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RET	Renewable Energy Technologies
SHC	Solar Heating and Cooling
UDI	Useful Daylight Index
VOC	Volatile Organic Compounds
VRV	Variable Refrigerant Volume
WMO	World Meteorological Organisation
WWR	Window-to-Wall Ratio





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INTRODUCTION

We are now at the heart of a process of transition as to the nature of the image which man has of himself and his environment. Men previously imagined themselves to be living in a world with ostensibly limitless resources, like the cowboy on the boundless plains. Since the late nineteen sixties, humankind has become aware that the world is a limited space with fixed boundaries, without unlimited reserves to be exploited or deteriorated leading to pollution. This vision of the world is usually described as Spaceship Earth. Although man should behave as a spaceman and be concerned with maintaining the stock of all vital resources, his cowboy demeanour cannot be overcome easily. The conditions of survival of a society, and on a global scale, of Planet Earth rely on the sole ability of humankind to preserve water, food and energy, all precious resources.

Global energy conservation cannot be realized without giving specific consideration to the building sector. According to the World Business Council for Sustainable Development¹, buildings account for 40 per cent of the world's energy use with the resulting carbon emissions substantially higher than those in the transportation sector. However, because of globalisation and technological change, the design of buildings does not give due consideration to the climate. One of the main purposes of buildings is to ensure comfort for the users (the other purposes being to ensure safety and privacy). However, the emergence of low-cost mechanical systems and the adoption by comfort standards of Fanger's model which imposes narrow thermal comfort ranges, have led designers to neglect passive thermal control approaches and to equip buildings with mechanical cooling systems. In many cases, the developers who decide on the building design do not operate the building. In such instances, many developers choose to economize during the design stage whatever the future cost associated with the operational phase of the building may be. In practice, developers design buildings with a minimum amount of openings to keep the cost low, and equip the building with low-cost equipment such as air conditioners or electric water heaters. This design approach has significant negative implications during the building operation as a considerable amount of energy will be required by the occupants to maintain indoor comfort conditions. This counteracts the reduction of energy consumed in buildings. In an effort to remedy this situation, regulations, standards and labels adapted to the tropical climate

¹ WBCSD, Transforming the Market: Energy Efficiency in Buildings report.
<http://www.wbcd.org/transformingthemarketeeb.aspx>

are required with the goal of altering building design in tropical climates and adopting an approach that takes both design and operation of the building into account.

The spread of this practice of mechanisation, particularly in the tropics where many developing countries are located, could result in an explosion of the energy consumption of buildings. We are agreeably witnessing the emergence of a trend of new standards that recognize the vernacular adaptive concept. This is, in our opinion, truly the first step towards a sustainable form of architecture that will allow the integration of buildings into their natural environment in a more respectful way. In this context, the concept of Net Zero Energy Buildings (Net ZEBs) started to emerge essentially in 2005. On an international scale, a joint task performed under the International Energy Agency that concerns “Net Zero Energy Solar Buildings” started in 2008 and is still on-going (IEA, 2008). The specific work presented in this PhD thesis is part of this international task. The case study of the ENERPOS building, located in Reunion Island, a French tropical overseas region in the Indian Ocean, is one of the 30 Net ZEBs selected by the IEA to create a database of demonstration projects worldwide. Chapter 1 will present the Net ZEB concept and the challenges that must be addressed to design such buildings in tropical climates. The main features of the ENERPOS building, the case study of this thesis, will be also outlined. Building design in tropical climates is characterised by a number of specific features compared to the buildings in temperate climates. In Reunion Island, electricity is the driving force behind all buildings, and air conditioning accounts for more of 60% of the overall energy consumption. Two architectural approaches are possible in order to reduce the high level of energy consumption: the high-tech (active) one and the low-tech (passive) one. Both are presented in chapter 1; however this thesis focusses solely on the passive approach as a foundation of the design process.

Passive buildings act as a filter between the outside conditions imposed by the weather, which is determined by the location, and the indoor conditions that need to meet occupant comfort requirements. Therefore, the passive design approach leads to dealing with comfort issues rather than energy issues, as is usually the case. This implies the need to develop adapted methods and simulation tools for the building design teams. Different approaches to thermal and visual comfort will be introduced in chapter 2 with the aim of proposing comfort evaluation criteria that are adapted to the design offices. With regard to thermal comfort, the Givoni comfort zones will be described and the reasons for selecting this approach will be given. Visual comfort will not be explored in depth in this thesis. However, the availability of daylighting will be evaluated by considering criteria such as the useful daylight index and the daylight autonomy into consideration. Even though we are aware that the use of natural ventilation can lead to acoustic discomfort, this will not be addressed in our study.

Reducing the energy used by air conditioning is the fundamental challenge in tropical climates. Therefore, the study of thermal comfort conditions is the basis for designing passive buildings for this purpose. To this end, chapter 3 will focus on the experimental feedback on the thermal comfort of the ENERPOS building. The results of a survey conducted during three summer seasons will be presented. This will lead us to recommend improvements of the Givoni comfort zones for a passive building using natural ventilation and ceiling fans.

Following the study of comfort, this thesis will concentrate on the design of passive buildings in tropical climates. Currently, building design focuses more on the sizing of the systems (air conditioning, artificial lighting) rather than on its passive optimisation. A gap exists between the net zero energy goal and the tools that are currently used by designers. This essential change in the building design process

implies that new simulation tools and methodologies are required in order to be able to optimise the passive features of building envelope. The two main passive principles to reduce the energy consumption significantly in buildings in tropical climates are efficient solar shading systems and natural cross ventilation. The study, presented in chapter 4, will concentrate on the design of solar shading as this plays an extensive role in tropical climates and has a direct impact on the thermal and visual comfort of building users. An innovative and multi-physics methodology based on optimisation will be proposed, taking into account the passive behaviour of the building (as opposed to the conventional approach with regard to its energy use) both in terms of thermal comfort and the availability of daylight.

Even though design plays a significant role in the life cycle of a building, the operation phase remains crucial, and yet, this phase is often overlooked or indeed omitted by the architect and the design team. That is what we propose to study, in chapter 5, using the example of the ENERPOS building. This chapter seeks to optimise the building performances in operation through measurements, control actions and energy education. The results of two years of energy monitoring of ENERPOS will be presented, as well as the results of the post-occupancy evaluation that has been carried out on building occupants. Lessons learned through the design and the operation of this demonstration building, that might help subsequent Net ZEB projects, will be shared. Finally, even if particular attention is given to comfort during the design process, comfort remains unique to each individual and users should be able to manage their own comfort conditions. In addition, users should also feel concerned about energy management and they should be informed about the use of the building they occupy. To conclude the work of this thesis, examples of communication methods will be given with the understanding that users are the keystone for a sustainable building.

Chapter

1

NET ZEB IN TROPICAL CLIMATES. CONTEXT AND DEFINITIONS

In our globalised, connected world, the design of buildings incorporating vernacular architecture tends to be overlooked due to lack of knowledge about the local climate. Moreover, the emergence of low-cost mechanical systems and the fact that comfort standards are generally based on Fanger's model imposes narrow thermal comfort ranges that have forced designers to neglect passive thermal control approaches and to equip buildings with mechanical cooling systems. The spread of this practice of mechanisation in the tropics where many developing countries are located could result in an explosion of the energy consumption of buildings. Adopting a passive approach for the design of buildings would be a viable alternative to solve this issue, though particular attention needs to be given to occupant comfort.

In this introductory chapter, the tropical climate is introduced with specific reference to that of Reunion Island, a French overseas department where the research on which this thesis is based, was undertaken. The concept of Net Zero Energy Building (Net ZEB) that is becoming prevalent all over the world is outlined.

On sait bien... où l'on veut aller, mais l'on ignore quand, comment, par quel chemin l'on y parviendra ; inutile de s'en trop soucier d'avance ; on verra bien.

THÉODORE MONOD, MÉHARÉES

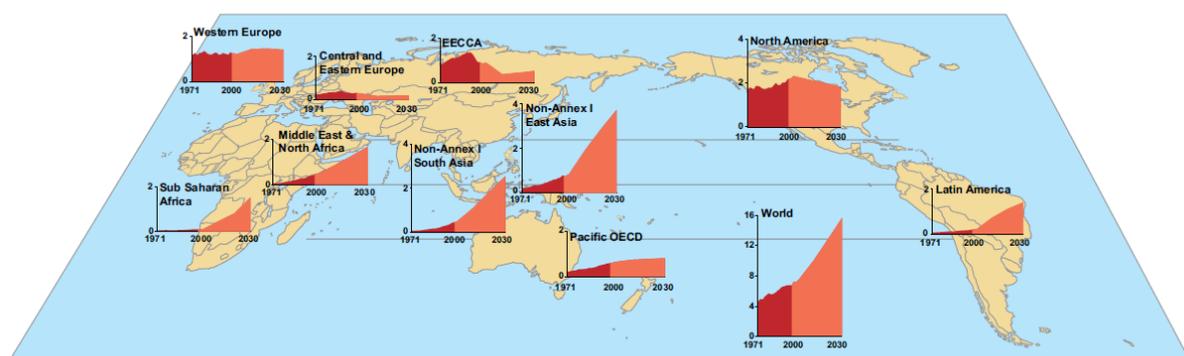
1.1. ISSUES AND PROBLEMS RELATED TO THE ENERGY PERFORMANCE OF BUILDINGS IN TROPICAL CLIMATES

1.1.1. ENERGY ISSUES IN THE TROPICS

The tropical zone between the Tropic of Cancer and the Tropic of Capricorn encompasses approximately 50,000 km² of land, corresponding to one third of the earth's landmass. The population in the tropics already accounts for 40% of the world population and is increasing incessantly. By 2060 it is estimated that at least 60% of the human population will live in the tropics, due to high birth rates and migration (Laar et al., 2002).

More than 3.3 billion people reside in the tropics, mostly in developing countries. Many lack essential goods and services such as food, clean water, medicine and housing. Coupled with the requirement to meet basic human needs, the high economic growth forecast for India, China and Southeast Asia over the next 20 years will result in an unprecedented demand for products and services suited to tropical conditions (Beattie, 2010). The tropical belt – where large areas of Southeast Asia, India, Africa, and parts of both North and South America are located – forms the biggest landmass in the world and has one of the highest numbers of rapidly developing cities (Bay et al., 2006).

Sustainable buildings in the tropics are becoming a major issue of our time. Many of the one hundred countries, which can be classified as having a tropical climate at least in some respects, are on the threshold of becoming industrialized. The energy consumption of those countries will increase with their prosperity. While the current energy consumption per capita in Africa and Asia is approximately 0.5 tons of oil equivalent (toe) and in Latin America approximately 1 toe, the per capita consumption in Europe is estimated at 3.5 toe and in the USA almost 8 toe. The implications of the European or American way of life on the whole world are more than apparent (Laar et al., 2002).



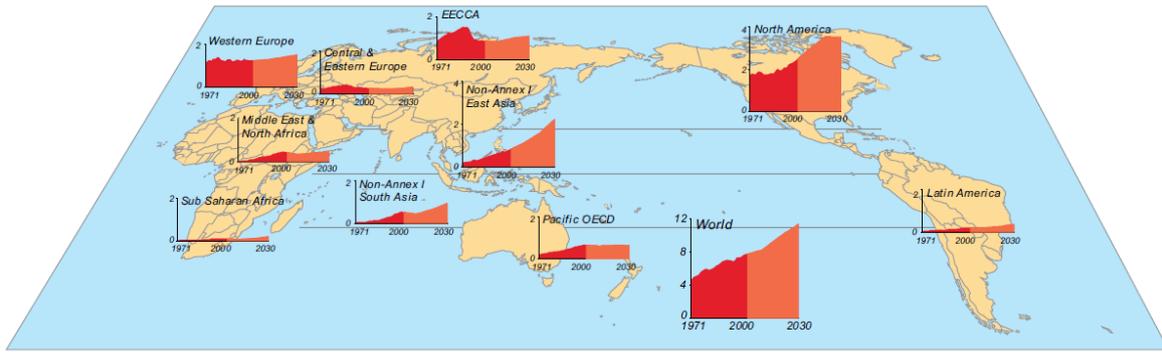


Figure 1-1. CO₂ emissions for residential and commercial buildings: A1B (top) and B2 (bottom) IPCC (Intergovernmental Panel on Climate Change) scenarios. Note: Dark red – historic emissions 1971-2000 based on (Price et al., 2006). Light red – projections 2001-2030 data based on (Price et al., 2006). EECCA = Countries of Eastern Europe, the Caucasus and Central Asia. Source: (Levine et al., 2007).

The CO₂ emission scenarios for the building sector up to 2030 presented in figure 1-1 show that the largest increases will be mainly in the emerging countries located in the tropics. In scenario A1B which predicts rapid economic growth, especially in the developing nations, the entire increase in CO₂ emissions occurs in the developing world: Developing Asia, the Middle East/North Africa, Latin America and Sub-Saharan Asia. In absolute terms, the A1 scenario projects that the two Asian regions will have exceeded the amount of CO₂ emitted in North America, currently the highest emitting region, by 2030. An observation of the climate classification, given in figure 1-2, illustrates that most of those countries that are expected to experience a high increase in CO₂ emissions have a tropical climate. In scenario B2, which has a lower level of economic growth, especially in the developing world (except China), two regions account for the largest proportion of increased CO₂ emissions from 2004 to 2030: North America and Developing Asia.

The majority of the developing nations intend to evolve in a sustainable manner. Sustainable development is defined as the development “that meets the needs of the present without compromising the ability of future generations to meet their own needs”. The task for those who share the goal of sustainable development is to use energy efficiently, intelligently, and wisely. Through the knowledge of both thermal comfort and human behaviour in terms of the energy utilization in buildings, the best strategies can be adopted (Zain et al., 2007).

1.1.2. CHARACTERISTICS OF TROPICAL CLIMATES

A simplification of the Köppen climate classification is given in figure 1-2. The weather conditions of the tropical zone are divided into several climates:

Equatorial climates characterised by a high humidity level, high rainfalls, warm temperatures and low diurnal temperature ranges;

Tropical wet and dry climates characterised by a warm rainy season and a colder dry season. The monthly mean temperature is above 18°C for every month of the year;

Monsoon climates noted as a special category within tropical climates and characterised by a hot and dry season as well as the monsoon season that is hot and very wet;

Hot semi-arid climates characterised by three seasons: a warm and dry season, a hot season and a warm and wet season. Diurnal temperature ranges are greater than 5°C;

Arid climates featuring a hot and typically exceptional hot period as well as a cold period where temperature differences between day and night are significant and precipitations are rare;

Mediterranean climates not located in the tropical zone but whose characteristics can be close to the tropical climates with a warm summer and a temperate winter.

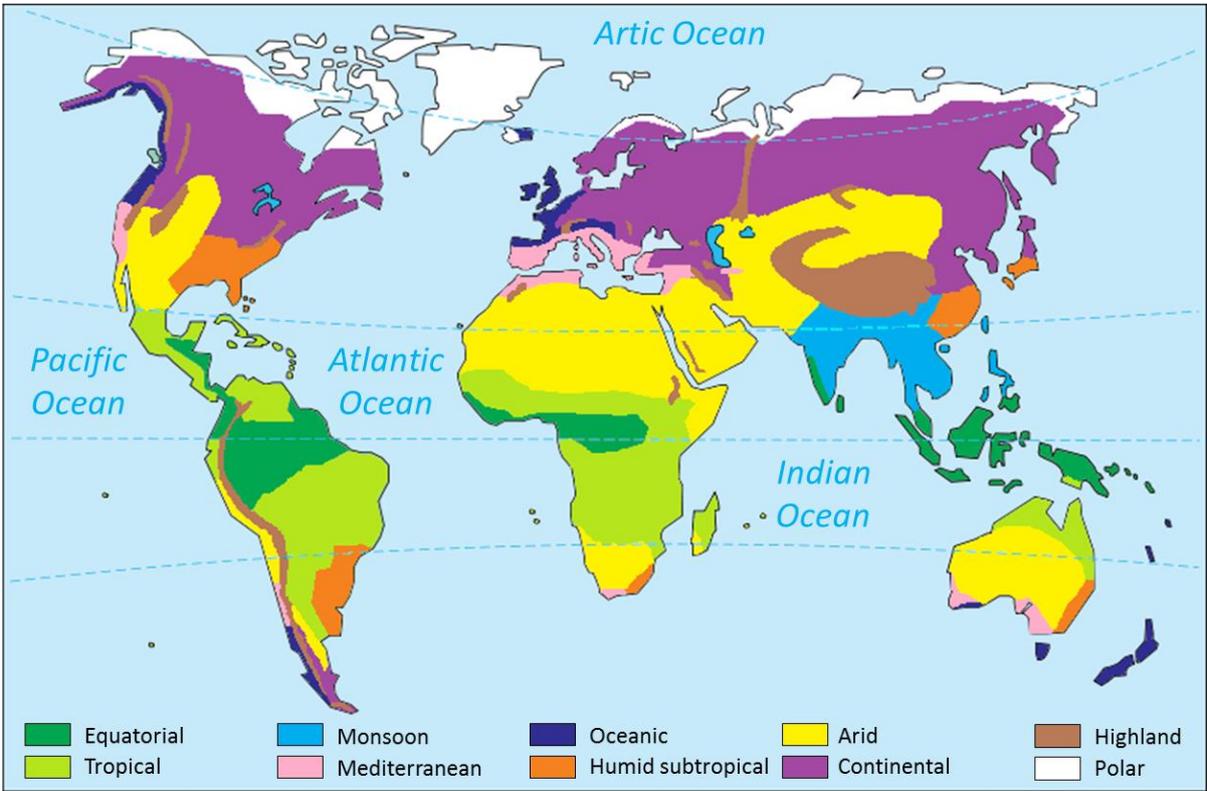


Figure 1-2. World map with the classification of the warm climates - adapted from the Köppen climate classification.

The tropics, whose climate is characterised by hot and humid conditions, lie along the Equator between a latitude of 23° North and 23° South. In the Köppen climate classification (Peel et al., 2007), reference is made to non-arid climates in which all twelve months have mean temperatures above 18°C. Mean annual temperatures reach a maximum of 30°C during the day and 24°C at night. Diurnal ranges tend to be low, approximately 8°C.

The tropical temperature remains relatively constant throughout the year contrary to the area outside the tropics that features strong seasonal variations in day length and temperature. Seasonal variations in the tropics are dominated by precipitation: the year is marked by two seasons, a wet and a dry one. The duration of the wet season decreases in accordance with the distance from the Equator. Humidity levels vary from 60% to 100% and a tropical climate is accompanied by high levels of rainfalls during the rainy season when the annual mean rainfall can exceed 1000 mm. The remainder of the year, the climate is characterised by a lack of rainfall, this is referred to as the dry season. Days and nights are colder with temperatures below 20°C. Monsoons, hurricanes and earthquakes are also typical in tropical environments.

Trade winds influence the tropical wet and dry climate. They blow predominantly from the northeast in the Northern Hemisphere and from the southeast in the Southern Hemisphere, strengthening during the winter.

The main characteristics of this climate are high humidity levels, temperatures and solar radiation.

1.2. REUNION ISLAND: A LABORATORY IN THE TROPICS

1.2.1. THE CLIMATE OF REUNION ISLAND

Reunion Island is located in the sub-tropical area in the Southern Hemisphere off the eastern coast of Madagascar and 200 km West of Mauritius in the Indian Ocean. The longitude and latitude of Reunion Island are: 21.3° South and 55.5° East (see figure 1-3). The climate is humid, tropical along the coastline and temperate in altitude.



Figure 1-3. Map of Reunion Island.

Two distinct seasons are experienced during the year. From November to April, the austral summer is characterised by hot and humid weather with a risk of cyclones and tropical depressions. The temperature along the coastline varies between 26°C and 32°C. By contrast, between May and October, the austral winter is drier and cooler (26°C to 32°C on the coastline) with a predominance of the east to south-easterly trade winds. All year long, the mean solar radiation is significant on the coast (5.6 kWh/m².day and 2,044 kWh/m².y). The diurnal temperature difference is approximately 5 to 7°C and remains constant. This phenomenon is mainly due to the thermal mass of the ocean. The east and the west coasts experience two different rainfall regimes. The downwind coast (west) is protected from the wind and thus is dry, whereas the upwind coast (east) is wetter because of its exposure to the wind.

During the summer season, because of the temperature differences between the land and the water, a wind phenomenon referred to as the cooling breezes, is created (figure 1-4). Land breezes blow from the land to water during the night and sea breezes bring cooler air from the ocean during the day.

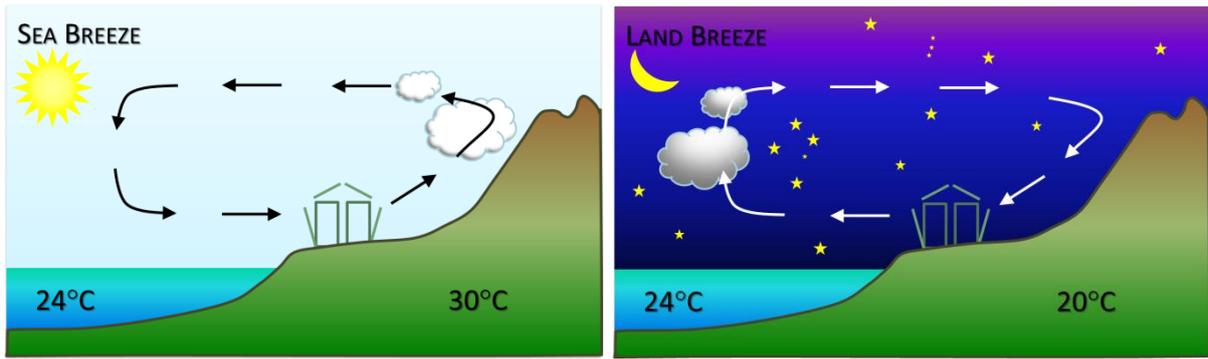
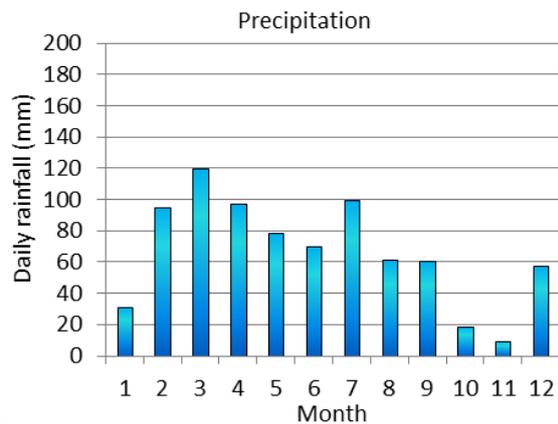
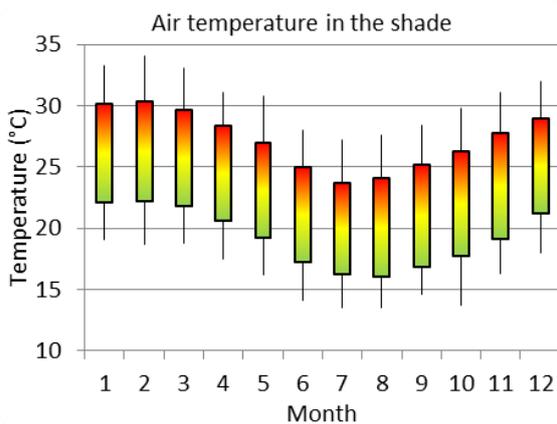


Figure 1-4. Cooling breezes, a wind phenomenon that drives clouds and rainfalls in Reunion Island. Adapted from (Soler, 1997).

The ENERPOS building - which has been used as a case study for this thesis (presented in Appendix A -) - is in Saint-Pierre, the second-largest city located in the South of Reunion Island. The weather conditions in Saint-Pierre for 2011 are listed in table 1-1.

Table 1-1. Weather conditions in Saint-Pierre, obtained from a weather station located in the University Campus (year 2011).

	Average temp °C	Min. temp °C	Max. temp °C	Mean HR %	Mean air speed m/s	Mean global solar radiation kWh/(m ² .day)
Summer	25.4	16.9	31.9	72.4	2.5	6.3
Winter	21.8	15.1	30.0	72.2	2.5	4.7



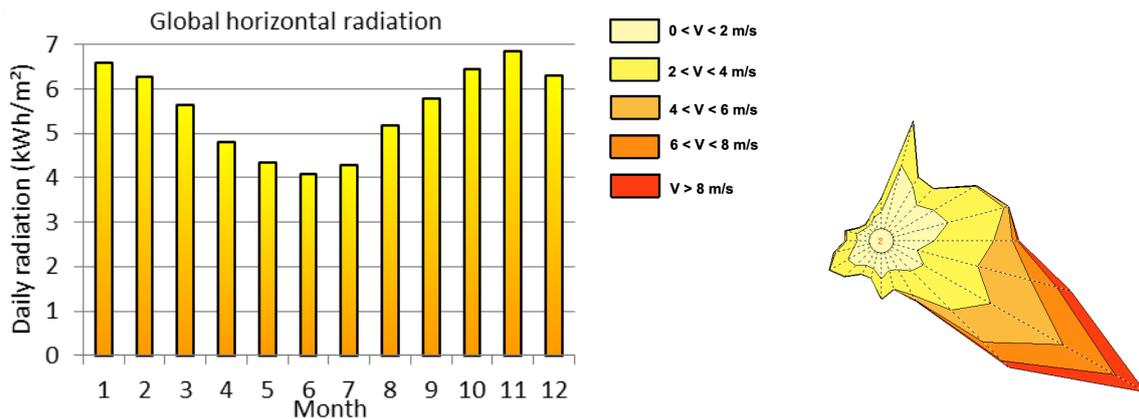


Figure 1-5. Weather conditions in Saint-Pierre (Reunion Island). Source: PERENE².

1.2.2. THE ENERGY CONTEXT IN REUNION ISLAND

The energy context is complicated due to the size of Reunion Island and the lack of energy resources. The economic and demographic growth of the last 20 years have resulted in a sharp increase in energy demand and supply. Between 1980 and 2000, the energy consumption was multiplied by 2.5 while power consumption quadrupled. Hydropower plants, which covered almost all electrical needs in the 1980s, could no longer meet the accelerating demand of the island. The proportion of renewable energy in the electricity mix dropped from 100% in 1982 to 34% in 2010 (ARER, 2011). New oil and coal power plants have emerged to supplement the former means of electricity production. Reunion Island is now dependent on external and fossil resources.

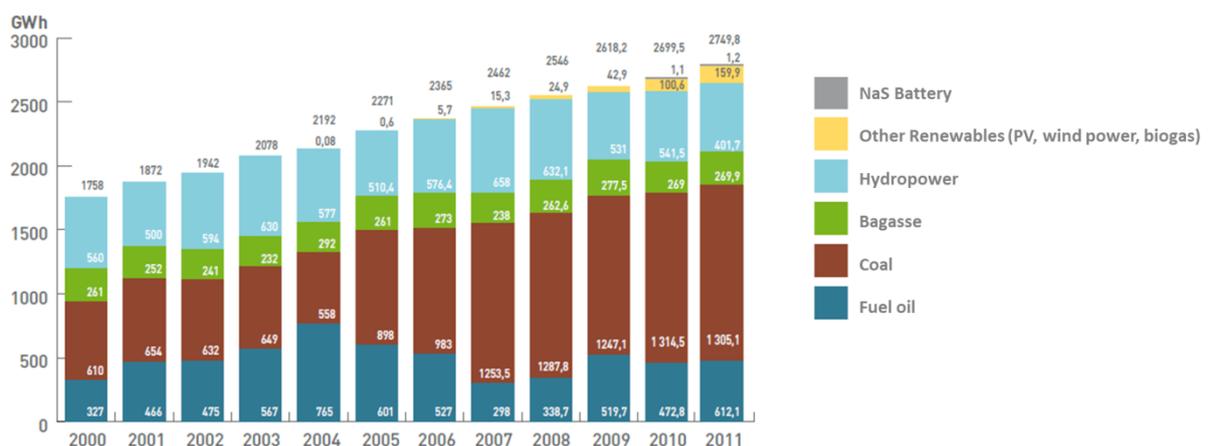


Figure 1-6. Evolution of the electricity generation in Reunion Island from 2000 to 2011. Source: (ARER, 2012).

² PERENE 2009: *Performance Energétique des bâtiments*, French for: “Building Energy Performance” http://www.reunion.equipement.gouv.fr/les_grands_dossiers/reglementation-construction/perene_2009.pdf

The electricity produced is expensive and one of the most polluting in the world with 820 g CO₂/kWh_{el} (close to eight times higher than in mainland France). Electricity shortages occur at higher frequency, often because the French public utility EDF cannot cope with the energy demand in summer. The primary energy conversion factor in Reunion Island is 3.3 which is higher than that of mainland France (2.58). Figure 1-7 presents the performance factors for several national grids. The Reunion Island power grid is amongst the least efficient worldwide, both in terms of pollution and efficiency.

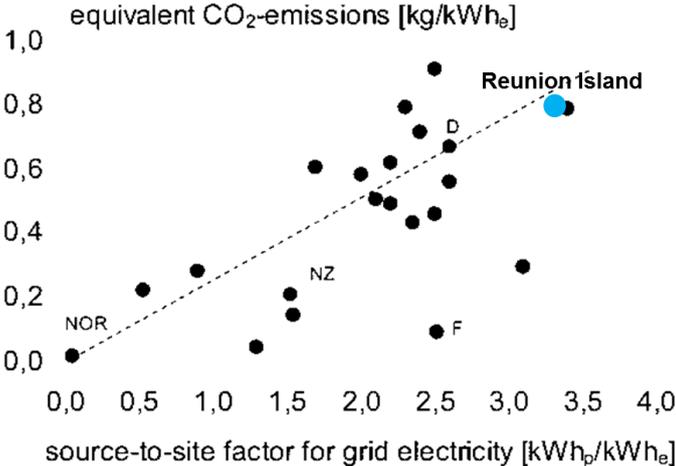


Figure 1-7. Performance factors for national grids. Source: IEA.

To address these constraints, the Regional Council has decided to adopt an active policy of energy conservation and renewable energy development, with the objective of becoming energy self-sufficient by 2030³. The building sector, a high energy consumer, is obviously at the core of this approach.

1.2.3. THE BUILDING SECTOR IN REUNION ISLAND

Currently, the vast majority of commercial buildings are badly designed with no respect for the basic bioclimatic principles; with little or no roof insulation and poor protection from solar radiation. The active systems such as air conditioning and artificial lighting are often over-sized and therefore highly energy consuming. Most buildings are air-conditioned for at least 6 months per year, if not all year long. The average energy index for an office building is 100 kWh_{FE}/m².yr (final energy, per square metre of net floor area and per year) (Lenoir et al., 2011). The three main sources of energy usage are air conditioning (58% of the electricity bill), artificial lighting (12%) and plug loads (26%) for a standard office building (figure 1-8). The efforts in energy savings must focus on these three end-uses, particularly because lighting and computers are mainly responsible for the indoor thermal loads in the building that subsequently increase the need for air conditioning.

³ GERRI: “Green Energy Revolution Reunion Island”, <http://www.gerri.fr>

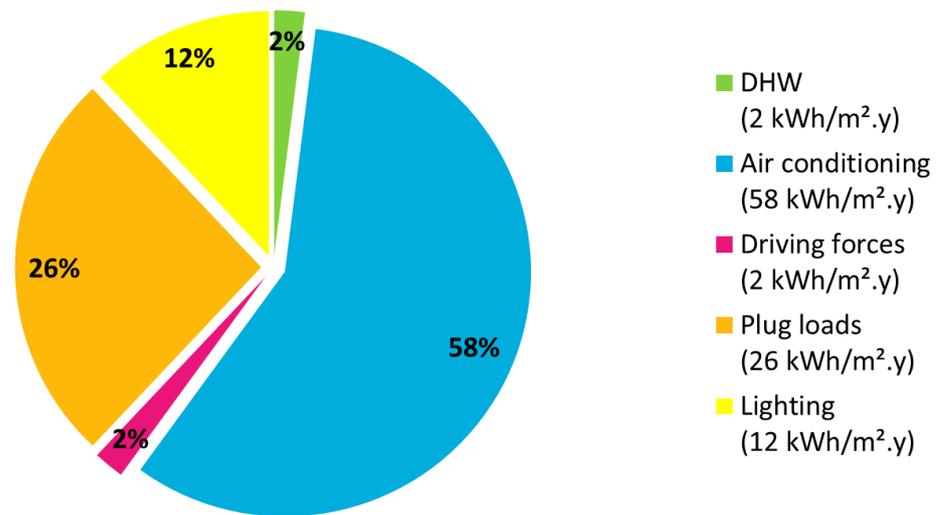


Figure 1-8. Distribution of the use of energy in non-residential buildings of Reunion Island.

There is a wide disparity between the requirements of the energy performance of buildings in mainland France, and more widely in Europe, and those of Reunion Island. Under specific French thermal regulation - RT - enacted in 2012, the target for all new buildings is 50 kWh_{PE}/m².yr (primary energy per square metre of net floor area, and per annum) calculated by counting the five end-uses defined by the RT2012 regulation (heating, cooling, ventilation, interior lighting and domestic hot water). Currently, office buildings in Reunion Island consume on average 200 kWh_{PE}/m².yr (for cooling, ventilation and interior lighting). A ratio of 1:4 exists in order to comply with the energy performance requirements of mainland France in Reunion Island.

Clearly, actions taken to reduce the energy consumed by buildings must focus on the three main sources: air conditioning, plug loads and electrical lighting. Possible solutions to decrease the amount of energy used by air conditioning include passive cooling using natural ventilation and ceiling fans. To avoid the use of artificial lighting, daylight conditions must be improved. Both natural ventilation and daylighting can also be sources of discomfort for the occupants of the building. Therefore, thermal and visual comfort issues should not be overlooked, particularly in tropical climates where the weather conditions can approach the limit of occupant comfort. Chapters 2 and 3 focus on thermal and visual comfort conditions in tropical climates. Chapter 4 proposes a methodology to optimise the design of a building using the comfort approach. Decreasing the amount of energy used by the plug loads is a challenge, as computers and office equipment are a necessity, whatever the professional context. Nevertheless, there is some room for manoeuvre, as we will demonstrate in chapter 5.

1.3. NET ZERO ENERGY BUILDINGS IN THE TROPICS

1.3.1. GROWING AWARENESS OF THE NEED FOR SUSTAINABLE BUILDINGS

MECHANICAL ENVIRONMENT

In developed countries, prior to World War II, buildings using a large array of passive strategies had very low energy consumption. After the war, most architects and engineers were more interested in the potential of air conditioning, ignoring all earlier-used passive strategies. The vernacular architectural styles of the tropics were gradually replaced by sealed concrete boxes without operable windows, fans or external sunshades. The development of low-wattage fluorescent lights led to natural lighting being progressively replaced with artificial lighting. One of the main reasons for the phasing out of the passive environmental techniques was the easily-affordable fossil fuels used to produce electricity.

Moreover, most people in the developed countries now expect that comfort will be maintained continuously by air conditioning systems. As a result, people have become disconnected from the seasonal climatic changes and daily changes in the weather. Expectations of thermal comfort have been shaped by the increasing availability of indoor control technologies and equipment, an issue that environmentally conscious architects have to now address with more efficient strategies to cool building passively.

ENERGY-EFFICIENT ENVIRONMENTS

The economic and ecological crises in the 1970s led to a re-examination of energy use in buildings and a rediscovery of passive strategies. Public concern about environmental issues grew as a result of the oil crisis of 1973. The decrease of energy reserves and a significant rise in fuel costs led to a reconsideration of passive techniques as a free option when it comes to cooling buildings (Zain et al., 2007). Architects, engineers and builders developed strategies to naturally illuminate, ventilate and supply power to buildings.

HEALTHY ENVIRONMENTS

In the mid-1980s when fuel costs were no longer exorbitant, a renewed purpose towards the environmental movement in architecture came about with the pursuit of healthier environments in buildings, by improving air quality and occupant health.

SUSTAINABLE ENVIRONMENTS

By the 1990s, sustainability in architecture started to emerge. Even if there is no easy definition of a sustainable building, a number of rating systems are used to evaluate their environmental impacts such as BREEAM⁴ in the UK, LEED⁵ in the USA or HQE⁶ in France. In Reunion Island, a thermal standard label was developed in 2004. Called PERENE⁷; this label proposes specifications for the building envelope and the systems as well as a requirement to attain a minimum annual energy ratio for all

⁴ BREEAM: Building Research Establishment Environmental Assessment Method, <http://www.breeam.org/>

⁵ LEED: Leadership in Energy and Environmental Design, <http://www.leed.net/>

⁶ HQE: *Haute Qualité Environnementale*, French for : “ High Environmental Quality ”, <http://assohqe.org/hqe/>

⁷ PERENE: *Performance Énergétique des bâtiments*, French for: “Building Energy Performance”

http://www.reunion.equipement.gouv.fr/les_grands_dossiers/reglementation-construction/perene_2009.pdf

types of buildings and climatic zones on the island (Garde et al., 2005). Following five years of experience and feedback, a new label was proposed in 2009 with significant improvements in the design of solar shadings. A simple and quick “rule of thumb” analysis leads to the design of various types of solar shadings and various shapes of windows (Garde et al., 2010).

1.3.2. NET ZERO ENERGY BUILDINGS ARE TO BE MANDATORY ON A WORLDWIDE SCALE

The topic of Net Zero Energy Buildings (Net ZEBs) has received increasing attention in recent years, as a result it is becoming part of the energy policy in several countries. In the recast of the EU Directive on Energy Performance of Buildings (EPBD) it is specified that by the end of 2020 all new buildings shall be “nearly zero-energy buildings” (EPBD, 2010). According to the EPBD, a nearly zero-energy building has a very high-energy performance and its very low energy consumption should be derived predominantly from renewable sources. For the Building Technologies Program of the US Department of Energy (DOE), the strategic goal is to achieve “marketable zero energy homes in 2020 and commercial zero energy buildings in 2025” (DOE, 2008). An international effort on the subject is ongoing in the International Energy Agency (IEA) joint Solar Heating and Cooling (SHC) Task 40 and Energy Conservation in Buildings and Community Systems (ECBCS) Annex 52 entitled “Towards Net Zero Energy Solar Buildings” (IEA, 2008).

The objectives of this Task are to study current Net Zero, Near Zero and Low Energy Buildings and to develop common understanding, harmonized international definition framework (Sartori et al., 2012), new design tools (Athienitis et al., 2010), innovative solution sets and industry guidelines. One of the aims is to provide the people involved in the building process (decision makers, building planners, architects, engineers) with a clear definition of what a Net/Nearly Zero Energy Building is.

Task 40 / Annex 52 commenced in October 2008 and will end in September 2013. It involves approximately 50 national experts from 19 countries, mainly from Europe (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Norway, Portugal, Spain, Sweden, Switzerland, the United Kingdom), North America (Canada and the USA), but also from Australia, New Zealand, South Korea and Singapore. The Task work has been organized into four subtasks:

Subtask A (led by Germany/Italy) aims to establish an internationally agreed understanding of Net ZEBs based on a common methodology (Marszal et al., 2011; Voss et al., 2011);

Subtask B (led by Canada/the USA) aims to identify and refine design approaches and tools to support the adoption of innovative demand/supply technologies in Net ZEBs by the industry (Athienitis et al., 2010);

Subtask C (led by France, Reunion Island/New Zealand) aims to develop and test innovative whole building net-zero solution sets for cold, moderate and hot climates with exemplary architecture and technologies that would be the basis for demonstration projects and international collaboration (Lenoir et al., 2010; Musall et al., 2010; Cory et al., 2011; Lenoir et al., 2011; Lenoir et al., 2012);

Subtask D (involving all national experts) aims to support knowledge transfer and the market adoption of Net ZEBs at national and international level.

In the framework of subtask C, 30 Net ZEBs have been identified worldwide to establish a database and determine innovative solution sets for different building types and climates using a cross analysis. The buildings of the database have been chosen according to 7 criteria:

1. Mandatory monitoring;
2. Net ZEB energy performance < 50% of standard buildings (primary and final energy);
3. Innovative solution sets and/or innovative technologies: ventilation, daylighting, architectural integration;
4. Energy supply/integration of Renewable Energy;
5. Mismatch management (Near or Net zero energy building);
6. Net ZEB lessons learned (feedback from architects, engineers, builders, users);
7. Indoor environment data.

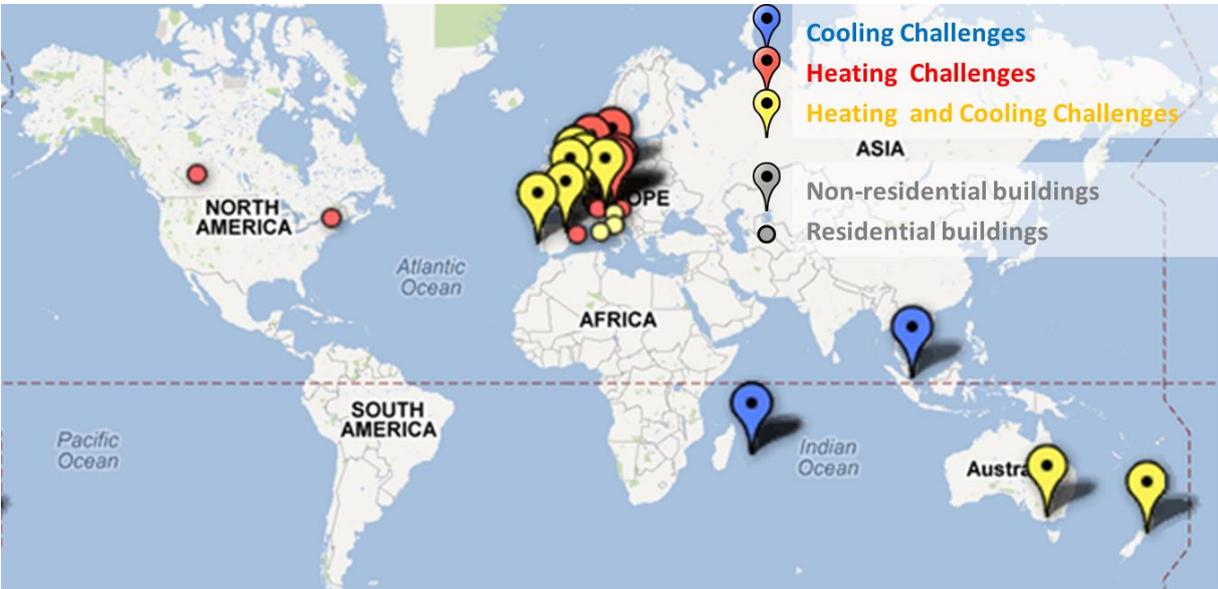


Figure 1-9. Map of the 30 Net ZEBs of the IEA STC database.

1.3.3. A FRAMEWORK TO DEFINE THE NET ZEB CONCEPT

The concept of Net ZEB is still generic, and there is no harmonized understanding of what a Net ZEB really is (Torcellini et al., 2006; Torcellini et al., 2010). A Net ZEB is a building that balances its low-energy consumption using on-site renewable energy.

The most important issues to which special attention should be given before developing a Net ZEB definition are the metric of the balance, balancing period, type of energy use included in the balance, type of energy balance, accepted renewable energy supply options, connection to the energy infrastructure, requirements for energy efficiency, indoor climate and building-grid interactions (Marszal et al., 2011).

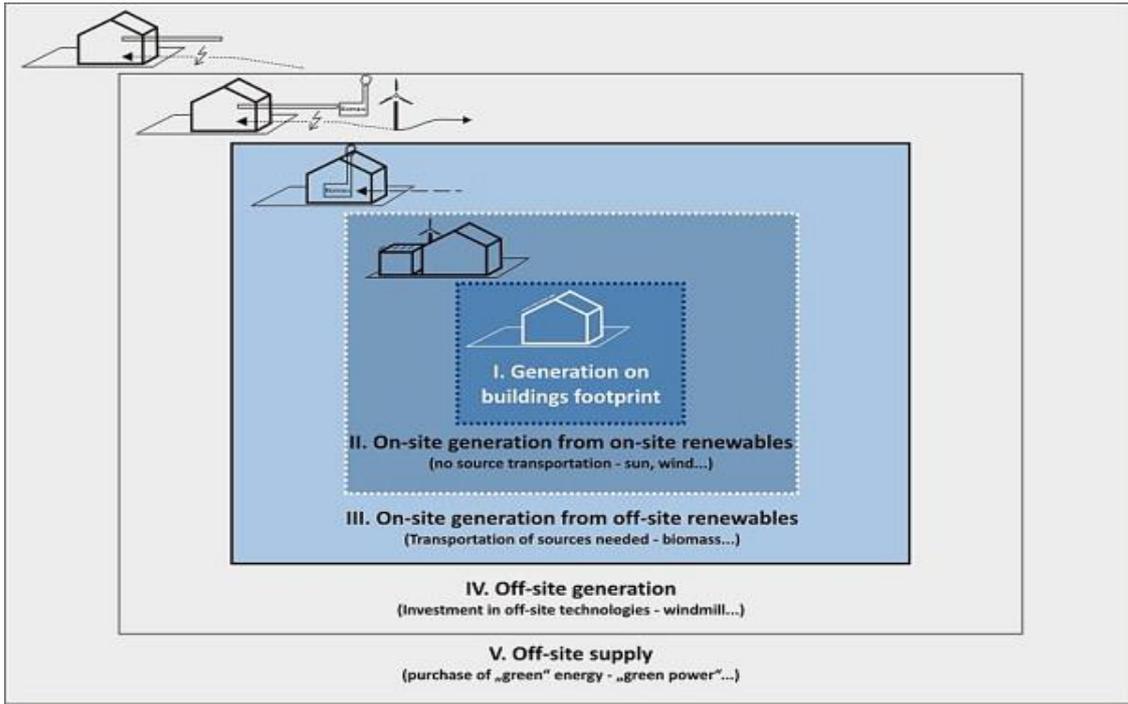


Figure 1-10. Overview of possible renewable supply options. Source: (Marszal et al., 2011).

The term Net ZEB indicates a building connected to the energy grid. The sole satisfaction of an annual balance is not sufficient to fully characterise Net ZEBs and the interaction between buildings and energy grids needs to be addressed.

To characterise the temporal energy match, two criteria can be defined (Voss et al., 2010), (Salom et al., 2011): the Load Match Index (eq. 1-1) and the Grid Interaction Index (eq. 1-2 and eq. 1-3).

$$f_{load,i} = \min \left[1, \frac{on\ site\ generation}{load} \right] \cdot 100 \quad [\%] \quad i = time\ interval\ (h, d, m) \quad \text{Eq. 1-1}$$

All generated power exceeding the load is considered as part of the grid electricity, so that the maximum load match index becomes 100%.

The Grid Interaction Index is based on the ratio of the net grid metering over a given period compared to the maximum/minimum within an annual cycle. A positive value describes a net exporting building. The Grid Interaction Index describes the average grid stress using the standard deviation of the grid interaction over the period of a year:

$$f_{grid,i} = \frac{net\ grid}{\max|net\ grid|} \cdot 100 \quad [\%] \quad i = time\ interval\ (h, d, m) \quad \text{Eq. 1-2}$$

$$f_{grid,year} = STD(f_{grid,i}) \quad \text{Eq. 1-3}$$

1.3.4. DESIGN PRINCIPLES OF NET ZEBs

Two steps must be followed to move from a standard building (reference building) to a Net ZEB. The first one is to decrease the energy demand of the building by using passive techniques, energy efficient systems and by adopting energy conservation measures in the building. The second one is to supply energy to balance the low consumption of the building (see figure 1-11).

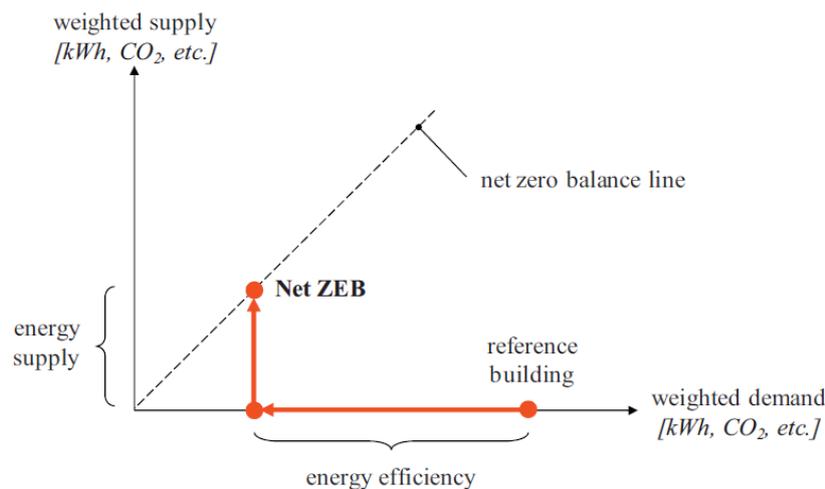


Figure 1-11. Graph representing the Net Zero Energy balance concept. Source: (Sartori et al., 2012).

The pyramid presented in figure 1-12 shows the four different steps to achieve zero energy that are detailed in following paragraphs.

DESIGN AT THE BASE OF THE PYRAMID: OPTIMISATION OF THE ENVELOPE

An appropriate design is very valuable for a building and it often represents the greatest potential for savings as well as the most cost-effective strategies. The envelope of a building plays the role of a passive climate moderator (Henry, 2007). Design measures tend to persist for a long duration, often the entire life of the building, thus it is better to invest in the design rather than in specific components. In most cases, it is impossible or cost prohibitive to correct a poor design. The fourth chapter of this thesis will present a methodology to optimise the building envelope with specific reference to solar shading, taking into account the thermal and visual comfort of the occupants.

ENERGY EFFICIENCY

After the building has been well designed, several efficiency measures can be utilized. Efficiency delivers the same or better benefits to the users without any inconvenience, for example choosing a

more energy efficient air conditioning system that produces the same amount and quality of comfort while using less energy. However, the designer should also bear in mind that efficiency measures are useful only when there is a need for replacement (sometimes by a less efficient measure or system due to cost constraints).

ENERGY CONSERVATION: OPTIMISATION OF THE OPERATION

Energy conservation concerns first and foremost all the control strategies that will be adopted during design in order to reduce energy use, (e.g. motion sensors on light control, programmable thermostats for heating and cooling) but also the process of measurements, verifications and energy education to bring about a change in occupant behaviour during the use of the building.

At the start of the IEA project and during preliminary discussions on how to define a Net ZEB, a question was raised about the monitoring of such buildings. Most certifications of the energy performance in buildings are currently issued on the basis of design input data and several important assumptions, such as weather conditions, user behaviour and how the building is regulated (HVAC plant setting, shading system use). Those assumptions do not reflect the real use of the building in operation and the energy consumptions calculated during design can be very different from the actual data. It is questionable whether the Net ZEB target should be a calculated or a measured rating. For this reason, a proper monitoring of the buildings is of primary importance and should include performance assessments in the operation phase. This monitoring issue is even more essential for high performing and ambitious buildings such as Net ZEB because it is through the feedback and lessons learned from the first experimental buildings of this type that it will be possible to structure the industrial revolution leading to zero energy buildings. To publish industry guidelines with solutions sets, we must have knowledge of the energy consumed or produced by the different systems used in the building. It is important to run POE (Post-Occupancy Evaluation) analysis in order to ascertain the feedback of the occupants. The monitoring issue leads to the achievement of the best compromise between lowering the energy of the building and meeting the comfort of occupants. When designing or studying sustainable buildings, the emphasis is often put on technical systems and their potential for reduction in resource use and resultant ecological loadings (Cole, 2003). Many building sustainability rating tools require a high level of energy efficiency of the building but no conditions are imposed with regard to the indoor environmental quality.

Two main actions were launched on monitoring in the framework of Task 40 / Annex 52. The first one consists in a survey based on seven Net ZEB to obtain information about the measurements and verification protocols of Net ZEB (Napolitano et al., 2011). The second task is to study the 30 Net ZEBs of the subtask C database in order to rank their monitoring levels. On the one hand, in terms of monitoring requirements, it appeared that fewer than 15 buildings out of the 30 have a high level of monitoring with detailed and complete data (eg. monthly data). On the other hand, the literature review of the monitoring of high performance buildings is quite poor (Bøhm et al., 2004; Danny S, 2009; Oliveira Panoa et al., 2011; Wittkopf et al., 2012). It is rare to come across papers dealing with real data and experimental feedback of high performing buildings.

The fifth chapter of this thesis will focus on the optimisation of the building operation developed through three main principles:

- Optimisation of the level of comfort with Post-Occupancy Evaluation and the control of the environment by occupants;
- Energy monitoring of Net ZEB with the example of a case study in Reunion Island;
- Energy education in order to change the behaviour of building occupants.

RENEWABLE ENERGY SYSTEMS

Renewable Energy Technologies (RETs) supply energy from resources that emit fewer Greenhouse Gases (GHG) compared to conventional fossil fuel production. They do not reduce energy use but lower the need for conventional energy sources. Because of the cost of RETs, they should be considered solely when all of the design, efficiency and conservation potentials have been exhausted. However, renewable energy strategies should be explored in the early design phase even if they may eventually be cancelled because early design choices have a great impact on the efficiency of the renewables (e.g. appropriate solar orientation for PV panels).

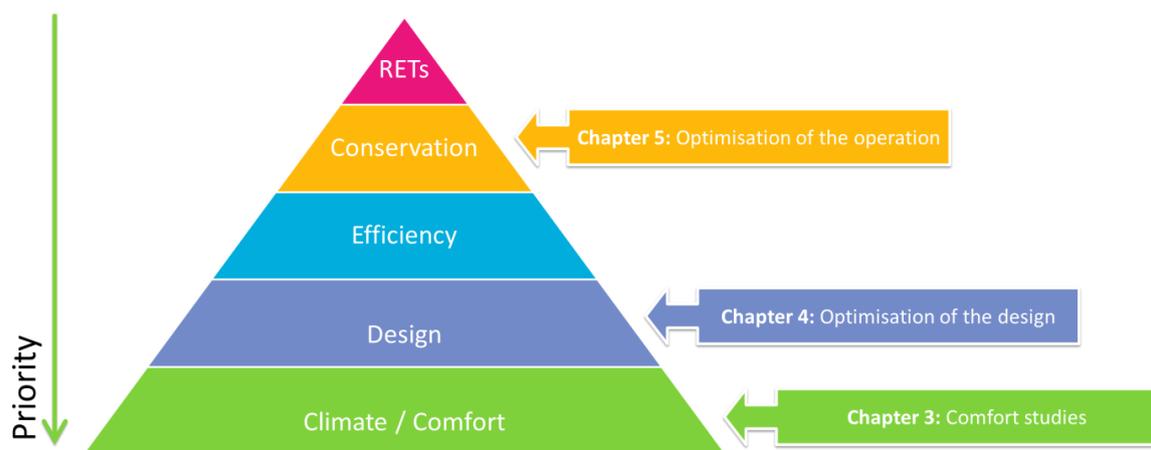


Figure 1-12. Design approach of Net Zero Energy Buildings. Adapted from the energy policy pyramid (Vieira, 2006)

1.3.5. IMPLICATIONS OF NET ZEBs IN TROPICAL CLIMATES

In tropical climates, the maximum energy load of the building occurs in summer when the temperature is the highest that corresponds to the maximum energy generation, occurring when the solar radiation is at its highest. The usual definition taken for Net ZEB is to balance the consumption by the production of renewable energy on an annual basis. In a tropical climate, it is possible to be net zero on a daily basis. The reduction of the energy consumption is mainly reached by fulfilling the basic passive requirements of the building design in tropical climates i.e. cross-ventilation and efficient solar shading systems and by working on the energy efficiency of the active systems (mainly HVAC systems, artificial lighting and computers).

1.4. OCCUPANT CONSIDERATIONS IN THE ACTIVE APPROACH

The development of new technologies has led to high-tech buildings in which highly advanced technological systems with the least possible energy loss have been created, to work towards autonomous buildings. The increased use of equipment and systems to control the indoor environment of sealed concrete boxes has an impact on the energy use of buildings, on the health of occupants and their comfort.

1.4.1. ENERGY

Studies show that a large part of the energy use of commercial buildings is during non-working hours; this sometimes represents more than half of the total energy use of a building. This arises largely from occupants' behaviour of leaving lights and equipment on at the end of the day, the so-called "dark side of occupants' behaviour on building energy use", and partly due to poor zoning and controls (Masoso et al., 2010).

In a building that has large number of equipment, the risk of unnecessary or superfluous energy consumption increases. To mitigate this risk and reduce energy use, there is growing interest in controlling the equipment with building management systems (BMS). The goal of reduced building energy is often coupled with the desire for improved occupant comfort. For both energy and comfort, the most critical systems include heating, ventilation, and air conditioning (HVAC), lighting, as well as electrical appliances and devices.

Today, traditional building management systems lack real-time input of dynamic factors including occupancy, occupant preferences, occupant actions and decisions. Even with this information, current systems still lack intelligent reasoning to deal with such dynamic and distributed input. New building energy and comfort management strategies must be evolved and implemented to adjust both device control and occupant behaviours. Occupant behaviours are defined as actions and decisions taken by building occupants that have an impact on the energy use of their building. These include actions on objects within an occupant's personal control such as doors, windows, lights, and computers, as well as actions of the occupants themselves such as changing clothing, locations, or schedules.

There is also a contradiction between the enormous expenditure of energy required to set up high-efficient systems leading to the least possible loss of energy.

In addition, the designer of a building must always bear in mind operation in the downgraded mode, in case of system breakdown, power failure, or as a result of damage due to bad weather, especially on islands where the grid is unstable and where tropical storms or cyclones are frequent. But, it should also be remembered that a building is constructed for 50 to 100 years whereas the equipment and systems lifetimes are in the order of 10 years.

1.4.2. HEALTH

To improve energy efficiency, modern offices are frequently made more airtight than older structures. Furthermore, advances in construction technology have brought about a much greater use of synthetic building materials. Whilst these improvements have led to more comfortable buildings with lower running costs, they have led to more polluted indoor environments. In most air-conditioned buildings, natural ventilation is impossible or ineffective.

Poor indoor air quality often leads to complaints from building occupants of symptoms such as sensory irritation of eyes, nose, throat, neurotoxic or general health problems and skin irritation. The combination of such symptoms is known as the sick building syndrome and could concern up to 30% of new and refurbished buildings (WHO, 1984). Sick buildings are generally energy-efficient and characterised by airtight envelopes. Studies showed an increase of between 30% to 200% in the prevalence of the sick building syndrome in buildings with air conditioning systems, compared to those with natural ventilation systems (Seppänen et al., 2002). People in such buildings lack control over their environment; for example, the windows cannot be opened. Inadequate maintenance of the building's air conditioning plant may also contribute to the prevalence of symptoms (Vincent et al., 1997).

1.4.3. COMFORT

The comfort of the occupants in buildings is affected by the controls that they can have on their environment and the width of the comfort “zone” will depend on the capacity to control the environment (Nicol et al., 2002). There is more forgiveness with regard to buildings in which the occupants have more access to building controls. If the control is left to the building manager (through the HVAC system) a smaller envelope of acceptable conditions exists, comfort changes more quickly with temperature and the occupants appear less forgiving. However, many modern buildings seem to take control away from the human occupants and try to place control in automatic systems which then govern the overall indoor environment conditions, thus, denying the occupants any means of intervention.

More specifically with regard to visual comfort, several surveys have documented that people believe daylight is superior to electric light in its effects on people. The preference for daylighting is attributed to the belief that working by daylight results in less stress and discomfort than working by electric light (Galasiu et al., 2006).

1.5. THE PASSIVE APPROACH IN HOT AND HUMID CLIMATES

1.5.1. LESSONS LEARNED FROM VERNACULAR ARCHITECTURE

By looking at the vernacular housing architecture in Reunion Island, we see that the veranda or sunroom (called “varangue” in French) is an architectural solution that allows protection from the sun and is open to the wind. The thermo-hydraulic conditions under the veranda are comfortable even during the hottest period of the year.

The main strategies adopted in the traditional architecture in Reunion Island and in other tropical zones consist of limiting the amount of solar radiation and increasing the air movement inside the building to decrease the perceived air temperature.



Figure 1-13. "Kaz créole": the creole house is the typical and vernacular housing in Reunion Island and other French overseas departments. The veranda (“varangue” in French) is an essential element of this architecture; it symbolizes an insular state of mind, Creole dawdling and also the relaxed rhythm of life found in the tropics. Source: information panel at Saint-Benoit high school, Reunion Island, Architect: Perrau / Reynault.

1.5.2. PASSIVE STRATEGIES IN THE TROPICS

This paragraph gives a description of the passive solutions that can be used in hot and humid countries to reduce energy consumption in buildings.

ORIENTATION AND SURROUNDINGS

The north-south orientation of the main facades limits the amount of sunlight falling on east and west gables. Wind directions should be included in the choice of the orientation of the building. Generally, the building should be protected from the trade winds that are strong winds blowing during the austral winter. Cooling breezes that blow perpendicularly to the coasts during the hot season should be

optimised for natural ventilation. To make natural ventilation and daylighting possible, the plan of buildings should be rather narrow, with a depth of up to 12-15 metres (Kleiven, 2003).

In tropical climates and countries experiencing a hot summer, the vegetation is of prime importance. The thermal label for buildings in Reunion Island, PERENE, requires peripheral vegetation at least three metres wide around buildings, in order to avoid letting the air heat up and penetrating the building when it is naturally ventilated. The interest of endemic plants is that they do not need a lot of water to grow and they are well suited for extreme conditions such as cyclones (the roots are vertical, thus the plant is wind-resistant).

EXAMPLE:

Offices of Ilet du Centre, Saint-Pierre

In the offices of Ilet du Centre, a buffer zone is created with a double skin made of strips of wood and a planted area that creates protection from the heat of the street outside.

Figure 1-14 shows the temperature in the street, in the planted patio and in the offices of Ilet du Centre in Saint-Pierre. The importance of vegetation around a building can be seen very clearly as the passive gains in terms of temperature are up to 7°C for the maximum temperature during a very hot summer day.

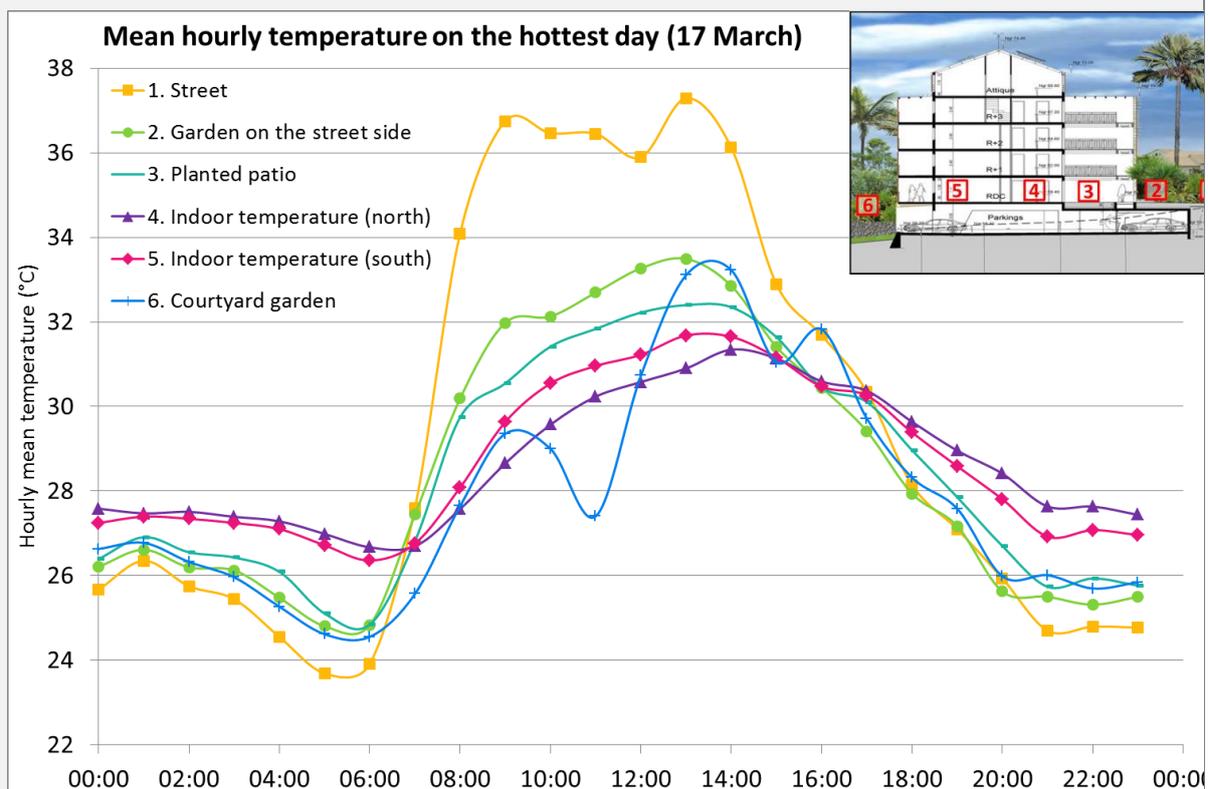


Figure 1-14. Impact of the vegetation on the thermal performances of an office building in Reunion Island. Comparison between temperatures in the street, in the planted patio and in the offices. Source: (Tsiavanga, 2011).

NATURAL VENTILATION

The basic principle in a tropical climate is to have rooms that allow cross-ventilation, by having an opposite exterior facade with a window to wall ratio (WWR or porosity) above 20%. This requirement is outlined in the PERENE label.

Natural ventilation must be provided at night, without the risk of intrusion and with protection from the rain. In Reunion Island, this function is usually performed by louvres. But other solutions are also applicable in France: the use of windows to ensure night ventilation (provided that the problems of rain and intrusion are taken care of), the design of a fully protected opening (glazed or opaque, motorized or not).

Thanks to this principle, it is possible to recycle the air at rates of 40 to 100 volumes per hour with interior speeds of 1 m/s for wind speeds of about 2 m/s.

THERMAL INERTIA

In this mode of building operation based on ventilation and air permeability, it is essential to control all internal and solar thermal loads, but thermal inertia should not be overlooked.

In tropical climates, the diurnal temperature difference is approximately 8°C and remains constant. It is therefore unnecessary, even harmful, to retain the heat of the day in this type of climate. However, in a highly ventilated room, the effects of thermal inertia are overshadowed by those of ventilation. In fact, if the ventilation is strong, we can say that the thermal inertia has only a very small effect on the behaviour of the building and cannot be qualified or as harmful or even less so as favourable, but what is certain is that it is not required.

On the other hand, the art of building in Reunion Island has come to rely more and more on the use of concrete and it is therefore inevitable that a minimum of inertia is present in most new buildings. Floors, walls and facades of the envelope present a significant inertia in many cases. Several precautions should always be taken:

- the control of solar thermal radiation through openings and walls (especially east and west orientated walls) through the thermal insulation of the walls or solar shading for the facades;
- strong ventilation, particularly at night, to eliminate any heat stored during the day.

EXAMPLE:

ENERPOS building, Saint-Pierre, Reunion Island

Figure 1-15 shows the evolution of temperatures in two classrooms, one open and the other one closed, as functions of the outside temperature during a sunny and hot summer day. Both classrooms were unoccupied having the same characteristics of orientation. We can calculate the thermal delay of a classroom, i.e. the time that elapses between the peak heat of the day and when the room reaches its maximum temperature.

The thermal delay of the building is around two hours when the louvres are closed. By contrast, there is almost no thermal delay when the louvres are opened. The effect of inertia exists in this concrete building but when there is natural ventilation, this effect becomes almost non-existent.

This curve also shows the effect of natural ventilation on the indoor temperature. It remains almost always lower than the outside temperature during class schedules. It shows that natural ventilation is an efficient provider of comfort in a building when it is coupled with effective solar shading. However, it should be noted that this result was obtained when the classroom was empty.

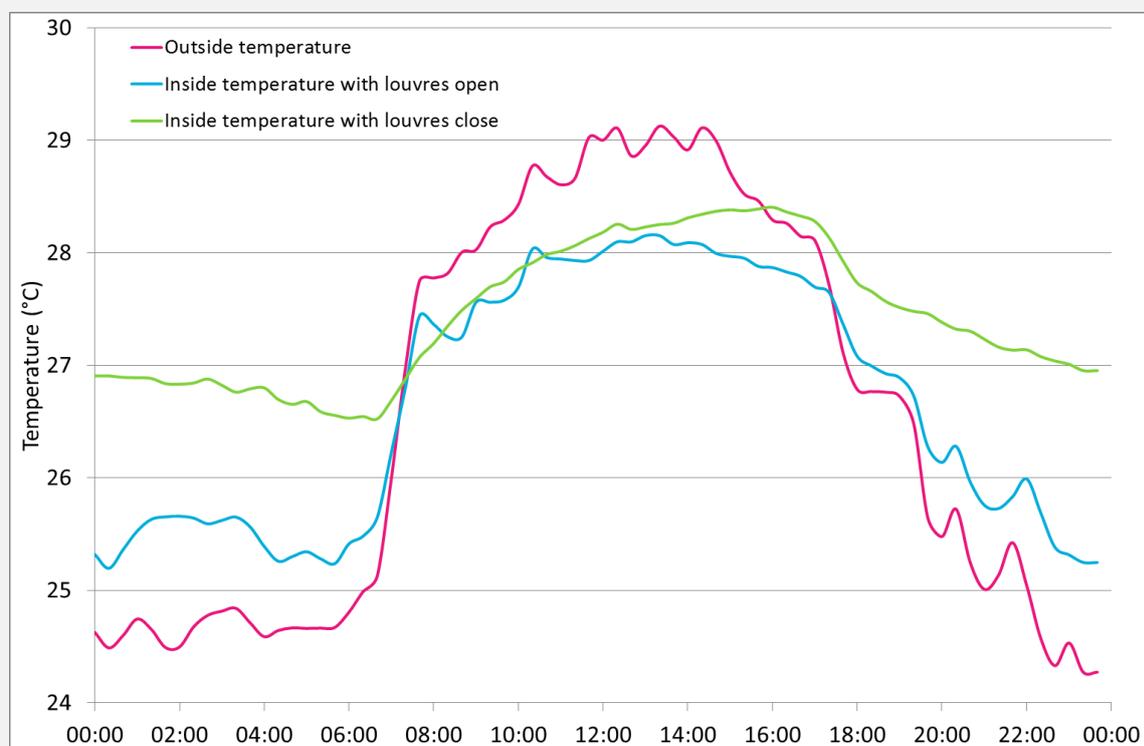


Figure 1-15. Inside temperature of two ENERPOS classrooms (one fully open and the other closed) compared to the outside temperature of a sunny and hot summer's day.

DAYLIGHTING

The utilization of daylighting in buildings may result in significant savings in electricity consumption for lighting (Lee et al., 1998; Tzempelikos et al., 2007) while the benefits in terms of higher productivity of office workers are also high (Heschong, 2002). Nevertheless, large fenestration areas may often result in excessive solar gains and highly varying cooling loads. In addition, intense daylight leads to glare problems, especially for solar oriented facades of office buildings.

SOLAR SHADING

In the tropics and therefore in Reunion Island, buildings are subject to significant cooling requirements due to the high intensity of solar radiation which penetrates through openings. Although the prevention of solar radiation is a crucial factor, one drawback of using shading devices is the risk of reducing the daylight level; as a consequence the use of artificial lighting is increased, this in turn increases the internal loads of the building. Shading strategies can be classified into three groups: natural shading (trees, self-shading based on orientation or shading masks created by buildings in the vicinity); external shading devices (horizontal, vertical and egg-crate) and internal shading devices (venetian blinds and roller screens). Both external and internal shading devices can be fixed or movable.

The best compromise between thermal comfort and daylighting is obviously formed by movable shades that will only stop the sunlight when needed and let in the maximum amount of natural light during the rest of the day. In Reunion Island, this solution is often difficult to implement due to cyclones. Fixed shading should then be completed with a device (which may be internal) to modulate light. However, internal shading devices can be a source of energy consumption rather than an energy-saving tool as researchers have ascertained that blinds or curtains are not usually redeployed to take advantage of natural light when high glare conditions have disappeared.

Experience shows that the solar protection must be provided on all fronts, including the south facades (in the Southern Hemisphere) or north facades (in the Northern Hemisphere). Indeed, these facades still receive diffused solar radiations, as well as direct solar radiations for a few months of the year.

A copious amount of literature is available about the design of solar shading (Dubois, 1997). Previous studies have focussed on its impact on the use of energy, for instance, the guidebook edited by REHVA on how to integrate solar shading in sustainable buildings (Beck et al., 2010). One way to take both cooling loads and natural light utilisation into consideration in the design of shading devices is to study its impact on energy use for cooling and artificial lighting, using an energy simulation programme (Raeissi et al., 1998; Ossen et al., 2005; Tzempelikos et al., 2007). Simple indices are proposed to compare the thermal and visual effectiveness of solar shading in non-residential buildings (David et al., 2011). Those indices also focus on the energy demand of the building including the annual cooling energy and lighting energy.

This methodology is not applicable for passive buildings and thus for Net ZEBs where the aim is to avoid the use of energy. There is a real need for a method based on the comfort approach to design solar shading and to a large extent the envelope of buildings.

A first step was taken in that direction with the development of the PERENE label in 2004 (Garde et al., 2005) and its update in 2009 (Garde et al., 2010). The method proposed by PERENE uses the solar factor S to design solar shading systems. The solar factor S is the ratio of solar energy transmitted by the device composed of glass and solar shading. It is directly proportional to the shading coefficient C_m that is the fraction of the glazing beam solar radiation with and without the use of solar shading. The shading coefficient depends on the type and the size of the solar shading as well as the orientation of the opening. The update of the PERENE label in 2009 includes a method of calculation of C_m by

proposing a wide range of solar shading: overhangs (infinite or limited to the window), overhang with left and/or right side fins as well as horizontal slats.

However, this methodology does not take into account the availability of daylighting in the room. As a consequence, the PERENE label can lead to the design of gloomy buildings integrating too much solar protection in which the use of artificial lighting is required almost all year round.

The real need lies in the development of a methodology which will take both thermal and visual comfort for the design of solar shading into account. The fourth chapter of this thesis investigates the effect of solar shading on thermal comfort as well as daylight availability to propose a methodology to optimise the design of solar shading.

DESIGN OF THE FACADE

In a bioclimatic approach, the facade is an essential component of building, providing a filter with respect to different dynamic flows between the inside and outside (solar radiation, light radiation, heat flux, air movement, sound waves...). It allows protection from the outside environment and also draws its energy from the sun, outdoor air, soil, and wind. It will be characterised by:

- the strong presence of effective shading, i.e. external. Thermal insulation can be used to protect the facades without openings and that will not necessarily need solar shading;
- the presence of a device for natural ventilation allowing for the opening, closure or modulation of the flow of air between the outside and the inside;
- the acoustic protection of the facades in noisy areas with acoustic devices suitable for natural ventilation or double facades.

EXAMPLES:

High School “Saint-Benoit IV”, Reunion Island

An example worth considering is the “Lycée Saint-Benoit IV”, a high school located in Saint-Anne on the East coast of Reunion Island where rainy and windy weather prevails. These premises are composed of approximately ten buildings whose width does not exceed 10 metres in order to naturally ventilate and light the classrooms and offices. All the buildings are raised on stilts, creating green spaces around and under the buildings, so that the permeability of the soil is increased, and allowing greater water infiltration. In the classrooms, daylighting is optimised by the use of light shelves inside and shading outside.



Figure 1-16. High school in Saint-Anne, Reunion Island. Architects: Antoine Perrau / Michel Reynault.
Picture credits (left): Jérôme Balleydier.

Residence “Ilet du Centre”, Saint-Pierre, Reunion Island

At the residence and offices of Ilet du Centre in Saint-Pierre, all dwellings are naturally cross ventilated. The offices are located in an open space, naturally cross ventilated with louvres on both the north and the south façade. The frosted glass panels are very useful for natural daylight while preserving the intimacy of the office occupants. A buffer zone is created with a double skin made of strips of wood and a planted area that acts buffer from the heat of the street. Walkways are distanced from the façade to increase the privacy of the residents.



Figure 1-17. Residence and offices of Ilet du Centre. Architects: Antoine Perrau / Michel Reynault.
Pictures credits: Hervé Douris.

ZEB@BCA Academy, Singapore

The ZEB @ BCA Academy project is located in Singapore and is one of the 30 case study buildings of the Task 40 Net ZEB database, facing cooling dominated challenges. It is intended as a demonstration of the efficient use of energy in a building through both passive and active means. Glazing, lightweight wall systems, shading devices, light shelves and green walls are incorporated into the west facade. The roofs are covered with solar panels to generate sufficient electrical energy to be self-sustaining. A part of the roof incorporates a ventilation stack to test the effect of convection air movement within a naturally ventilated environment.

The principle behind solar chimney ventilation is the buoyancy of air. Air in the chimney expands when heated by the sun and being relatively lighter, it rises, allowing cooler air to enter the building through the openings. This pull effect is complemented further by the push effect of the ambient wind. During a typical hot day, the surface temperature of the solar chimney can reach up to 60°C, while the air within can achieve a temperature of 47°C and a speed of 1.9 m/s. This leads to a positive temperature time lag of one to two hours in the classroom, a higher air speed reaching a maximum of 0.49m/s and an average of 9 air change rate per hour (ACH) in the afternoon.

Vertical greenery systems are installed on west façade. Both vertical and rooftop greenery systems provide shading on the building façade and roof to reduce the heat gain in the building, and enhance the cooling effect due to evapotranspiration. The study shows that there is a significant reduction in the temperature of the wall and the roof surface being shaded by the greenery systems. The reduction is up to 10°C for the vertical greenery on west façade, 6°C for the vertical greenery on south façade, and 24°C for the rooftop greenery.

Light shelves have been installed on west facade windows. Field measurements were conducted to compare the performance of light shelves with and without a reflective surface during the afternoon. The results showed that the light shelves with a reflective surface can increase the illuminance level by 50 to 100 Lux; however, they increase the mean radiant temperature by approximately 0.5°C.



Figure 1-18. ZEB @ BCA Academy, Singapore. Architects: DP Architects. Source: Task 40 Net ZEB database.

Fixed and mobile solar shading

Solar shading is essential in tropical climates to control the amount of heat and light admitted to a building. Several types of fixed or mobile shading can be used depending on the orientation, on the type of building and on architectural choices: overhangs, side fins, vertical or horizontal external blinds. Some examples are given in the pictures below.



Figure 1-19. Examples of fixed solar shading. Left: Residence of Flores-Malaca, Le Port, Reunion Island. Architects: Antoine Perrau / Michel Reynault. Right: Head office of CIREST, Saint-Benoit, Reunion Island. Architects: Sylvain Guy / Guillaume Hazet.



Figure 1-20. Examples of mobile solar shading. Left: University housing and offices of CROUS, Saint-Denis, Reunion Island. Architects: T & T architecture. Right: Head office of DIREN, Saint-Denis, Reunion Island. Architect: Olivier Brabant.

WEATHER DATA PRESENTED ON THE BIOCLIMATIC CHART

The bioclimatic chart, represented in figure 1-21, combines the weather data of Saint-Pierre with the specific boundaries of the passive cooling techniques overlaid on the psychrometric chart. These techniques include evaporative cooling, thermal mass, natural ventilation cooling and passive heating. According to this chart, the best design strategies in Saint-Pierre are those incorporating passive heating in winter and mostly natural and mechanical ventilation in summer. The study of thermal comfort with air movements is therefore crucial in the design of passive buildings which are in harmony with the climate.

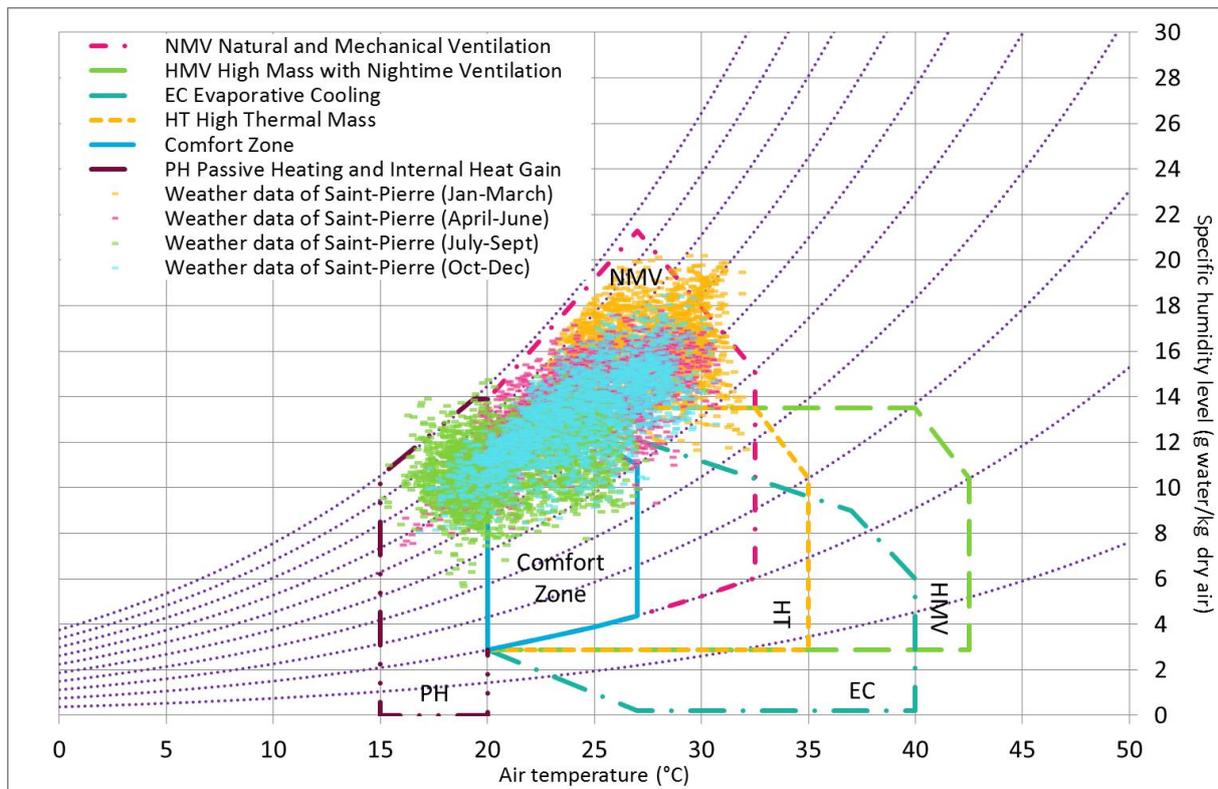


Figure 1-21. Bioclimatic chart: Saint-Pierre weather data illustrating the main passive strategies in hot and humid climates.

COMFORT CHALLENGES IN THE BUILDING DESIGN PROCESS

Problems of thermal and visual comfort in passive buildings will be studied in chapter 2 with a bibliographical study of comfort in hot and humid climates and its modelling in the design of a building. The thermal and visual comfort of a passive building in operation will be studied using experimental results in chapter 3. Chapter 4 will focus on the optimisation of the building envelope with particular emphasis on solar shading which is a critical component in passive buildings in hot and humid climates. The purpose of this type of optimisation is to improve the thermal and visual comfort of the occupants while reducing the use of active energy consuming systems.

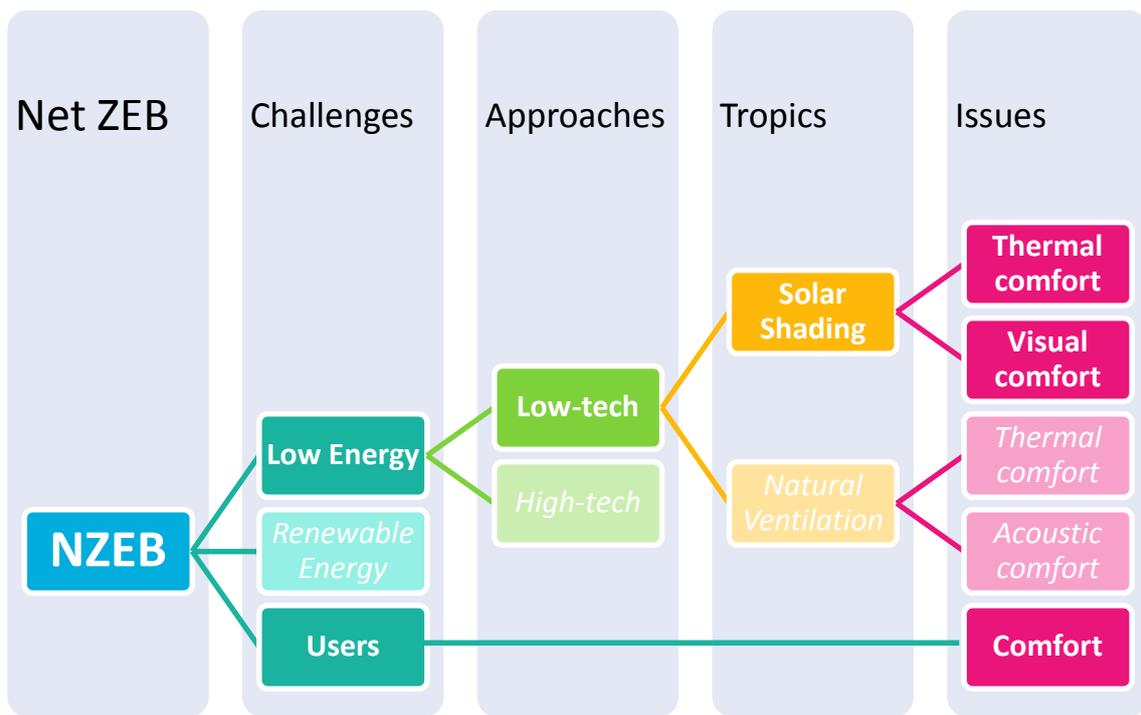


Figure 1-22. Description of the design challenges, approaches and issues of Net-ZEBs in tropical climates. This figure summarizes the aspects that are dealt in this PhD work.

1.6. SCIENTIFIC AND TECHNOLOGICAL STAKES

1.6.1. RISKS ASSOCIATED WITH THE PASSIVE AND ACTIVE APPROACHES

In this chapter, two approaches have been presented for the design of low energy buildings in hot and humid climates.

In the active or system approach, even if high efficient systems are preferred, there is a major risk that the energy use will be high. On the one hand, if there are not enough controls of the systems, the users can use them when it is not necessary or leave equipment on when leaving the building, leading to an unnecessary increase in the consumption of energy. On the other hand, too much control on the systems will leave the occupant with no control to monitor his/her own environment. In this case, the comfort zone will be reduced and the occupants will appear less forgiving on the indoor environment. Added to this is the fact that health problems may be increased by the tightness of air-conditioned buildings and poor system maintenance. Besides, the systems selected during design are only effective until they are replaced, often with less effective equipment due to the cost. In all cases, it is complex to find a satisfactory compromise between comfort and energy use.

In the passive approach, comfort issues can also appear. The role of the user is highly important in this type of building because all actions carried out have a high impact not only on the energy use but also on the occupants' own comfort. This will be discussed in the following chapter.

1.6.2. DESIGN PROCESS ISSUES

The design process of a building still has issues that need to be studied. The issues come from the building performance simulation tools that are not always adapted to the design process, which are not always properly used by architects or engineers and from which it is sometimes difficult to understand and interpret the results (Lenoir et al., 2012). Furthermore, a lot of assumptions are made throughout the design process that could lead to uncertainties that even if they cannot be eliminated, they should always be checked against the performance results that are obtained.

SIMULATION TOOLS

Performance simulation applications are developed and applied by people. Professionals (architects, engineers, researchers, educators) are expected to use performance simulation tools to understand, analyse, and predict the behaviour of buildings. For such tools to be effective, it is necessary but not sufficient for the embedded algorithms to be reliable. Simulation environments must also exhibit a high degree of usability in order to facilitate generating building models effectively and process simulation results toward decision support throughout the building delivery process.

The design simulation tools need to be adapted to the design offices. The last decade has seen multiple advances of how to analyse the overall performance of buildings numerically. Dynamic thermal simulation is becoming an essential part of successful building design. However there is a gap between the expected energy performance of buildings in the future and the tools used by engineers. The

working habits focus more on the sizing of the systems (air conditioning, artificial lighting) and not on the passive optimisation of the building. For example, the current daylighting design practice still favours the use of rules of thumb during schematic design and largely relies on the daylight factor and illuminance distributions under clear sky conditions during solstice and equinox days (Reinhart et al., 2011).

There are several barriers to the adoption of these technologies and tools:

Cost-prohibitive tools: Many countries located in the tropics are developing countries. That means that the basic HVAC practice cannot afford expensive CAD or simulation tools. This implies that open source and efficient simulation tools must be suggested. This was one of the results of the French National Research project ENERPOS that focused on the development of new methods and tools for the design of Net Zero Energy Buildings in hot climates (Garde et al., 2011);

No single simulation environment: A part of the problem may be that different technical advances, in terms of thermal performances, daylighting, comfort or specific systems, etc. have been made in different simulation environments and without appropriate graphic user interfaces. Besides, most of the time, the CAD tools used by the architect cannot communicate with the simulation tools used by energy consultants and it is usually impossible for them to use the 3D-model drawn by the architect. It is therefore time-consuming to draw the building in each of the simulation tools used by the design team to study each aspect of the performance of the building. The interoperability between simulation applications and other digital tools and environments used in the building delivery process promises more efficient patterns in relation to the deployment of tools;

Simulation time: Another practical concern is that some of the advanced simulation techniques tend to require prohibitively long computation times for implementation by a design team in a standard project. It is especially true for ray tracing daylighting tools such as Radiance or for the study of natural ventilation with CFD tools;

Too complicated a simulation process: The poor and difficult-to use interfaces and the lack of interoperability is a barrier to the use of efficient simulation tools by designers;

Misuse of tools: Building performance simulation is rarely applied by primary building designers toward optimisation of early designs. Rather, simulation is typically conducted late in the process by specialists for design verification and system configuration. For example, generally the lighting tools used by engineers are developed by the light manufacturers only to determine the number of luminaires required to reach the minimum illuminance level;

Inability to interpret simulation results: An additional barrier is that casual software users - even if they manage to produce correct simulations - oftentimes lack the expertise to interpret the simulation results as well as the know-how to correct design problems raised by the simulation. The multitude of currently available performance simulation tools provides a broad range of simulation results. Moreover, these results are computed, formatted, and presented in very different ways. Indicators that come from European countries, such as daylight factors, are not adapted to the tropical climate and lead to oversized lighting devices. The evaluation of alternative designs based on the comparison of performance indicator values require appropriate and effectively supported methods for information visualization and data aggregation in spatial and temporal domains. An important step in

this direction would be the development of well-structured and generally applicable data classifications as well as schemes for building performance indicators.

ASSUMPTIONS AND UNCERTAINTIES

The lack of discussion between the people involved in the design process, i.e. the architect and the engineers, is an obvious weakness in optimising the passive design of the envelope and the systems. Throughout the design process, several assumptions are made that do not necessarily represent the project reality. These sources of errors due to inadequate exchange between the different actors of the project show that it is not possible to describe the real situation of the building during design.

Assumptions made about the users will also lead to uncertainties. The occupancy schedules and usage scenarios have a direct impact on the energy use predicted during design (e.g. reduced cooling set point compared to the initial design will lead to differences between prediction and reality). These can only be estimated when designing buildings.

Finally, the goal of simulation in the design process is not to describe the real situation, but to optimise the passive behaviour, the use of systems and the operation of the building. Too often, the simulation tools are used during design to size the systems only, whereas they should be used to optimise the building envelope before adding systems, if necessary.

1.6.3. SCIENTIFIC ISSUES

To all risk of errors previously stated may be added those arising from the simplifications of physical phenomena that are difficult to describe such as natural ventilation or inertia.

Concerning natural ventilation, the design of the doors and windows in the facade is performed during the preliminary design. Much research has been carried out on the modelling of natural ventilation by decision support tools, but also on more precise tools for detailed simulations of the ventilation behaviour of the building (Stephan, 2010). Consulting firms are starting to use this type of tool to model the impact of natural ventilation on the thermal behaviour of buildings. But given the length of the simulation time and the unreliable results, these tools are not yet suitable for the building design process. Inertia which also influences the thermal behaviour of buildings is also poorly described in the simulation tools currently available.

This chapter has shown that there are different ways to save energy, but the first essential one is to ensure occupant comfort in buildings. It is not possible to optimise the design of a building without studying comfort. Comfort and occupant behaviour are fields that are difficult to describe physically and whose assessment can only be subjective. This will be dealt with in detail in chapters 2 and 3.

This thesis will focus on optimising the passive approach of bioclimatic buildings and will not deal with the active approach. Chapter 4 concentrates on the optimisation of the building envelope with particular emphasis on solar shading which is a critical component in passive buildings in hot and humid climates. The purpose of this type of optimisation is to improve the thermal and visual comfort of the occupants while reducing the use of active energy-consuming systems.

Chapter

2

ENSURING COMFORT IN PASSIVE BUILDINGS IN TROPICAL CLIMATES

When one addresses a subjective concept such as thermal and visual comfort, it is always difficult to determine an appropriate equation in order to define it mathematically. Each person is unique and there is no absolute truth about comfort as it is unique to each of us. In this chapter, we present the interactions between the building and its occupants that affect the thermal and visual environment and consequently comfort conditions. In particular, in the case of the design of passive buildings, the aim is to limit discomfort inside by reducing the use of energy-consuming equipment (e.g. air conditioning, artificial lighting) that would otherwise be required to ensure comfort.

There is, therefore, an essential need for methods to characterise comfort in relation to the physical parameters of the environment. The method that is proposed here does not purport to maximise or optimise comfort, but rather to limit the main sources of discomfort. This chapter will present different approaches to thermal comfort to introduce the concept of comfort zones. Visual comfort indicators will also be introduced in order to maximise the use of natural lighting while minimising some risks associated with visual discomfort.

This is no time for ease and comfort. It is time to dare and endure.

WINSTON CHURCHILL

2.1. COMFORT ARISES FROM INTERACTIONS BETWEEN THE BUILDING AND ITS OCCUPANTS

Comfort signifies strong interaction between the occupant and the building and several configurations are possible:

- The building influences the occupant;
- The occupant acts on the building;
- The building and occupant influence each other.

The investigation of comfort conditions leads to study phenomena where multiple factors interact.



Figure 2-1. The interactions between building and occupants leading to comfort. Adapted from (Nicol, 2007).

2.1.1. INDOOR AIR QUALITY IN LOW ENERGY BUILDINGS

The life-style of the urban population has been rapidly changing over the past decades. The increased amount of time spent indoors, even in tropical countries, has brought the question of indoor air quality (IAQ) to the fore on a worldwide scale. People spend 80-90% of their time indoors, and the indoor environment has important effects on human health and work efficiency. The factors associated with the perceived IAQ are not fully understood. They mainly include temperature, humidity, air exchange rate, air movement, ventilation, particle pollutants, biological pollutants, gaseous pollutants and psychosocial factors (Jones, 1999).

One of the consequences of the worldwide energy crisis in 1970s is the public recognition of the importance of energy saving. However, the measures adopted to reduce the consumption of energy can be conflicting with both comfort and air quality issues. For example, in order to reduce the heating or cooling demands, buildings have become more airtight and the use of fresh air is reduced in air conditioning systems. Meanwhile, synthetic materials and chemical products (e.g., building materials and decorating materials) have been widely used indoors. The combination of low ventilation rates and the presence of numerous synthetic chemicals result in elevated concentrations of indoor particle pollutants and volatile organic compounds (VOCs).

The need to address this user behaviour issue has become more significant in the development of ambitious, energy efficient building concepts. User behaviour will have a relatively larger impact on total energy consumption. For bioclimatic buildings that follow the daily and seasonal climate changes, thermal comfort is hard to maintain and overheating may occur. Hot and humid climates are the most difficult ones to design for. The temperature maxima may not be as high as in the hot-dry climates, but the diurnal variation is minor (less than 10°C), thus the “mass effect” cannot be relied on. As humidity is high, evaporation from the skin is restricted and evaporative cooling will neither be effective, nor desirable, as the level of humidity would increase even more.

Natural ventilation is a satisfactory option to design low energy buildings in tropical climates, but other comfort issues such as acoustics and draughts can also arise. With daylighting the use of artificial lighting is reduced; it must however be noted that both glare and direct sunlight are sources of visual discomfort in a building.

2.1.2. THE ROLE OF THE USERS IN BUILDINGS

Energy performance in buildings is directly linked to their operational and space utilization characteristics as well as to the behaviour of their occupants. Users have influence due to their presence and activities in the building, but also their control actions to improve thermal and visual comfort (Hoes et al., 2009).

In passive buildings, indoor comfort (thermal and visual) should be achieved thanks to free natural resources of energy such as the sun and wind, with active energy-consuming systems used only as a last resort. Consequently, the users’ behaviour has a high impact on the final energy use depending on their utilization of active systems when this is not necessary. As buildings become more energy efficient, the behaviour of occupants plays an increasingly significant role (Lenoir et al., 2012).

Two roles can be distinguished for building users leading to either a passive or an active effect (Mahdavi, 2011). The passive effect is caused only by the presence of people in the building. This plays a role on the hygro-thermal conditions of the building. Man degrades energy substrates continuously, consuming oxygen, producing carbon dioxide, water and emitting energy in order to ensure all vital functions. Even while at rest, a hundred watts are constantly produced and the energy released as sensible and latent heat spreads from inside to outside the body. Depending on their activity, people release more or less heat. In the majority of cases, the passive effects due to the people’s presence in the building are modelled with standard occupancy schedules depending on the type of building.

Buildings are typically equipped with components and systems that can act as control devices. Windows, shades, luminaires, fans, and other similar devices can be operated by building occupants with the intention of bringing about desirable indoor conditions (Mahdavi et al., 2006). The actions users take to influence the indoor environment are referred to as people’s active effects.

2.1.3. PERCEPTION OF COMFORT AND THE FORGIVENESS FACTOR

The perception of comfort in the indoor environment is a complex process consisting of several aspects such as physical wellbeing, privacy, acoustics, visual comfort, air quality, materials, ergonomics, spatial design. Complaints about thermal comfort are the most common complaints in office buildings. Several studies show that a comfortable working environment will lead to increased productivity and reduced sick leave days (Leaman et al., 1997; Tanabe et al., 2007; Akimoto et al., 2010). The more comfortable people say they are the more productive they say they are (Leaman et al., 1997).

There are other aspects of building services which affect the comfort of occupants. There is more forgiveness of buildings in which occupants have more access to building controls (Leaman et al., 1997). Also, occupants with higher levels of environmental concern are more tolerant of their building, particularly those featuring aspects of green design, such as naturally-ventilated facades and operable windows (Deuble et al., 2010).

Forgiveness means that the attitude of the occupants towards the building is affected so that any shortcomings in the thermal environment will be overlooked more readily. In buildings where the occupants are in control, variability may result from people adjusting conditions to suit themselves.

2.1.4. ADAPTIVE OPPORTUNITIES

The adaptive capacity is the property of a system to adjust its characteristics to expand its coping range. People have a natural tendency to adapt to changing conditions in their environment. This natural tendency is expressed in the adaptive approach to comfort that states that:

“If a change occurs such as to produce discomfort, people react in ways that tend to restore comfort.”

(Nicol et al., 2002)

In thermal comfort literature “adaptive opportunity” is defined as the ability of a building occupant to make adjustments to the local environment (behavioural adaptation) or to one’s own state (psychological and/or physiological adaptation). The range of conditions considered comfortable is affected by the characteristics of the building and the opportunities for individual adaptation by occupants. Occupant control is a key element in adaptive thermal comfort but it also includes dress code, working practices and other factors which influence the interaction between the occupant and the building. Changes in clothing, activity and posture as well as the promotion of air movement will change the conditions which people find comfortable (Table 2-1). Many of the adaptive opportunities available in buildings will have no direct effect on comfort conditions but will allow the occupants to change the conditions to suit themselves.

Table 2-1. Adaptive behaviours for people.

Climate	Involuntary - physiological mechanisms	Voluntary
Exposure to heat	Sweating (perspiration)	Removing clothing
	Vasodilation (increased blood flow)	Decreasing metabolism
Exposure to cold	Open body position	Fanning
		Drinking cold liquids, eating less
		Moving to a cooler area
		Shifting work schedule
		Turning on fan
		Opening windows
	Vasoconstriction (narrowing of the blood vessels to decrease the blood flow)	Adding clothing
	Shivering (involuntary increase in muscle activity in an attempt to create warmth by expending energy), goose bumps	Increasing metabolism
	Closed body position	Huddling
		Drinking hot liquids, eating more
		Moving to a warmer area
		Shifting work schedule
		Changing thermostats

Therefore, contrary to conventional cooling which is based on pre-calculated temperatures and humidity levels, the adaptive approach is based on a non-fixed set of conditions, taking into account both thermal perception and user behaviour, requiring the person to take an active role in controlling the immediate indoor environment.

A number of actions can be taken by occupants to improve user comfort in passive buildings and these will have implications on indoor comfort and on the energy performance of the building. A user who is not well informed about the use and the control available to modify the local environment may bring about a form of anti-comfort behaviour, conflicting with the energy optimisation of the building.

2.1.5. COMFORT CONSIDERATIONS IN THE BUILDING DESIGN PROCESS

THE ENGINEERING DEFINITION OF COMFORT

All models of thermal comfort make the inherent assumption that there is some predictable comfort response for a given physiological state of the body. It is neither known if this “Holy Grail” of thermal comfort does exist nor how it may be defined. Comfort is not only a physiological response, but also a psychological one and many non-physical factors affect comfort perceptions (Jones, 2002). For example, features such as the architectural openness or the lack of enclosure strongly affect expectations and thus provide perceptions of thermal satisfaction that are distinctly different from those in enclosed spaces (Henry, 2007).

The engineering definition of occupant thermal comfort can be defined as the psychological response to physical heat and moisture balance with the thermal environment, or “that state of mind which expresses satisfaction with the thermal environment”. This is expressed as specific ranges of temperature and humidity conditions (ASHRAE, 2003).

However, the engineering definition must be viewed within the context of its necessity in the design process. An engineer needs a quantitative statement of desired outcomes on which to base designs for interior environmental control. The design of the system to provide these defined comfort conditions is based on the identification of a control volume, usually the building envelope, as well as the effect of heating/cooling, humidification/dehumidification, and ventilation loads on the control volume.

DEFINITION OF THE BOUNDARIES

The issue of defining the boundaries of acceptable indoor conditions in buildings may have significant implications for building design as well as economic consequences. It affects the assessment of the usefulness of natural ventilation and the decisions concerning the need for mechanical air conditioning. It also influences the amount of energy used for ventilation and/or cooling depending on the building in question.

Setting upper limits of temperature and airspeed (often rather low speed) for the acceptable indoor conditions in air-conditioned buildings means that when the indoor temperature rises above that limit, the mechanical cooling system will be activated, although in many cases, higher temperatures with a higher airspeed, would be comfortable for the occupants.

The impact of humidity control affects the energy used to dehumidify the air. As the effect of humidity on comfort depends greatly on airspeed (paragraph 2.3.2), low permissible indoor airspeed increases the energy spent on dehumidification.

In passive buildings, comfort standards affect the design strategies with regard to the choice of building materials and design principles.

2.2. THE IMPACT OF OCCUPANT ACTIONS ON BUILDING COMFORT AND ENERGY USE

2.2.1. WINDOW OPENING

In naturally ventilated buildings, there could be two main reasons for the occupants to open their windows: to improve indoor air quality or to help improve thermal comfort by reducing indoor temperature and thus encouraging air movement. But the outdoor acoustic environment around the building can restrain the occupants from opening the windows. The use of natural ventilation in buildings conflicts with the control of external noise through openings. However, field research has shown that allowable indoor noise levels with the use of natural ventilation could be higher than for a sealed, air-conditioned building (Ghiaus et al., 2005). People's sensitivity to noise changes in naturally ventilated buildings because their appreciation of non-acoustic benefits facilitates compromise with noise levels. A space which is only mechanically ventilated is considered a "controlled" space and the occupants expect noise to be controlled to a low level (Field et al., 2008). Surveys have also shown that current international noise standards are unnecessarily stringent for naturally ventilated buildings. It has also been found that there are differences in the tolerance of noise from one climate to another. People in those countries in which windows are customarily open for most of the year seem to be more tolerant of noise (Bies et al., 2009).

2.2.2. USE OF LIGHTING

Users may have a positive or negative impact on the total energy consumption according to their attitudes towards lighting systems. An extremely common form of energy waste emanates from the consumption of artificial lighting switched on in an unoccupied room or in the presence of an abundant amount of natural light. Indeed, studies have shown that most of the occupants switch on their luminaries when arriving at work and are not likely to switch off the lights upon leaving unless they remain absent for one hour or more (Mahdavi et al., 2006).

In addition, artificial lighting increases the internal heat gain in the room, if superfluously used; this will increase the cooling loads or become a source of thermal discomfort when there is no air conditioning.

To improve the efficiency of artificial lighting, designers work on the ergonomic features of offices in particular. The type of furniture and its arrangement can have considerable repercussions on the distribution of light in terms of space and occupant comfort. For example, items that obstruct light should not be placed in the centre of the room and the essential elements of the usual visual task (table, desk...) should be placed appropriately depending on the location of the openings for natural lights. If these ergonomic features are not accepted and adopted by the occupants, the daylighting of offices will not operate as planned during the design stage and the use of artificial lighting energy will increase.

2.2.3. USE OF BLINDS OR CURTAINS

The use of venetian blinds is popular nowadays as they are adjustable and movable, which allows them to respond easily to the occupants' changing requirements, e.g. radiation levels, daylight or thermal needs. But their treatment in building simulation is often a source of error for overoptimistic energy-saving predictions as it is often assumed that blinds are retracted all year round, thus providing the maximum daylight availability (Reinhart, 2002). In a naturally ventilated building, curtains can also cut off air inlets and lead to thermal discomfort.

Shading devices can provide the following benefits:

- Protection from glare;
- An outside view;
- Privacy.

Several field studies have been conducted on their use especially in office buildings because of their significant impact on energy consumption. From the literature, some assumptions can be made with regards to the use of blinds in offices:

- Occupants don't use blinds very often (Zhang et al., 2012). Most people operate blinds based on perceptions of sun light and solar heat gained over long periods of time, rather than primarily in response to current conditions. Changes in the sky condition within a day are essentially ignored. Once closed, the blind remains closed for the entire day.
- It is found that occupants adjust their blinds more often on arrival than during the whole period of their stay. There is no significant increase in the action rate when occupants leave their offices (Haldi et al., 2010).
- Building orientation affects the occupant's operation of blinds and results in different manual control patterns as blinds are operated in response to the amount of sunshine present and the position of the sun (Reinhart et al., 2003). A very high discomfort probability (0.5 - 1) occurs when the illuminance is below 200 Lux and then increases gradually for larger illuminances until it reaches 1, close to 3,000 Lux (Lindelöf et al., 2007).
- Sunlight entering the space (especially more than 2 m from the facade) triggers the use of shading devices.
- Air temperature (outside and inside), illuminance (global and work plane), solar radiation and penetration are identified as the driving forces. The "blind/curtain usage" increases with the rise in indoor and outdoor temperatures but the rate of usage is small compared to windows and fans as it is likely that the blinds are used to avoid glare rather than heat (Raja et al., 2001).

2.2.4. FANS

Fans are used to increase the air movement around the occupants in order to decrease discomfort due to high temperature, increasing convective heat transfer.

In naturally ventilated buildings, fans play a significant role in reducing the heat stress. The use of fans modifies the indoor climate by regulating and increasing air movement. But at the same time, it increases the energy consumption as well as the internal heat loads inside the room. Issues with fans can be compared to those with lights i.e. the fans left switched on in an unoccupied room lead to wastage of energy.

2.3. MODELLING THERMAL COMFORT

Two methods have been suggested to study the conditions that are most likely to provide thermal comfort in buildings:

The heat exchange method or analytic approach is based upon the physics of the heat exchange between the human body and the environment, together with thermal physiology to predict people's response to the environment.

The field study method approaches people in their everyday context at home or at work, simultaneously evaluating their thermal sensation and measuring their thermal environment, using statistical techniques to define what will constitute comfortable conditions.

2.3.1. THE ANALYTIC APPROACH TO THERMAL COMFORT

The analytic approach to thermal comfort is based on the calculation of the heat balance of the human body with physical and physiological models. The objective is to predict the occupants' thermal sensations in order to identify the environmental conditions for thermal comfort.

Fanger's comfort model was the first one to be elaborated. It was first published in 1970. The mathematical model developed by P.O. Fanger is probably the most well-known and is the easiest to use (Fanger, 1970). This model is based on theoretical analyses of human heat exchange with the environment and was calibrated using the results from experiments in special climate-controlled laboratories or climate chambers. It served as the basis for the international standard ISO 7730 (ISO, 1994). This defines the Predicted Mean Vote (PMV) that predicts the mean response of a large group of people according to the ASHRAE thermal sensation scale (see table 2-4). This is expressed by Fanger as given by eq. 2-1.

$$PMV = (0.303 e^{(-0.036Mr)} + 0.028)L \quad \text{Eq. 2-1}$$

Mr Metabolic rate

L Thermal load – defined as the difference between the internal heat production and the heat loss to the actual environment

The Predicted Percentage of Dissatisfied (PPD) index is related to the PMV as defined in figure 2-2 and eq. 2-2. It is based on the assumption that people voting +2, +3, -2, or -3 on the thermal sensation scale are dissatisfied, and the simplification that PPD is symmetric when close to a neutral PMV.

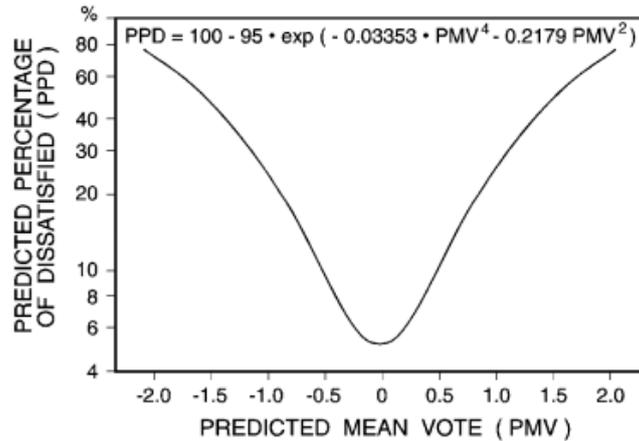


Figure 2-2. The Predicted Percentage of Dissatisfied (PPD) in relation to the Predicted Mean Vote (PMV).

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad \text{Eq. 2-2}$$

Because of differences from one individual to another, it is impossible to prescribe a thermal environment that will satisfy everyone. A certain percentage of occupants will always be dissatisfied. However, it is possible to describe environments designed to be acceptable to a certain percentage of occupants. Table 2-2 defines three classes of thermal comfort based on the PPD allowed. The class of comfort must be specified by the user and the acceptable PMV range corresponding to a given class is determined from this table (ASHRAE, 2003).

Table 2-2. Three classes of acceptable thermal environments for general comfort

Comfort Class	PPD	PMV range
A	< 6	-0.2 < PMV < + 0.2
B	< 10	-0.5 < PMV < + 0.5
C	< 15	-0.7 < PMV < + 0.7

ASHRAE 55 Standard (ASHRAE, 2003) is based on the Gagge model which is also a static model.

2.3.2. PASSIVE COOLING

THE RESPONSE OF THE HUMAN BODY TO HOT AND HUMID CONDITIONS

Humans are warm-blooded mammals and any excess heat must be evacuated in order to maintain the deep body temperature as close as possible to 36.7°C thus preventing serious medical complications. The body accomplishes this through physiological thermoregulatory mechanisms that provide an equilibrated heat balance (Lavoye et al., 2008).

The body has a number of mechanisms to dissipate heat when the environment is overheated (see table 2-1, column “Involuntary - physiological mechanisms”). It exhibits all normal heat transfer mechanisms (conduction, convection and radiation) in addition to the ability to perspire and cool itself by evaporative heat loss.

If the temperature is in the region of 24°C and the relative humidity close to 50%, most body rejection occurs through convective and radiative heat transfer with only about 20% occurring through evaporation. But if the air temperature comes close to the skin temperature (about 32°C), approximately 80% of the body’s heat loss must occur through evaporation, requiring abundant perspiration. Under these conditions radiation and convection are much less important than evaporation.

Humidity does not directly affect the heat load exerted on the body but it determines the evaporative capacity of the air and therefore cooling efficiency due to perspiration. If the air has a high relative humidity, the potential for evaporation to take place is greatly reduced because the air cannot absorb more moisture easily. Theoretically, when the relative humidity reaches 100% and the air temperature exceeds that of the skin, the body can no longer evaporate moisture or convect heat away from itself and the potential for heat strokes exists. When both the air temperature and the relative humidity exceed a certain level (28°C-30°C; 70-80%), more importance is placed on humidity with regard to the assessment of thermal comfort. Beyond this level, it is considered as a minor parameter (Deval, 1984).

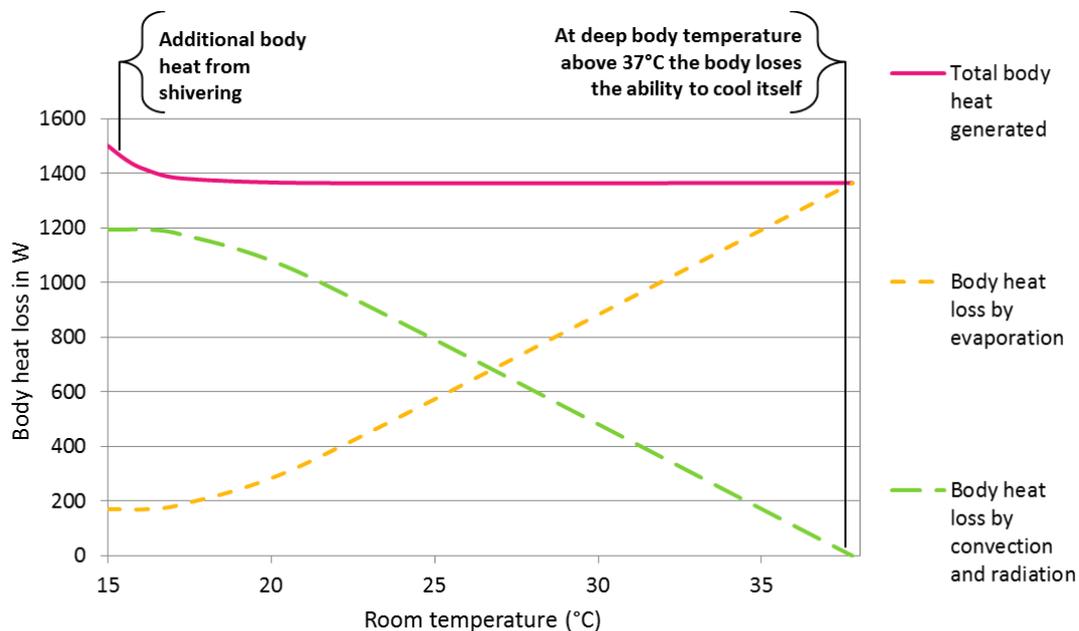


Figure 2-3. Body heat loss and air temperature, adapted from Fairey (Fairey, 1981).

ACCLIMATISATION

Acclimatisation is also a contributing factor to thermal comfort which is of great importance in hot and humid climates. We can distinguish short-term physiological adjustments to changed conditions which

are achieved in 20-30 minutes and long-term adjustments that may extend beyond six months and which constitute the acclimatisation process.

In hot climates the increase of blood volume (by up to 20%) which in turn increases the effectiveness of vasodilation, must be taken into account. The sweat secretion rate also increases over a period of several weeks and this will increase the evaporative regulation mechanism. The tangible results include decreased sensations of discomfort, improved work performance and in general an increased feeling of well-being.

THE BENEFITS OF VENTILATION

Air movement caused by natural or mechanical ventilation aims to produce comfortable indoor thermal conditions.

Air motion across the skin accomplishes cooling through both convective energy transfer and latent energy transfer (evaporation of perspiration from the skin). Since skin temperatures are relatively high, even air temperatures at 32°C can carry off some excess heat. Additionally, at a very high level of relative humidity (even at 100%) if dry bulb air temperatures are lower than skin temperatures, evaporation from the skin will occur. In still air, a thin layer of air, whose temperature is close to that of the skin, forms an insulating barrier just above the skin surface. If dry bulb air temperatures are lower than the skin temperature then the relative humidity of the air in contact with the skin is lowered and both skin evaporation and heat loss are increased. Increasing air motion heightens this effect. This is accomplished by both decreasing the thickness of the insulating air layer and carrying off excessively heated and moisture-laden air.

Table 2-3. Effects of air velocity on comfort. Source: (Olgay, 1963).

Air speed		Probable effect
<i>Up to</i>	0.25 m/s	Imperceptible
0.25	0.5 m/s	Pleasant
0.5	1 m/s	Constantly aware of the movement of the air
<i>Over</i>	1.5 m/s	Discomfort with regard to health

However, it is important to remember that too high an air speed can be a source of discomfort. Table 2-3 shows that from an air velocity of 1m/s, ventilation induces an annoying sensation of airflow, and that beyond 1.5 m/s it becomes detrimental to health. ASHRAE Standard 55 indicates that the air speed may not be higher than 0.8 m/s (ASHRAE, 2003). Large individual differences exist between people with regard to the preferred air speed. Therefore the elevated air speed must be under the direct control of the affected occupants and adjustable in steps no greater than 0.15 m/s.

2.3.3. SUBJECTIVE JUDGEMENT SCALES

Different scales exist to quantify thermal comfort. The majority of these scales have 5 or 7 degrees (or levels) of evaluation (ISO, 1995).

The thermal sensation scale: this scale is used to describe the occupant's thermal perception of the occupied room therefore it provides an indirect assessment of comfort. It is also referred to as the ASHRAE thermal sensation scale (ASHRAE, 2003).

The thermal preference scale: this scale is used to describe the thermal preference of the occupant. Some individuals state that they are comfortable, but prefer a slightly cooler or warmer environment.

The thermal judgment scale (5 degrees): this scale is used to characterise the level of comfort directly, but may include other psychological parameters rather than just physiological ones. A correlation with the thermal sensation scale may prove interesting in order to ascertain the influence of thermal and non-thermal parameters on the perception of comfort.

Table 2-4. The scales used to assess the thermal environment.

Thermal sensation (ASHRAE scale)		Thermal preference		Thermal judgement	
<i>How are you feeling?</i>		<i>What temperature would you prefer?</i>		<i>How do you judge the thermal environment?</i>	
+3	Hot	+3	Much warmer		
+2	Warm	+2	Warmer	4	Extremely uncomfortable
+1	Slightly warm	+1	Slightly warmer	3	Very uncomfortable
0	Neutral, neither hot nor cold	0	No change	2	Uncomfortable
-1	Slightly cool	-1	Slightly cooler	1	Slightly uncomfortable
-2	Cool	-2	Cooler	0	Comfortable
-3	Cold	-3	Much cooler		

2.3.4. THE ADAPTIVE APPROACH TO THERMAL COMFORT

Many surveys have been conducted using the ASHRAE scale to observe the thermal sensation of subjects in tropical contexts (Webb, 1959; Matthews et al., 1995; de Dear, 1998; Nicol et al., 1999; Bouden et al., 2001; Ealiwa et al., 2001; Hussein et al., 2009). The conditions found comfortable by the subjects differ from the predictions of the PMV particularly when buildings are not mechanically heated or cooled (de Dear et al., 2002; Humphreys et al., 2002). The comfort range found in non-air-conditioned buildings (where conditions are dynamic and follow the changes in the external environment) is larger than that given by the analytic tools (Nicol, 2004).

These results are explained by the theory of adaptive thermal comfort which indicates that factors beyond physics or physiology influence the perception of thermal comfort (Nicol et al., 2002). Instead of being affected by the conditions of the immediate environment, the occupant responds by adapting to this environment. This approach questions the causal linear analytic approach (physic => physiology => comfort). The adaptation is expressed by feedback loops that are implemented in a situation of

discomfort. For example, these loops can be behavioural responses (2.2), acclimatisation factors, or occupant expectations. Thus, the more faculties of adaptation that are available in a building (window openings, fans, blinds), the greater the level of comfort may be (Cantin et al., 2005).

2.3.5. DEFINITION OF COMFORT ZONES

MESOCOMFORT ZONE

Between the optimum thermal comfort conditions specified by static models and the thermal environmental conditions that produce undesirable involuntary responses (see table 2-1), there is a significant opportunity for adaptation. To design to a broader standard that includes adaptation, an intermediate zone of comfort in its own right needs to be considered. This can be referred to as a mesocomfort zone. Research needs to be initiated on documenting the value of individual and combined voluntary behaviours to ameliorate comfort by using local, adaptive strategies (Kwok et al., 2010).

For the purpose of thermal comfort standards, the mesocomfort zone would be defined as the zone between optimal thermal environmental conditions and the boundary area at which involuntary physiological human response occurs. The size of the mesocomfort zone would be expected to be proportional to the adaptive capacity of a space when combined with the adaptive opportunities afforded to the occupant. Nicol and Humphreys found that the width of the comfort zone, if measured purely in physical terms, could be considerably wider with available adaptive opportunities but it could be as narrow as $\pm 2^{\circ}\text{C}$ in situations where no adaptive mechanisms could be used (e.g. modifying clothing, changing air movement or activity). Without defining such a mesocomfort zone, system designers will adhere to the traditional comfort zone as defined by the static model climate chamber research and be compelled to continue the design of conservative systems because of liability concerns.

ASHRAE Standard 55 implies this idea of a mesocomfort zone with a section on adaptive comfort for naturally ventilated buildings, recognizing a wider range of comfort temperatures possible in naturally ventilated buildings. The U.S. Green Building Council's Leadership in Energy and Environmental Design (LEED) certification system allocates three points to thermal comfort, one of which specifically applies to the control of operable windows.

THE COMFORT ZONES REPRESENTED ON THE PSYCHOMETRIC CHART

Another method used to assess comfort in a building is the Building Bioclimatic Chart (BBCC) which includes comfort zones that define the temperature and humidity within which building occupants will statistically be comfortable. The parameters that can be represented on the psychometric chart (air temperature, radiant temperature, humidity and air velocity) reflect this physical and physiological comfort. Comfort also depends on psychological as well as other factors that are not necessarily quantifiable. The comfort zones are thus defined as areas where 80% of the population will statistically be able to experience thermal comfort (Fairey, 1981).

This method can be implemented simply as no special data processing or long calculations are required. Bio-climatic charts facilitate the analysis of the climatic characteristics of a given location from a human comfort perspective. They specify the building design guidelines to maximize the indoor comfort conditions of passive buildings. The optimisation of the envelope of a passive building is engendered when a maximum number of temperature and humidity dots are located within the comfort zones of the BBCC. Consequently, active means or systems are either limited or not necessary to reach indoor comfort.

In the early design stage, architects and engineers require simple tools and methods to study the climate and the comfort conditions inside the building. The comfort zones fulfil all of these requirements (Saber et al., 2006).

Several types of comfort diagrams have been defined, such as the ASHRAE comfort zones (ASHRAE, 2003) or Olgyay's bioclimatic chart (Olgyay, 1963). Only the comfort zones defined by Givoni are presented here.

THE GIVONI BIOCLIMATIC CHART

The original boundaries of comfort were based on research conducted in the United States, Europe and Israel. Givoni developed two zones, one for developed countries and the other for developing countries where the upper limits of accepted temperature and humidity are higher assuming that people are acclimatised to hot and humid conditions (Givoni, 1976; Givoni, 1998). The extension of these limits is based on personal evaluation by the author, taking into account data from studies which were conducted in hot countries (figure 2-4) and reported earlier.

As an extension of Givoni's studies, the different passive cooling techniques such as evaporating cooling, thermal mass, natural ventilation and passive heating are overlaid on the chart. The area of mechanical or natural ventilation (NVM) is of particular interest as it corresponds to the thermal comfort boundaries for temperature and humidity when the air speed is in the region of 1 m/s (figure 2-5).

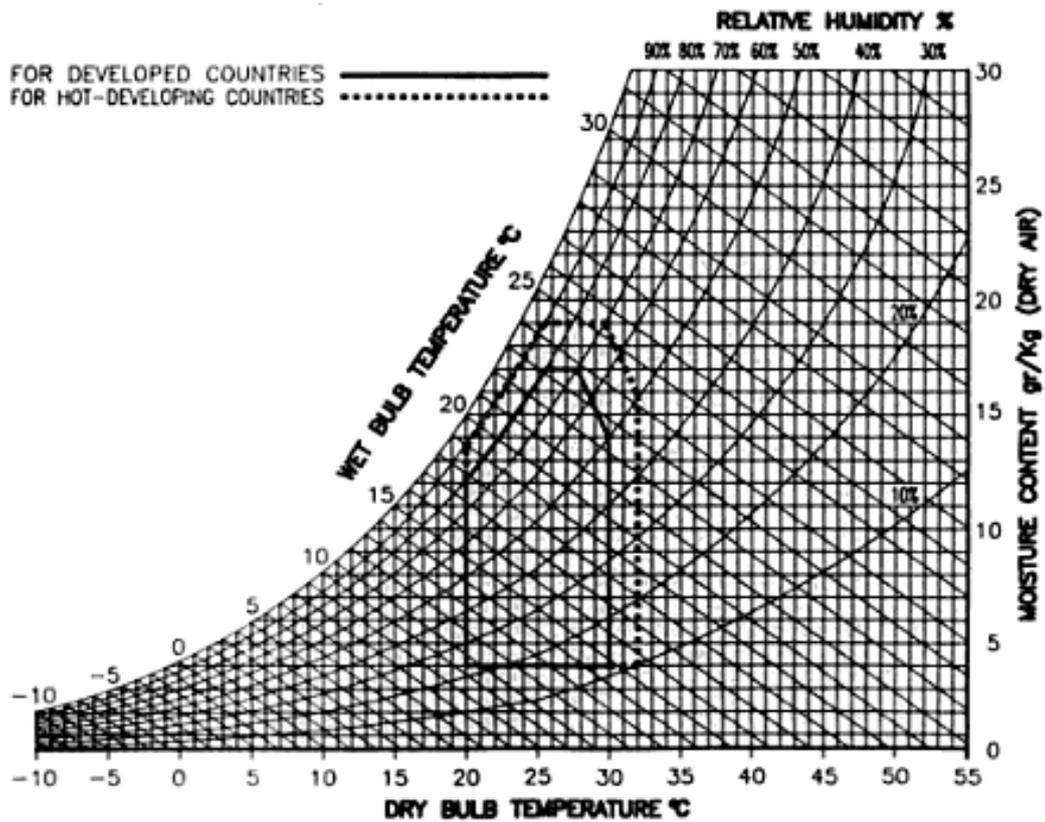


Figure 2-4. Comfort zones defined by Givoni (Givoni, 1976).

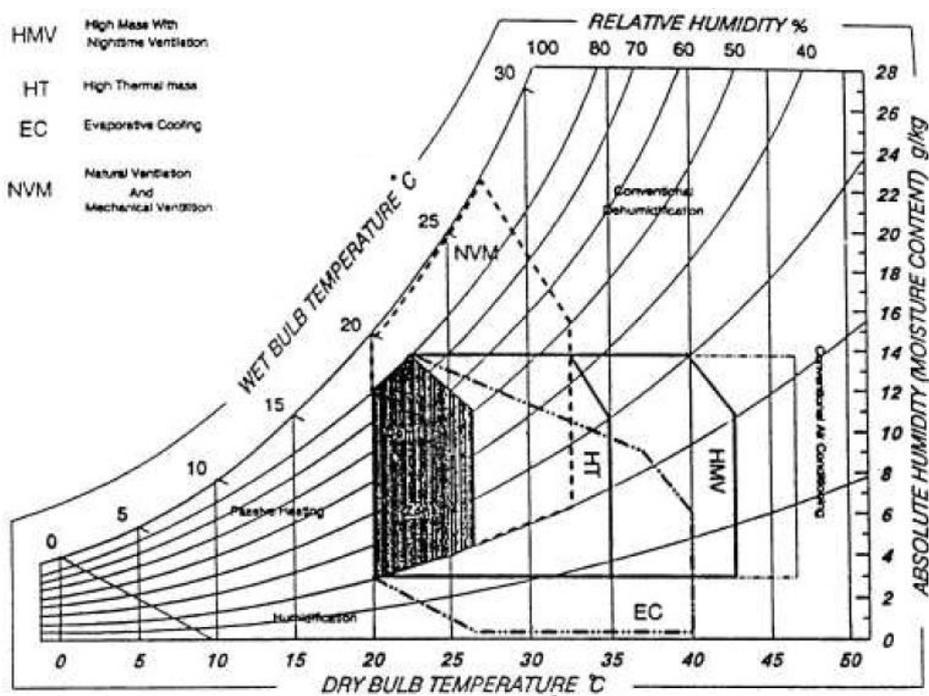


Figure 2-5. Passive cooling techniques represented on the psychrometric chart with Givoni's comfort zone (Saberi et al., 2006).

2.4. DAYLIGHTING AND VISUAL COMFORT

In this paragraph, the methods used by design offices for daylight modelling will be shown. Firstly, the daylight factor will be introduced to show its benefits and drawbacks, as it is widely used by designers. Then the daylight comfort zones for offices and classrooms where a minimum level of illuminance is required will be defined. Visual discomfort issues such as glare and uniformity will be discussed to introduce the useful daylight index.

2.4.1. THE DAYLIGHT FACTOR

The daylight factor (DF) is a very common and easy to use index for the subjective daylight quality in a room. The daylight factor method assumes the indoor illuminance at a given point to be proportional to the outdoor, unobstructed, horizontal illuminance for a CIE overcast sky. It describes the ratio of outside illuminance over inside illuminance simultaneously available on a horizontal plane, expressed in per cent. The higher the daylight factor, the greater the availability of natural light in the room. It is expressed as:

$$DF = 100 \times \frac{E_{in}}{E_{ext}} \quad \text{Eq. 2-3}$$

E_{in} Inside illuminance at a fixed point

E_{ext} Outside horizontal illuminance beneath a CIE overcast sky

A daylight factor can be measured for a specific point or expressed as an average. The latter is the arithmetic mean of the sum of point measurements taken at a height of 0.85 m in a grid covering the entire floor area of the room. Different countries have different regulations and may require the use of point or average measurements.

A daylight factor can also be expressed as an average using experimental formulae. Several formulae for estimating the average DF in a room are in use today. Depending on the country and its legislation, one or the other might be more common. One of these is given by the Building Research Establishment (BRE):

$$DF_{BRE} = \frac{A_{window} \times \alpha \times M \times t}{A_{total}(1 - \rho_m^2)} \quad \text{Eq. 2-4}$$

A_{window} Surface area of the window, excluding frame, bars and other obstructions [m²]

A_{total} Total internal surface area of the room [m²]

α Angle of visible sky from the midpoint of the window [°]

M Maintenance factor of the window

t	Transmission factor of the glazing
ρ_m	Average reflection factor of all internal surfaces

Rooms with an average DF of 2% are considered to be daylight. However, a room is only perceived as having good daylight when the DF is above 5%.

Table 2-5. Values of the Daylight Factor and implications for the appearance of the room and energy required.

Average DF	Appearance	Energy implication
< 2%	Room looks gloomy	Electric lighting needed most of the day
2% to 5%	Predominantly daylight appearance, but supplementary artificial lighting is needed	Good balance between lighting and thermal aspects
> 5%	A room with a distinct level of daylight	Daytime electric lighting rarely needed, but potential for thermal problems due to overheating in summer and heat losses in winter

The main advantage of the Daylight Factor is the fact that it only depends on the configuration of the room, it is quite easy to calculate for simple cases from tables or diagrams and it provides designers with an initial idea of the daylight available in the room.

But it does not depend on the climate or on the orientation of the openings as it is defined for an overcast sky. Except in the case of an overcast sky (less than 15% of the time on the coastline of Reunion Island), the daylight illuminances inside a room are not only proportional to the external illuminance but also depend on the exact sky luminance distribution at any given time. This is because a point in a room will receive direct light only from certain areas of the sky, and the illuminance within a room is not equally sensitive to changes in the luminance of different parts of the sky given that the sun's position varies under non-overcast skies. Since the DF method cannot account for the dynamic variations in daylight illuminance, for places where non-overcast days occur more frequently, the actual lighting energy savings due to daylighting schemes may not be accurately calculated using this simple method.

Moreover, the requirements fixed for the daylight factor are established for mainland France and are not consistent with the climate of Reunion Island. Table 2-6 gives the percentage of time where three values of outdoor illumination are met during a typical year. In France, the value of 5,000 lux is preferred in the calculations. The DF value of reference applied in France is 2.5% when cloudy sky conditions prevail. This rule is not adapted to tropical conditions where the mean illuminance is much higher when compared to that of mainland France.

Table 2-6. Percentage of time for three outdoor illumination levels in the French overseas territories and in mainland France. Source: (Martin et al., 2008).

	$E_{ext} = 15,000 \text{ Lux}$	$E_{ext} = 10,000 \text{ Lux}$	$E_{ext} = 5,000 \text{ Lux}$
Reunion Island	87%	92%	> 95%
French Guyana	96%	95% - 100%	95% - 100%
French West Indies	90%	95%	95% - 100%
Mainland France	55%	72%	87%

It appears that the single criterion of the daylight factor is not sufficient to characterise the performances in relation to daylighting.

2.4.2. DAYLIGHT COMFORT ZONES FOR OFFICES AND CLASSROOMS

Studying the whole area of a room is not suitable for an analysis of visual comfort. Inside a room, some zones are never dedicated to being working areas, for instance behind the door or close to walls.

For premises that have one or more openings on the same wall, three daylight comfort zones can be defined, starting from the front to the back of the room:

- a zone of discomfort along the facade: in temperate climates, walls are cold in winter. In all climates, this is an area with a high risk for the glare effect, sunspot or too much natural light. The depth of this area depends on the orientation of the room, on the quality of the glass and the type of shading devices: it varies between 0 and 1 metre;
- a comfort zone in terms of access to natural light and natural ventilation. Once entrenched in the discomfort zone on the facade, its depth varies between 3 and 6.50 metres, depending on the case. It should be possible to place all workstations planned in the project in this zone;
- another area of discomfort at the back of the room is inaccessible to natural light and to fresh air. This may be a circulation or storage area.

The types of premises studied in this thesis are offices and classrooms.

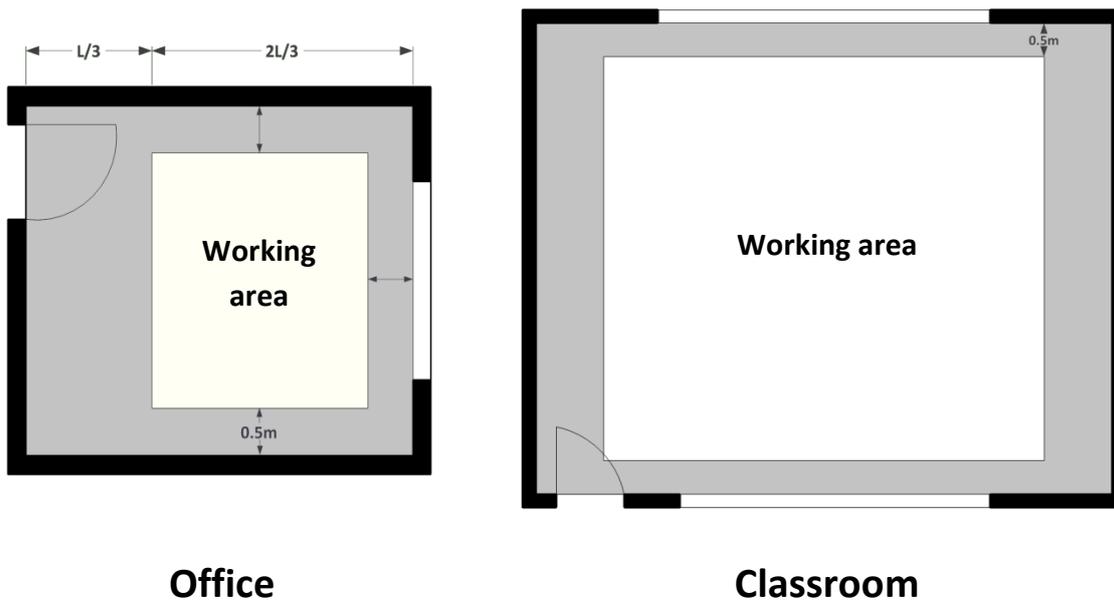


Figure 2-6. Definition of the daylighting comfort zones for an office and a classroom.

2.4.3. LEVELS OF ILLUMINANCE AND DAYLIGHT AUTONOMY

LEVELS OF ILLUMINANCE

Nowadays dynamic daylighting simulation software can quantify the annual amount of daylight in a space. The outputs of these programmes are the hourly or even sub-hourly time series of interior illuminances or luminances due to daylight that are generated using a local climate file. In order to become usable for design, this extensive data has to be converted into intuitive criteria.

The first step of this conversion process is to decide on the times of the year when the analysis should be carried out. A common choice is to concentrate on the periods when the investigated space will be occupied since daylight needs witnesses to have an effect.

The next step of the analysis is to decide which daylighting levels should be considered “adequate”. In France, the Labour Code sets minimum illumination levels by type of activity (art. R 232-7). For a standard office activity, the minimum illuminance level is 200 lux.

From a physiological point of view, figure 2-7 shows the relationship between visual acuity and illumination. Visual acuity is acuteness or clearness of vision, that is to say the ability to distinguish very close details, and in particular to recognize characters. Visual acuity increases sharply with natural light to reach a plateau in the region of 50 lux. It varies greatly with age. It reaches a maximum at about the age of 20 years and then remains practically constant until the age of 40, beyond which decreases rapidly.

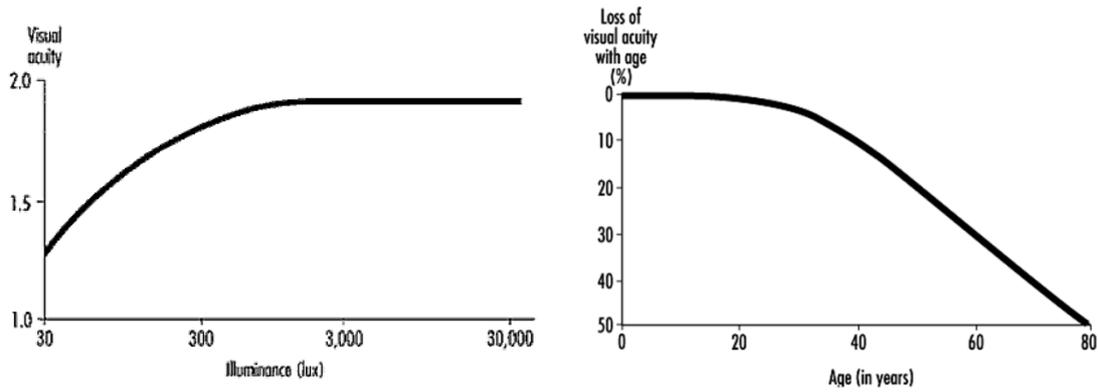


Figure 2-7. Left: Typical relationship between visual acuity and illuminance. Right: Loss of visual acuity with age. Source: (Stellman, 1998).

Obviously, the higher the level of illumination required, the higher the energy consumption for lighting will be. The level of 300 lux on the work plane is adopted by a large number of building standards or design guidelines and represents a satisfactory compromise between visual quality and energy efficiency. This level of 300 lux should be increased for activities requiring precision or for seniors.

DAYLIGHT AUTONOMY

Daylight autonomy is a climate-based metric defined as the percentage of occupied periods in the year during which minimum illuminance levels can be met by daylight alone. The IESNA (Illuminating Engineering Society of North America) committee currently favours a target illuminance of 300 Lux for offices and classrooms with occupied hours from 8 a.m. to 6 p.m. local clock time.

2.4.4. SOURCES OF VISUAL DISCOMFORT

Visual discomfort can be caused by two main sources: an unsatisfactory balance of illuminations or a glare effect.

UNIFORMITY

To represent the balance of illumination in a room, the uniformity index can be used. Uniformity may be defined as the ratio between the minimum illuminance and the average illuminance of a room. High uniformity leads to the increase of the lighting density and in most cases to the increase of installed power. Low uniformity is more favourable to energy management. However it can cause eyestrain resulting from too much adaptation of the eye to different levels of light. Arbitration is to be found between visual comfort, energy efficiency and flexibility (Table 2-7).

Table 2-7. Objectives of uniformity by zone.

Zone	Uniformity
Work plane (desk, conference table)	< 0.70
Surrounding area (the room without its periphery)	< 0.50
Peripheral area (50 cm at the periphery of the room)	N/A

THE GLARE EFFECT

Glare is caused by a significant ratio of luminance between the task (that which is being looked at) and the glare source. Several main sources of glare can be identified: lamps, windows and walls. Glare from windows usually arises when direct sunlight enters the room and shines into the eyes of occupants or reflects off visual tasks and surrounding surfaces. For computer tasks, where the normal line of sight is more horizontal than for reading or handwriting tasks, glare from windows is usually a significant concern and needs to be carefully controlled (Osterhaus, 2005). To reduce the risk of glare, the simplest solution is not to have the work plane with a viewing angle facing the window but parallel to the wall including the window. In addition, blinds may be considered an appropriate solution to modulate this parameter.

THE SUN PATCH INDEX

Glare from daylighting is quite complicated to assess but suitable ergonomic office features can decrease its risk. Another source of visual discomfort comes from sunspots especially those located on the work plane. The presence of direct solar illuminance on the working area can be characterised by the sun patch index. This corresponds to the ratio of the surface of the working area where the level of illuminance is higher than 8,000 Lux. This level of illuminance corresponds to a value which is too high to be considered solely as diffuse illuminance (David et al., 2011).

2.4.5. THE USEFUL DAYLIGHT INDEX

The useful daylight index (UDI) proposed by Nabil and Mardaljevic as a replacement for daylight factors (Nabil et al., 2006), is defined as the annual occurrence of illuminances across the work-plane that is within a range considered “useful” by occupants –100 to 2,000 Lux..

THE MODIFIED USEFUL DAYLIGHT INDEX

In order to link this index to daylight autonomy and to the sun patch index on the work plane, it is necessary to propose the use of new extreme values to derive the useful daylight illuminances. The minimum level required for office work will be taken as 300 Lux as defined in 2.4.3 and which corresponds to the lower limit of the daylight autonomy. The higher limit is taken from the sun patch index as 8,000 Lux.

The modified UDI is the percentage of occupied hours (from 8 a.m. to 6 p.m.) when the illuminance on the daylight comfort zones (defined in 2.4.2) is between the values of 300 and 8,000 Lux.

Although comfort is a subjective concept that is ambitious to define, there is a real need for methods aimed at minimising the risks of sources of discomfort, in order to design passive buildings. In this chapter, several methods have been presented to characterise both thermal and visual comfort. With regard to thermal comfort, the comfort zones drawn on the psychometric chart are a well-adapted tool for the assessment of thermal comfort in the tropical regions. This choice is suitable for design offices as it is very straightforward to use and understand.

Defining visual comfort is very challenging. The indicators proposed in this chapter do not guarantee visual comfort but attempt to reduce the source of discomfort with recommendations in terms of the ergonomic design of rooms. The useful daylight index indicates the number of hours during a year during which daylighting is likely to be an efficient and sufficient source of lighting.

The following chapter will deal with thermal and visual comfort from an experimental angle in order to develop a methodology applicable to Reunion Island. The experimental methodology proposed is applicable to other locations with the same objectives.

Chapter

3

EXPERIMENTAL FEEDBACK OF THERMAL COMFORT IN A NET ZERO ENERGY BUILDING

The aims of this chapter are to study the favourable conditions that provide thermal comfort to the occupants of a net zero energy building operating with natural ventilation. First, a survey was conducted on the students and teachers of the building over three summer seasons in order to characterise the environment variables that ensure thermal comfort. The results are compared with the zones of comfort defined by Givoni on the psychometric chart. This way, it is possible to propose an improvement in the assessment of thermal comfort in tropical climates.

Secondly, the impact of the occupants on thermal conditions inside the building is presented based on several experiments. Different scenarios of use of the natural ventilation of the building are tested. As a result, it will be possible to guide the occupants through the building operation with the opening of the louvres during days and nights.

Finally, the use of ceiling fans in order to improve the thermal comfort of the occupants will be studied. The aim is to compare the energy use when ceiling fans are in operation with the outside temperature, in order to derive the utilisation rate of ceiling fans in relation to the outside temperature.

Life begins at the end of your comfort zone

UNKNOWN SOURCE

3.1. THERMAL COMFORT VERIFICATION SURVEYS

3.1.1. AIMS OF THE STUDY

In this section, the results of a field study conducted on the ENERPOS building in Reunion Island are presented. This survey was carried out to investigate thermal comfort in energy efficient buildings under tropical climates. The study addressed the topic of maximum allowable indoor temperature and humidity during summer which is of great importance, particularly in naturally ventilated and passively cooled buildings. The first results of this study were presented in (Lenoir et al., 2009) and in (Lenoir et al., 2011).

The current standards, regulations and recommendations in mainland France mainly refer to air-conditioned buildings and favour narrow limits for indoor temperature which works against energy conservation. If applied in Reunion Island this would lead to restrictions in designing of passively cooled buildings.

The purpose of this first field survey, which was limited to the ENERPOS building, was therefore:

- to compare measurements with thermal sensation and thermal comfort votes in offices and classrooms of a naturally ventilated university building under tropical summer conditions;
- to compare these results with other approaches - particularly the comfort zones proposed by Givoni, presented in paragraph 2.3.5;
- to propose a new approach to thermal comfort for office buildings in Reunion Island;
- to gain experience with field surveys on thermal comfort in order to promote and carry out further investigations.

A total of 2,092 sets of environmental and subjective observations were recorded during 3 summer seasons. When compared with other surveys, for instance the European SCATs project (McCartney et al., 2001) that contained a total of 4,655 records, 1,449 of which were observed in naturally ventilated buildings, this amount is considered adequate to provide sufficient scope for a reliable analysis.

But it is important to be aware that this study was carried out on a particular sample which, while presenting some interesting lessons, does not provide a thorough characterisation of thermal comfort. The study of comfort is a delicate question because it concerns a subjective matter. Therefore, it is understood that this study could contain biases, but no study in the field can claim to be perfect when human behaviour is studied. Indeed, the main purpose of this research was not to highlight potential errors or uncertainties.

This work constitutes the first field study of thermal comfort conditions in a net zero energy building in the tropical climate. A study of this kind and scale has never been achieved before under these circumstances in an existing building. However, the results may lead to further and more thorough statistical analysis than that proposed.

3.1.2. METHODOLOGY

The methodology followed for this survey is similar to that of previous studies conducted on the thermal comfort of building occupants such as (Kwok et al., 2003; Hwang et al., 2006).

THE METHODOLOGY USED FOR SUBJECTIVE MEASUREMENTS

The thermal comfort survey was based on ISO 10551 (ISO, 1995). It has been developed by the *PHASE* laboratory based at the University Paul Sabatier in Toulouse in the course of the *ANR* (French National Research Foundation) project called ENERPOS (Garde et al., 2007). The evaluation was carried out on students during classes. Students were asked to fill in a questionnaire for each two-hour session, at the same time as the environmental variables were being recorded. They were asked to evaluate their environment at the beginning of the period of exposure (when they enter the classroom) and at the end of this period (when they leave).

The following responses were polled from the survey participants:

- Temperature assessment vote (7-point scale) and judgement vote (5-point scale);
- Air movement judgement vote (5-point scale);
- Humidity judgement vote (5-point scale);
- Lighting level assessment vote;
- Overall comfort;
- Details of clothing worn;
- Activity level in the previous hour;
- Use of environmental controls, e.g. doors, windows, ceiling fans.

Clothing garment checklists were adapted to the regional customs prevailing in Reunion Island and compiled from the extensive lists published in ISO 7730 (ISO, 1994).

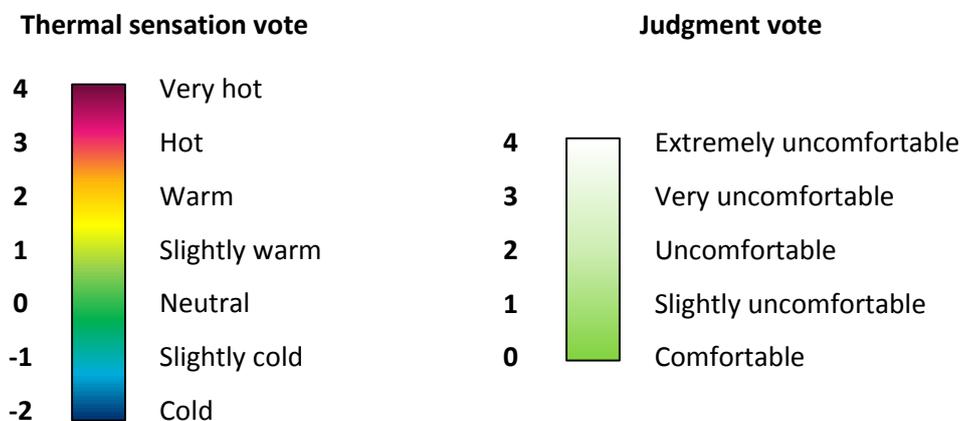


Figure 3-1. The wording of the subjective scales used to assess the influence of the thermal environment.

The three scales: perceptive, evaluative and preferential judgment, as defined by ISO 10551 (ISO, 1995) were implemented (Table 2-4). The hot and humid climate of Reunion Island led to the modification of the perceptive scale compared to that of ASHRAE. The perceptive judgment scale was used to express the thermal sensation and the thermal judgment was stated by the evaluative judgment scale (figure 3-1).

The answers given at the beginning of the period of exposure depend significantly on the previous activity levels of the respondents. Moreover, it is not characteristic of the interior environment as the human body needs time to respond to a change in the heat balance (Nicol, 2004). That is why the following results will only include the mean response at the end of the period of exposure corresponding to a two-hour session.

THE METHODOLOGY USED FOR OBJECTIVE MEASUREMENTS

An indoor climatic measurement system (figure 3-2) took measurements at a height of 0.8 m above the floor, representing the immediate environment of the seated subject's trunk, during class, automatically collecting parameters of thermal comfort while the respondent answered the questionnaire. The instrumentation remained stationary in the classroom for the duration of the survey. The environmental variables collected are:

- air temperature (T_a in [$^{\circ}C$]);
- globe temperature (T_g in [$^{\circ}C$]);
- dew-point temperature;
- air humidity (RH in [%]);
- air velocity (v_a in [m/s]);
- illuminance on the work plane (in lux).

The equipment used in this study complies with the criteria given in standard (ISO, 1986). Temperature and humidity sensor accuracy is within $\pm 0.1^{\circ}C$ for temperature and $\pm 2\%$ for relative humidity. The black globe temperature is measured with a black globe in the centre of which a temperature sensor is placed (Pt100, class B) the accuracy of which is $\pm 0.45^{\circ}C$. An omnidirectional, temperature-compensated anemometer measured the air velocity.

These values were logged every minute. In the following results, the measures taken into account are averaged over the last hour of exposure except for the air velocity which is averaged over 15 minutes. These measurement periods are defined by ASHRAE (ASHRAE, 2003).



Figure 3-2. Thermal comfort measurement equipment.

THE PEOPLE SURVEYED

The study was carried out during the hot seasons of 2009, 2010 and 2011 (October - April), and 2,092 questionnaires were filled in by approximately 700 students and their teachers during 125 two-hour sessions. Figure 3-3 shows the distribution of the surveys per month over the year. The Christmas holidays in Reunion Island are between mid-December and late January which explains the small number of surveys during that period.

Male and female distribution totalled 48% and 52% respectively. The average age was 22.5 years, 23.8 years on average for men and 21.2 years for women. Figure 3-3 shows the proportion of men and women in the different age ranges. The majority of the people surveyed were in fact between 19 and 21 years of age.

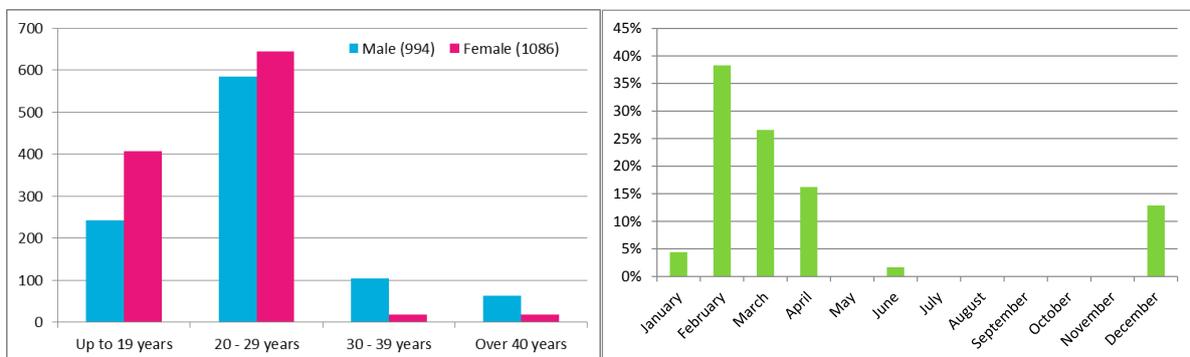


Figure 3-3. Number of surveys per sex and age, percentage of people surveyed per month over 3 years.

The activity of the students is assumed as an office activity of 1.2 met. The insulation of the clothing ensembles is estimated on the basis of the answers given in the survey where people are invited to describe what they are wearing.

THE DISTRIBUTION OF TEMPERATURE AND RELATIVE HUMIDITY

The histograms showing the distribution of the indoor black globe temperature and relative humidity in the course of all the surveys are presented in figure 3-4. The black globe temperature ranges from 24.5°C to 31.5°C (mean temperature 28.5°C). The relative humidity is rather high covering a range from 47.5% to 90% (mean 72.5%). The hot and humid climate of Reunion Island can be perceived from those data.

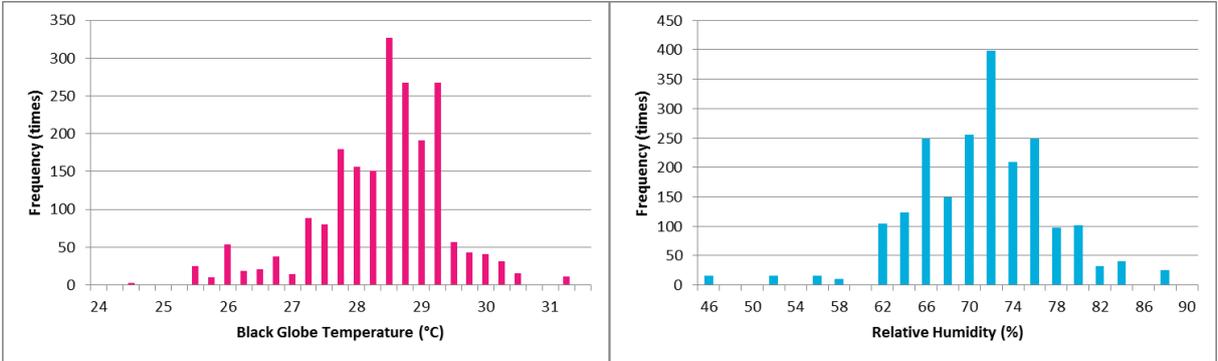


Figure 3-4. Distribution of temperature and relative humidity.

3.1.3. RESULTS OF THE SURVEYS

THE CLOTHING VALUES

Figure 3-5 shows the calculated thermal insulation of participants’ clothing for men and women. The calculated clothing values averaged in the region of 0.35 clo (0.36 clo for men and 0.34 clo for women). The clothing insulation levels are kept close to the lowest values that are culturally acceptable for students at university.

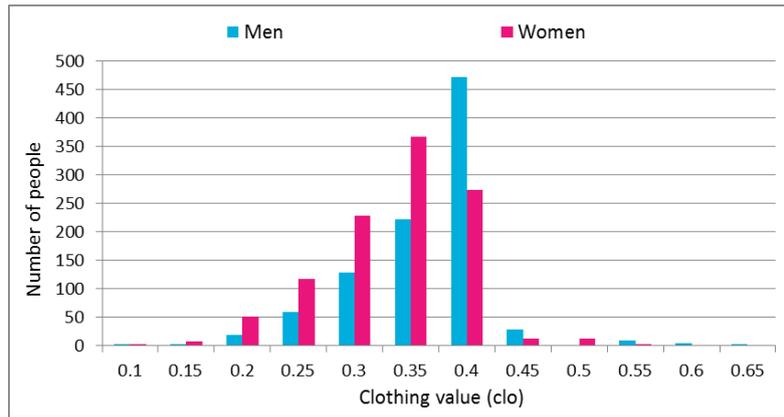


Figure 3-5. Clothing values by gender.

Figure 3-6 shows the variation of the clothing value function of the temperature during the session. The clothing values decrease when the temperature increases, apart from the sole value between 24°C and 25°C which is not particularly representative because there were only 3 respondents. This is proof of the adaptive opportunities taken by the people surveyed in terms of clothing. When the temperature increases, people will adapt their clothing to reach thermal comfort more easily.

The clothing values were much lower than the assumed summer value of 0.5 given in the ASHRAE Standard 55 (ASHRAE, 2003). This is explained by the fact that most people surveyed are students who wear shorts and open shoes at university rather than pants and closed shoes as the usual summer working clothing. The following results should be interpreted accordingly.

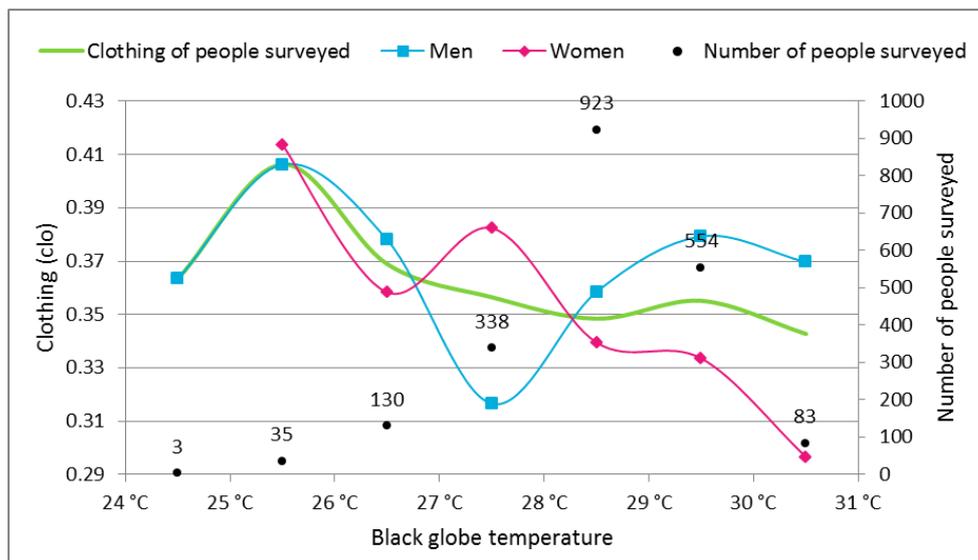


Figure 3-6. Average clothing values for different temperature ranges.

THE COMPARISON BETWEEN THE OPERATIVE TEMPERATURE AND THE BLACK GLOBE TEMPERATURE

ASHRAE standard 55 (ASHRAE, 2003) defines the operative temperature (T_{op}) as the average of the air temperature (T_a) and mean radiant temperature (T_{mrt}) weighted by their respective heat transfer coefficients (h_c and h_r). The operative temperature is often used to assess comfort as it takes into account not only the air temperature but also the wall temperature responsible for the radiant exchanges that account for 35% of the total heat transfers between the human body and the surrounding environment.

The measurement of the globe temperature enables the calculation of the mean radiant temperature (ISO, 1986).

$$T_{mrt} = \left\{ (T_g + 273)^4 + 2.5 \times 10^8 \times v_a^{0.6} (T_g - T_a) \right\}^{1/4} - 273 \quad \text{Eq. 3-1}$$

$$|T_a - T_{mrt}| \leq 4^\circ\text{C} \rightarrow T_{op} = \frac{T_a + T_{mrt}}{2} \quad \text{Eq. 3-2}$$

The operative temperature was calculated for the thermal comfort surveys database and plotted with the black globe temperature (see figure 3-7). A strong linear correlation ($R^2 = 0.9891$) between the two temperatures with a slope very close to 1 can be pointed out. Moreover the maximum difference between the calculated operative temperature and the measured black globe temperature is of the order of 0.48°C which is barely higher than the accuracy of the black globe thermometer ($\pm 0.45^\circ\text{C}$). On average, a difference of 0.02°C can be noted between the two temperatures. Given that the difference between the operative temperature and the black globe temperature is lower than the accuracy of the sensor, it can be assessed that the black globe temperature values are sufficient to represent the temperature perceived by a person in a room. The black globe temperature will be then used to present the results of the thermal comfort surveys.

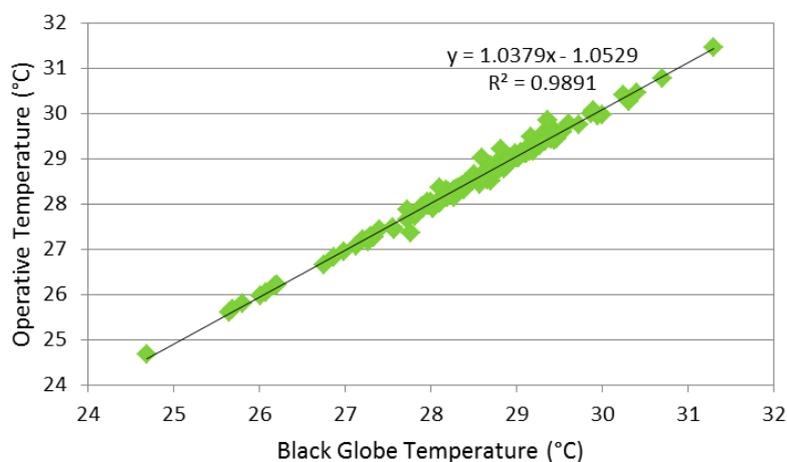


Figure 3-7. Operative temperature in relation to the black globe temperature for the database of the thermal comfort surveys.

THE BLACK GLOBE TEMPERATURE

Figure 3-8 illustrates the mean thermal sensation vote for 126 surveys against the mean black globe temperature (over 1 hour before the respondents presented their thermal sensation).

The first observation is that 82% of the points in this graph lie between -0.5 and 0.5 which matches the values representing comfort by analogy with the PMV. We can consider that in a well-designed building on Reunion Island, it is possible to obtain favourable comfort conditions for the occupants more than 80% of the time, especially as the surveys were conducted almost exclusively during the summer season.

Nicol reported that $0.25/^{\circ}\text{C}$ is the most common regression slope from field surveys (Nicol, 1993). Humphreys found a slope of $0.22/^{\circ}\text{C}$ from a worldwide review of field studies (Humphreys, 1976). Such slopes are less steep than the slope of $0.33/^{\circ}\text{C}$ found by Fanger from his climate chamber experiments (Fanger, 1970). According to Humphreys the lower values of the slope from field studies suggest the occurrence of the adaptation of respondents to their thermal environment.

Such a conclusion is in line with the findings from the present study. The results of the surveys showed that the respondents were thermally comfortable in a wider range of air temperatures than that which is indicated by current standards. The evidence of a lower regression coefficient (0.25) supports the fundamental principle of the adaptive approach to thermal comfort which postulates that the subject plays an active role to secure comfort.

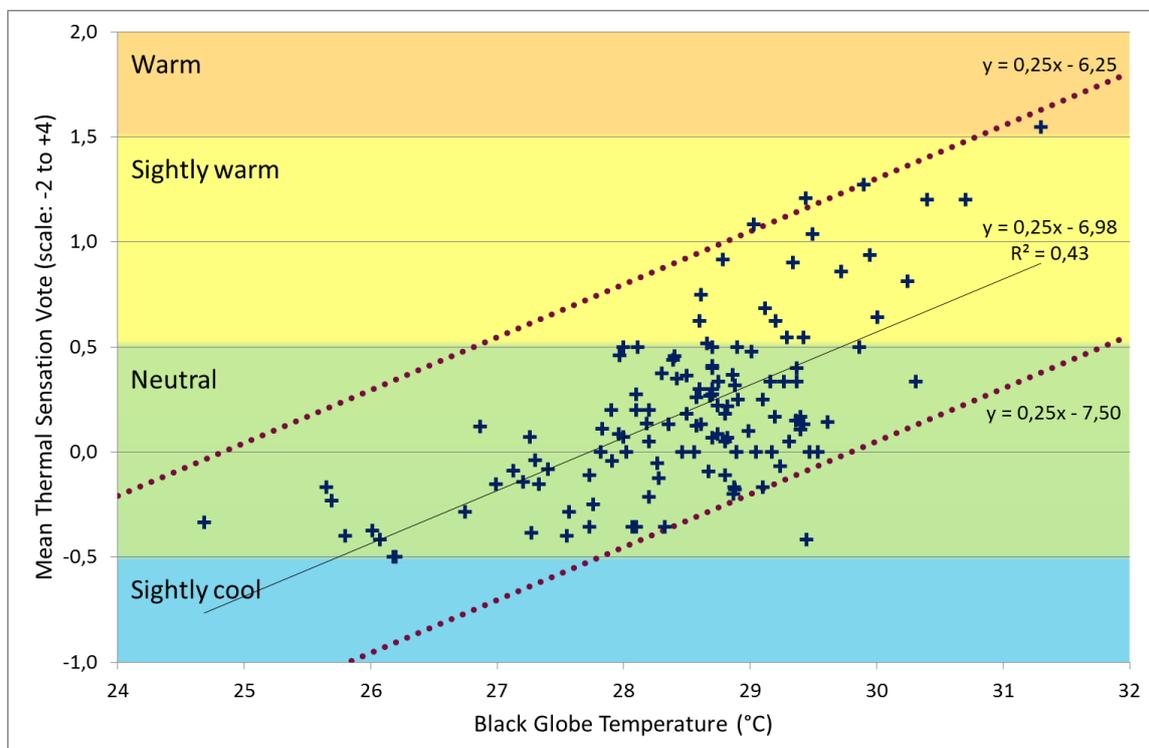


Figure 3-8. The mean thermal sensation vote for 126 surveys plotted against the mean black globe temperature (over 1 hour before the respondents indicated their thermal sensation).

Figure 3-8 shows the mean votes for each session of questionnaire. But with averaged values, information is lost, therefore it is interesting to look at the answers of each respondent during the entire investigation. These are shown in figure 3-9. The number of votes for each point of the thermal sensation scale is given by temperature ranges. It should be noted that in considering the totality of the questionnaires, 80% of votes fall between -1 and 1 which corresponds to a comfort situation for the occupants. The first conclusion of the above graph is that it is possible to obtain favourable conditions for comfort at least 80% of the time in a well-designed building in Reunion Island.

The percentage of comfort illustrated on the top line above the histogram in figure 3-9 corresponds to the percentage of votes between -1 and 1 (considered comfortable for the occupants). As seen in the previous chapter, comfort zones can assess that 80% of the population will be able to experience thermal comfort (Fairey, 1981). Figure 3-9 shows that up to a temperature of 30°C at least 80% of the people surveyed express a sensation of comfort.

This limit is higher than that generally accepted in comfort standards and used by building designers to assess thermal comfort.

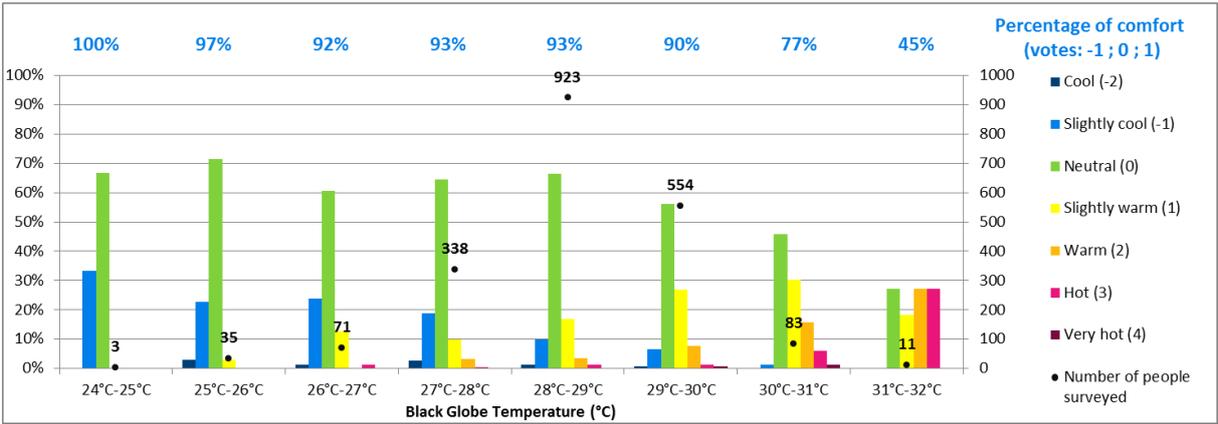


Figure 3-9. Thermal sensation votes by temperature ranges.

An examination of the thermal judgment votes by temperature ranges (figure 3-10) leads to the same deduction. More than 80% of the people surveyed are comfortable up to a temperature of 30°C but this percentage decreases when the black globe temperature rises above 30°C.

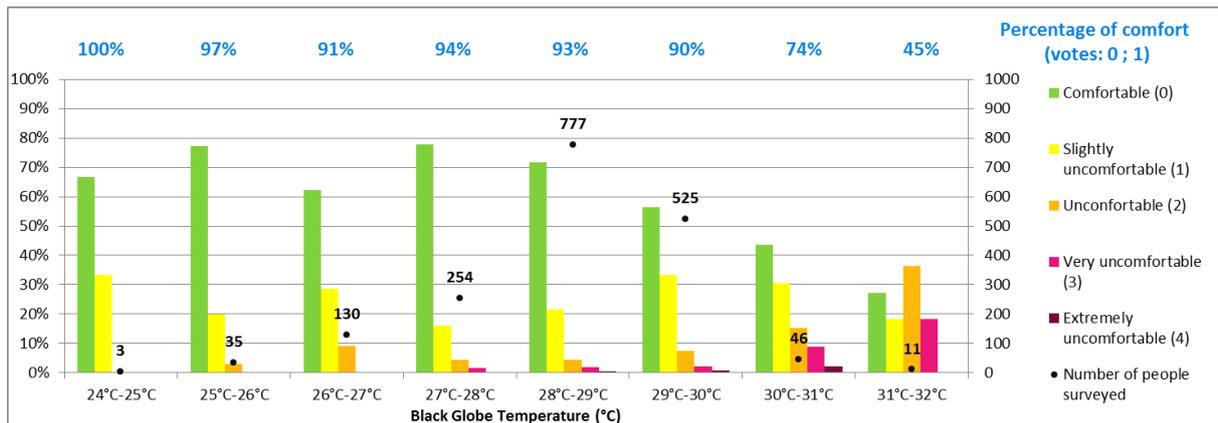


Figure 3-10. Percentage of thermal judgment votes by temperature ranges.

HUMIDITY

The people surveyed were asked to state if they were comfortable with the air humidity they experienced. The results of the humidity judgment votes by temperature ranges are given in figure 3-11.

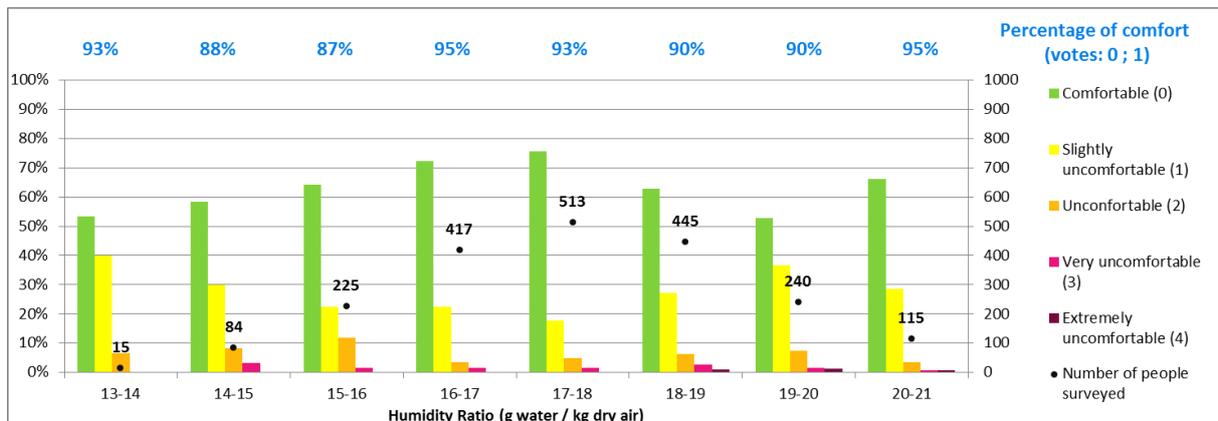


Figure 3-11. Humidity judgment votes by humidity ratio ranges.

The ASHRAE thermal comfort standard gives an upper recommended humidity limit of 12 g_{water}/kg_{dry air} (ASHRAE, 2003). During all the surveys conducted, the measurements of the humidity ratios were higher than this limit, nonetheless, the people surveyed still express their comfort. It is possible to assess that comfort can occur even with higher humidity levels than what is recommended by the ASHRAE standard.

The humidity judgments remain rather constant with the humidity ratios, on average 92% of comfort.

AIR SPEED

Arens defines a comfort zone that depends on the operative temperature and the air speed (Arens et al., 2009). This is extended from a PMV of -0.5, corresponding to the thermal sensation midway between what is considered as neutral (0) and slightly cool (1), to a PMV of +0.5, midway between neutral (0) and slightly warm (1). A comfort zone of the same kind is shown in figure 3-12. ASHRAE Standard 55 (ASHRAE, 2003) indicates a still-air range for an operative temperature in the range of 23.5°C to 27°C (for 0.5 clo). Starting with this range, comfort envelopes are defined based on Nicol's work on air movement (Nicol, 2004): when the air velocity exceeds 0.1 m/s, the comfort temperature can be raised according to eq. 3-3.

$$T = T_{op} - 7 + \frac{50}{4 + 10v^{0.5}} \quad \text{Eq. 3-3}$$

The same dots are drawn as in figure 3-8, differentiating the mean thermal sensation votes inferior to 0.5 (green squares, corresponding to a comfort situation), between 0.5 and 1 (orange triangles, corresponding to slight discomfort) and superior to 1 (pink circles, corresponding to discomfort).

The majority of the green dots are inside the comfort zone but a small number of green dots is located outside the comfort zone defined by Arens. This means that the occupant can feel comfortable with a temperature of approximately 29°C with lower air speeds than those defined by Arens.

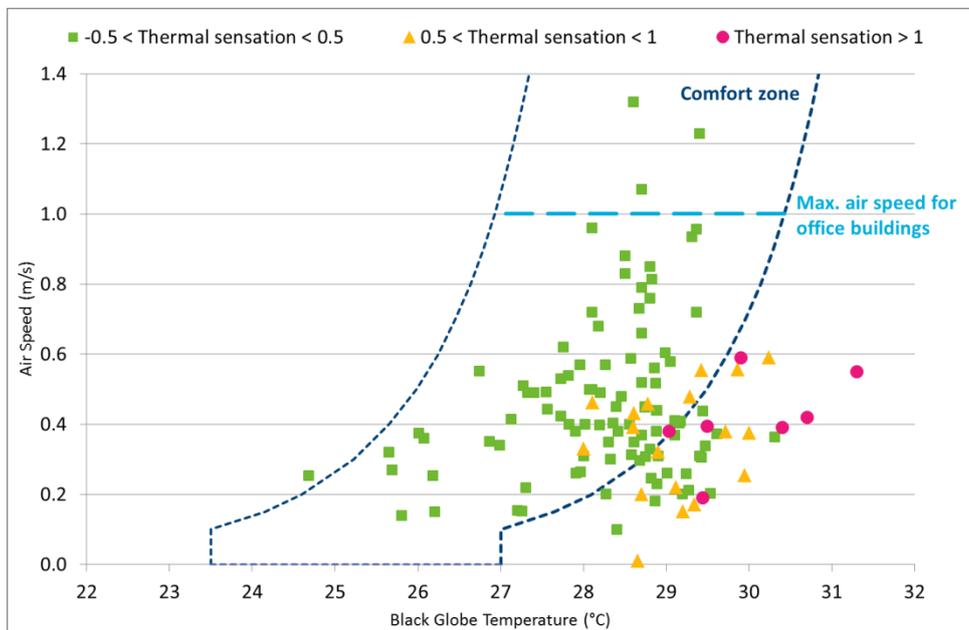


Figure 3-12. Air speed in relation to the black globe temperature.

Regarding the use of air speed to increase the maximum acceptable temperature, ASHRAE Standard 55 indicates that the air speed may not be higher than 0.8 m/s but also points out that large individual differences exist between people with regard to preferences for air speed.

Figure 3-13 gives the number of air speed judgement votes by air speed ranges. The percentages of comfort are higher than 80% when the air speed is below 0.8 m/s but is just below 80% when the air speed is between 0.8 m/s and 1 m/s. Unfortunately, the number of responses when the air speed is higher than 1 m/s concern too few people to provide reliable answers.

Furthermore, in the present study no research has been conducted on the risk of discomfort due to drafts or large variations in time and space with regard to the air speed. To achieve this, measurements of the turbulence intensity would be necessary, as it has been observed that the perceived “draftiness” of air is a function of the turbulence intensity of the moving air (Lavoye et al., 2008).

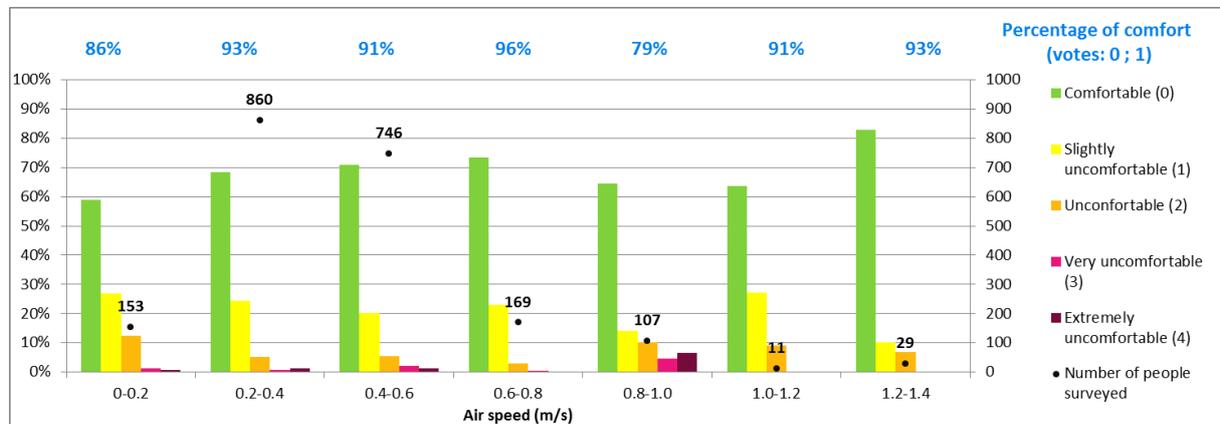


Figure 3-13. Air speed judgment votes by air speed ranges.

THE PREDICTED PERCENTAGE OF DISSATISFIED (PPD)

The percentage of dissatisfied can be calculated by examining the number of people who stated they were unsatisfied with their thermal environment (i.e. votes -2; 2; 3 and 4). In figure 3-14, the average thermal sensation vote is plotted against the percentage of dissatisfied. The curve represents the PPD function of the PMV as given in eq. 3-4. It is to be noted that the surveyed values of the percentage of dissatisfied follow the tendency of the curve, especially when the mean thermal sensation vote is greater than 0.5.

$$PPD = 100 - 95 \times \exp(-0.03353 \times PMV^4 - 0.2179 \times PMV^2) \quad \text{Eq. 3-4}$$

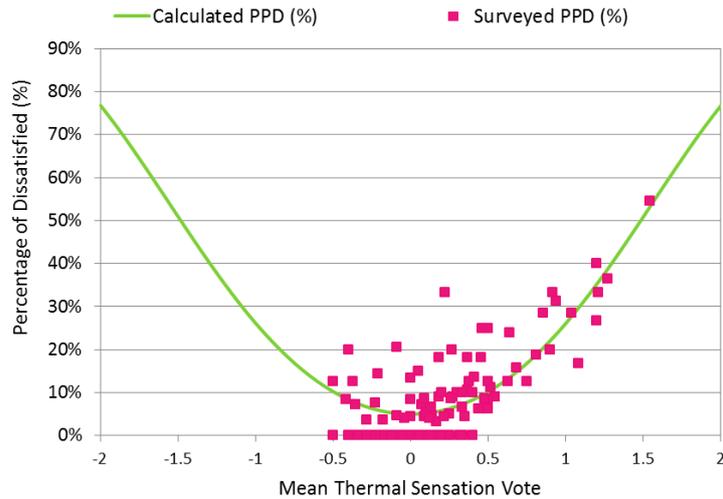


Figure 3-14. Correlation between thermal sensations and the percentage of dissatisfied compared with the calculated PPD (eq. 2-2).

THERMAL JUDGMENT

While the thermal sensation depends mainly on the heat balance of the human body, thermal judgment is more difficult to forecast because it depends also on psychological factors and thermal experiences. According to Humphreys (Humphreys et al., 2007), people in hot climates might prefer a sensation slightly cooler than neutral.

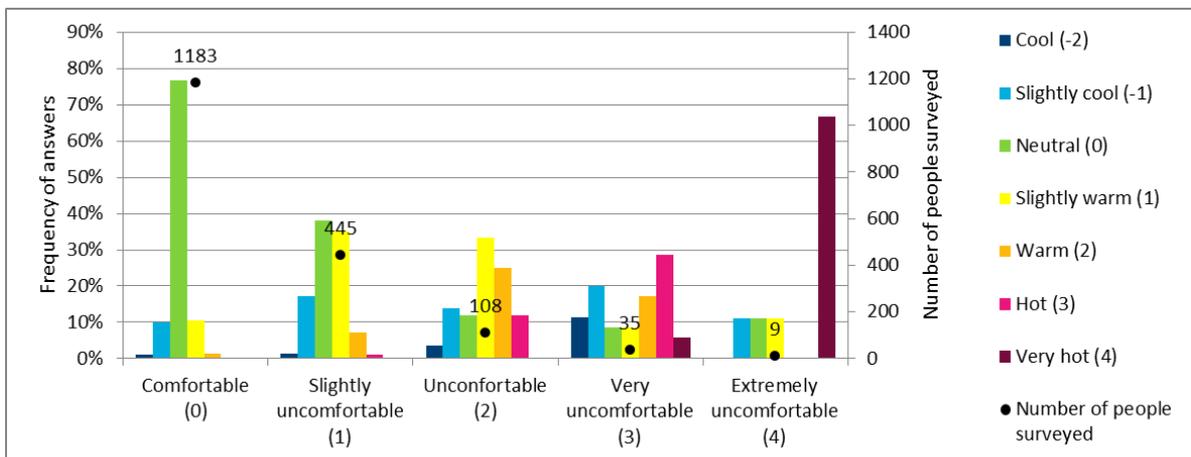


Figure 3-15. Frequency of the thermal sensation votes in relation to the thermal judgment votes.

This statement is not visible in figure 3-15 which represents the frequency of thermal sensation votes by thermal judgment votes. Of the 1,183 persons who stated that they were comfortable during all survey sessions, close to 75% claimed that they were feeling neutral, 10% felt they were slightly cold and 10% responded they were slightly warm. The increase of a person's perception of thermal judgement is seen to correspond to a wider distribution on the thermal sensation vote scale.

Figure 3-16 represents the mean thermal judgment votes as a function of the mean thermal sensation votes. The majority of dots are located in the comfort zone for a mean thermal sensation ranging from -0.5 to 0.5 and a mean thermal judgment lower than 1. When the mean thermal sensation is greater than 0.5, the mean thermal judgment increases at the same time. But during all survey sessions, the thermal judgment does not exceed 2 on average.

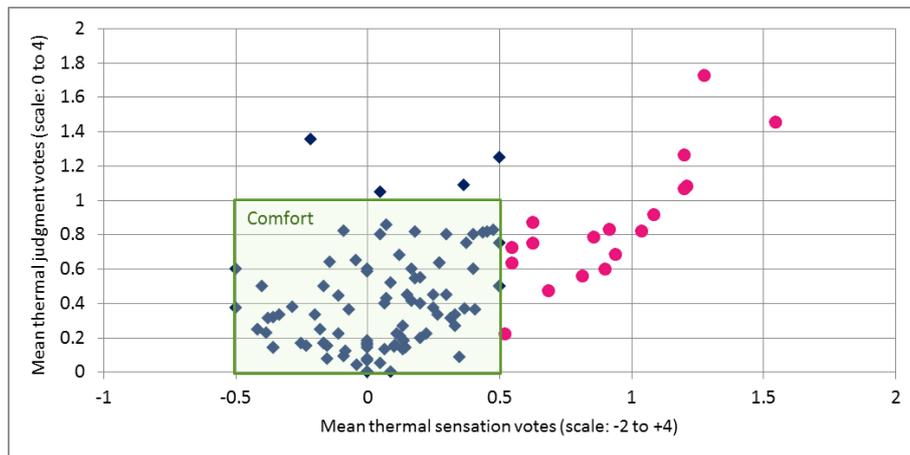


Figure 3-16. Thermal sensation votes represented in relation to thermal judgment votes.

3.1.4. CONCLUSIONS OF THE SURVEYS

This section aims to provide a substantial contribution that will enable progress to be made with regard to the issue of thermal comfort in hot and humid climates. Several conclusions can be drawn which will be useful to propose a new approach to thermal comfort in hot and humid climates. This will be outlined in the following paragraph (3.2).

- The concept of adaptive opportunities in relation to the weather is consistent with the clothing values that were recorded; indeed the clothing decreases when the temperature increases;
- Thermal comfort can be reached when the operative temperature is up to 30°C assuming that natural and mechanical ventilation (openings and ceiling fans) are properly sized;
- Based on the recorded values (13 to 21 $\text{g}_{\text{water}}/\text{kg}_{\text{air}}$), the humidity level has little effect on thermal comfort. High humidity levels (21 $\text{g}_{\text{water}}/\text{kg}_{\text{air}}$) are not contradictory with thermal comfort. This value is much higher than the upper humidity limit of 12 $\text{g}_{\text{water}}/\text{kg}_{\text{dry air}}$ recommended by ASHRAE Standard 55 (ASHRAE, 2003);
- The measured air speeds in order to increase the maximum acceptable temperature are lower than those given by ASHRAE. However, discomfort due to air movements can be observed when the air speed exceeds 0.8 – 1 m/s;
- Respondents generally feel comfortable when their thermal sensation is neutral (neither hot nor cold).

3.2. PROPOSAL FOR AN IMPROVEMENT IN THE ASSESSMENT OF THERMAL COMFORT

3.2.1. A COMPARISON BETWEEN THE EXPERIMENTAL DATA AND THE GIVONI COMFORT ZONES

With the results from the thermal comfort surveys presented in the previous section, it is possible to compare the experimental feedbacks given by the occupant of the building with the comfort zones proposed by Givoni on the psychometric chart.

According to eq. 2-2, when the PMV is between -0.5 and 0.5, the PPD is less than 10%. For a PPD of 20%, the PMV would be 0.85. As a comfort zone is defined for a maximum percentage of discomfort of 20%, the experimental data represented in figure 3-17 are divided into four categories:

- data where the mean thermal sensation votes are between -0.5 and 0.5, representing a situation of comfort (green dots);
- data where the mean thermal sensation votes are between 0.5 and 0.85, representing slight warm discomfort (orange triangles);
- data where the mean thermal sensation votes are between -0.85 and -0.5, representing slight cold discomfort (blue diamond shapes);
- data where the mean thermal sensation votes are greater than 0.85, representing more than 20% of people who are uncomfortable (red squares).

By comparing the experimental data from the survey with the comfort zones proposed by Givoni, several observations can be made.

The study showed that for a naturally ventilated building with solar shading and using ceiling fans, the upper limit of internal operative temperature can be of the order of 29-30°C. The maximum accepted humidity was found to be approximately 21 $\text{g}_{\text{water}}/\text{kg}_{\text{dry air}}$. It was shown that relative humidity was not a significant factor for the occurrence of hot discomfort. The previous paragraph showed that the air speeds required to increase the range of acceptable temperature are lower than 1 m/s.

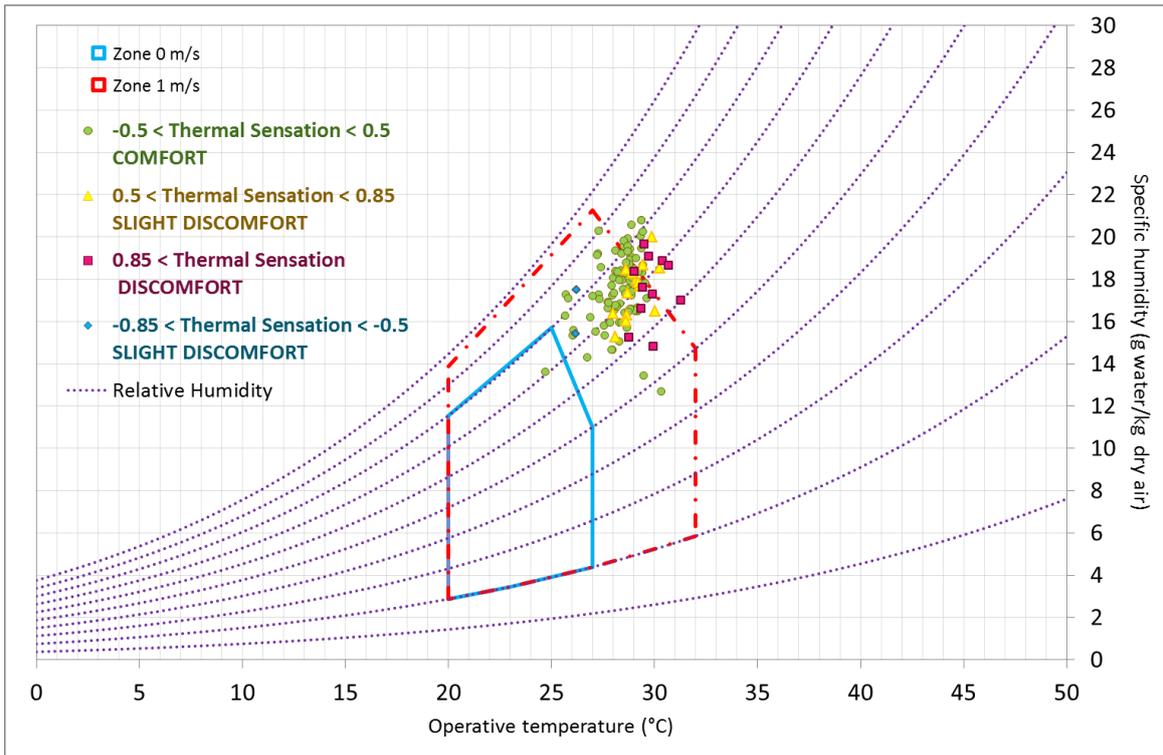


Figure 3-17. Experimental data from the thermal comfort surveys compared to the comfort zones proposed by Givoni.

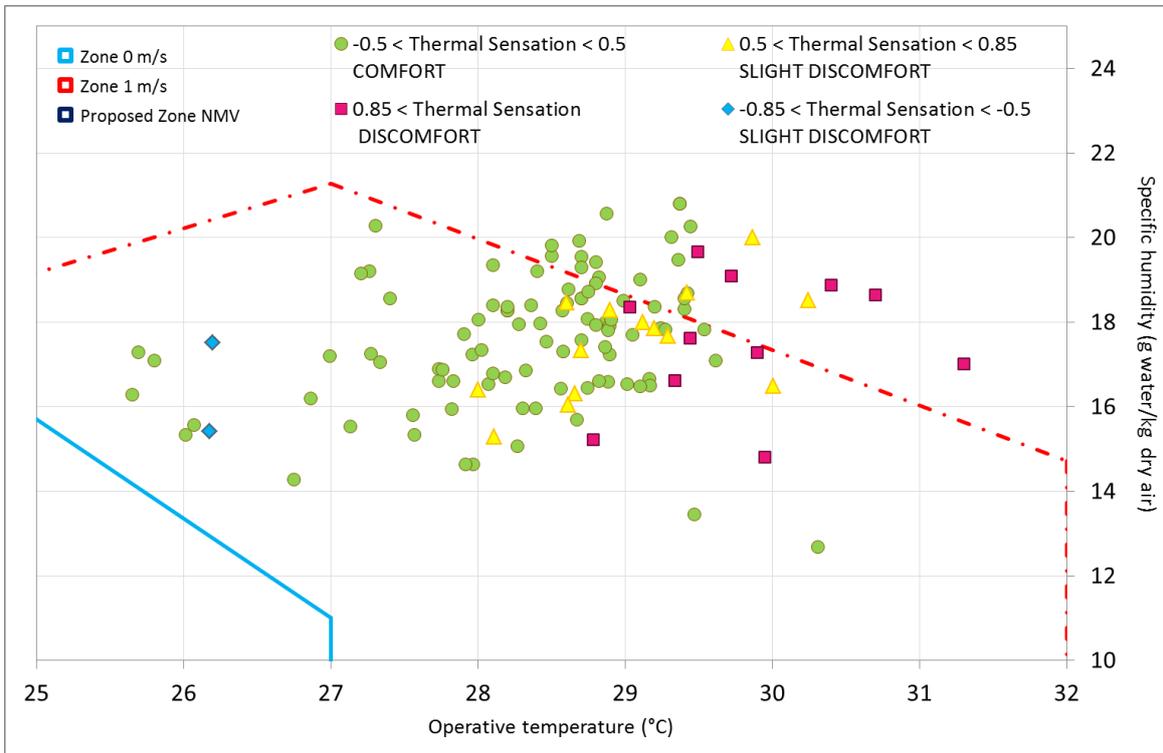


Figure 3-18. A closer view of the experimental data from the thermal comfort surveys compared with the comfort zones proposed by Givoni.

3.2.2. THE MODIFICATION OF THE COMFORT ZONE

Based on the conclusions of the survey and the previous remarks, a new comfort zone is proposed. A zoom of the experimental data is shown in figure 3-19 with the new comfort zone. The maximum temperature is lowered compared with that of Givoni from 32°C to 30°C. The higher limit for humidity is extended to approximately 21 $\text{g}_{\text{water}}/\text{kg}_{\text{dry air}}$.

Furthermore, taking into account the observations earlier made on air speed, the new zone is not associated with a specific air speed. It is indeed too risky to have discomfort due to air movement when the air speed is in the range of 1 m/s. The new zone proposes temperature and humidity ranges providing thermal comfort assuming that the natural and mechanical ventilation of the building (openings and ceiling fans) is properly sized. Moreover, it is crucial for the air speed to be under the direct control of the affected occupant and adjustable in relatively low steps of approximately 0.2 m/s. The proposed zone is named NMV (Natural and Mechanical Ventilation).

This zone is established from the results presented in figure 3-19 and figure 3-20. Figure 3-19 gives the mean hourly data for temperature and humidity (during the hour preceding the answers). Figure 3-20 gives the temperature and humidity data by minute as they were recorded for a few representative surveys.

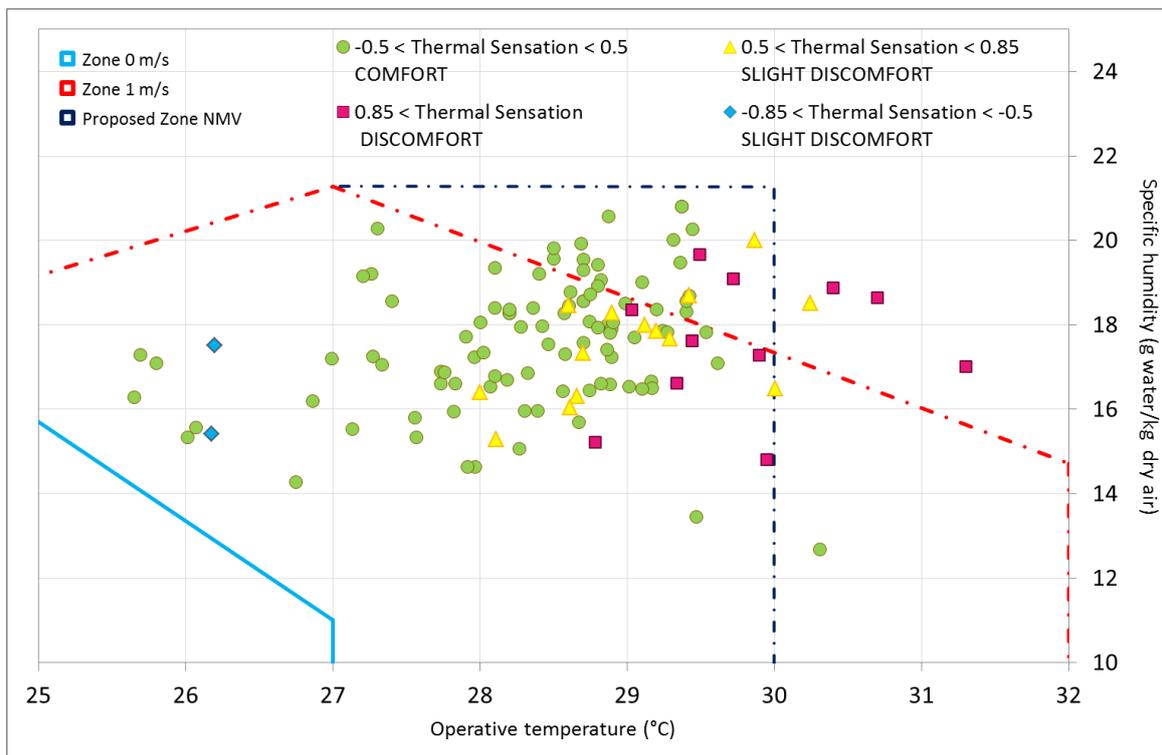


Figure 3-19. Experimental data from the thermal comfort survey and proposal for a modification of the comfort zone.

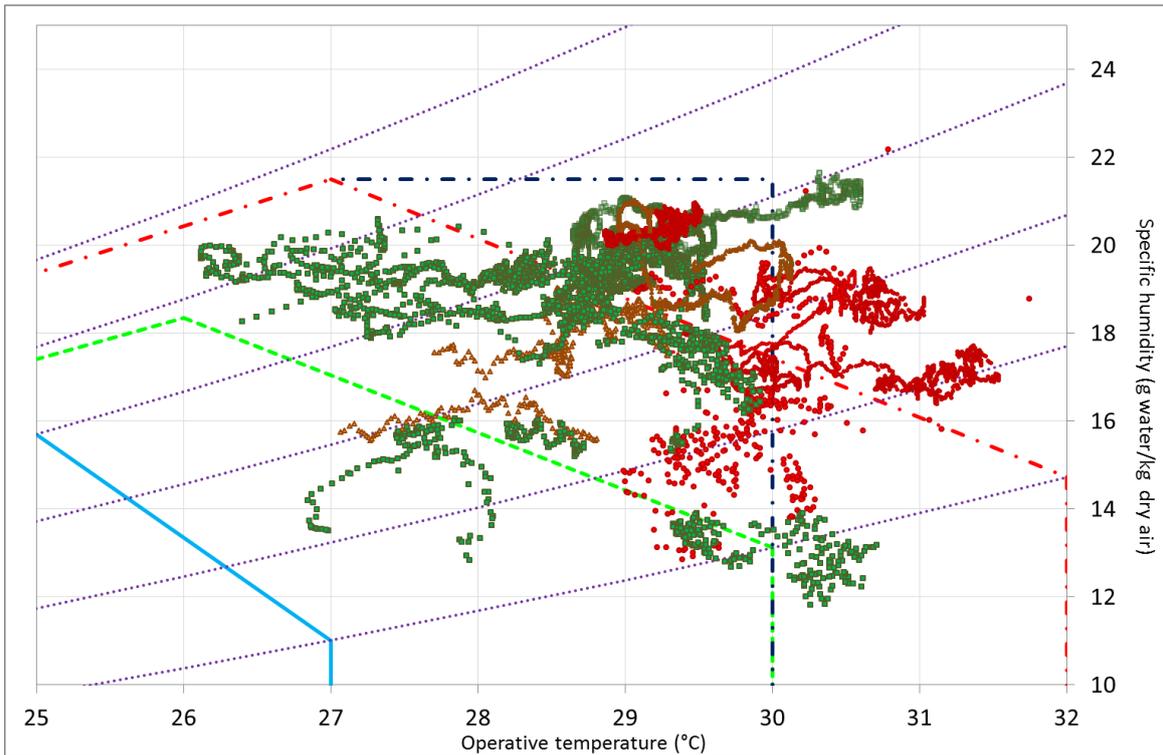


Figure 3-20. Experimental data by minute for selected comfort surveys.

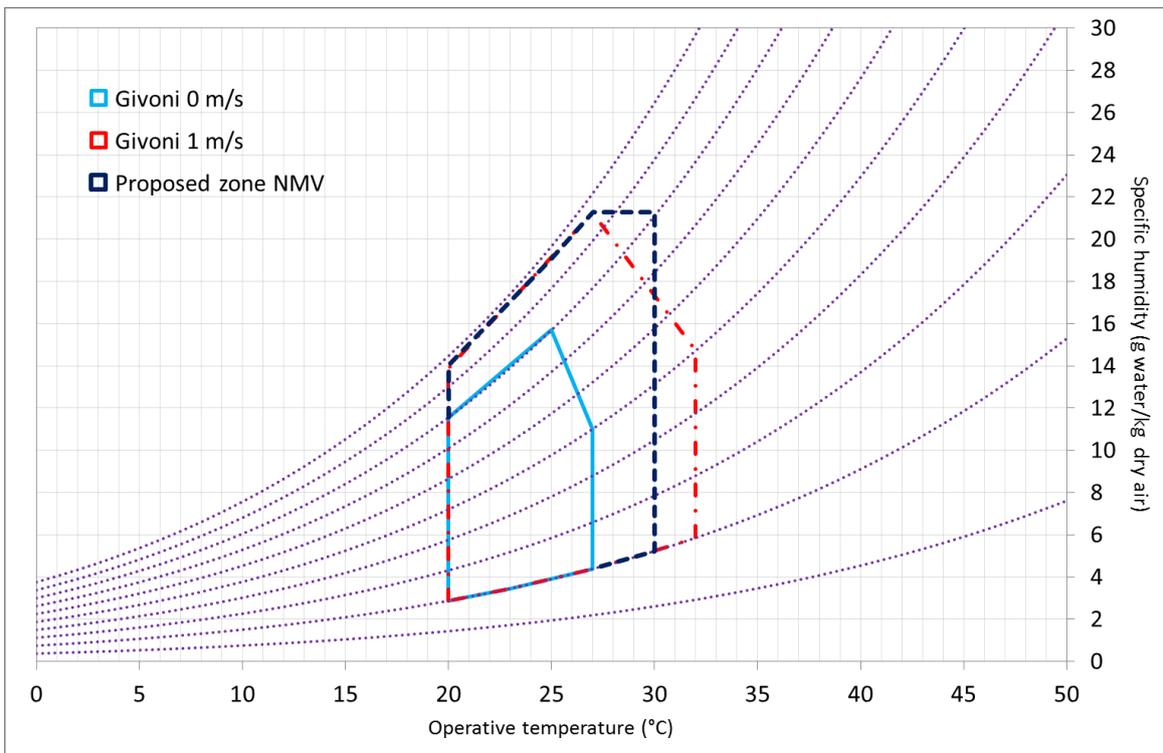


Figure 3-21. New comfort zone for a naturally and mechanically ventilated room.

Figure 3-21 presents the comfort zone on the psychrometric chart, compared to the comfort zone of Givoni. The zone developed in this study has the same lower temperature and humidity limits while the upper temperature and humidity limits are different.

3.2.3. A DIFFERENT TYPE OF REPRESENTATION OF THERMAL COMFORT

Another type of representation of thermal comfort can be proposed to visualise the temporal aspect over a year. In figure 3-22, each column represents a week of the year and each line represents an hour between 8 a.m. and 6 p.m. A green cell indicates that there is less than 10% of discomfort during all hours of the week in question. Orange or red cells indicate that the percentage of discomfort is greater than 10%.

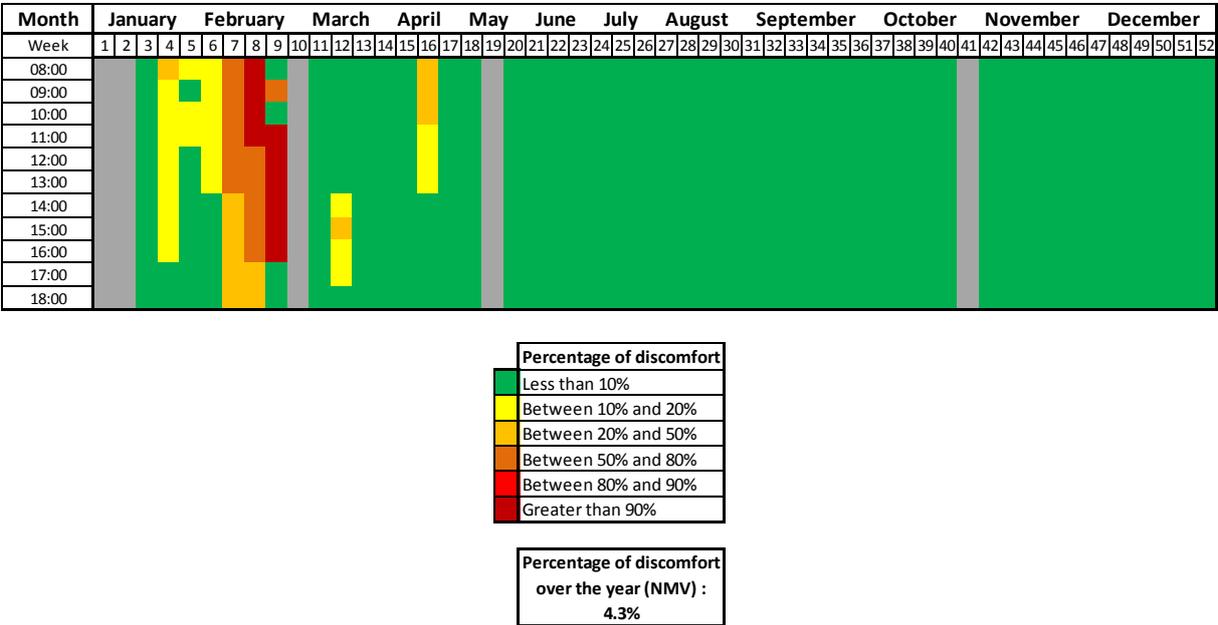


Figure 3-22. A different type of representation of thermal comfort. The data presented are those recorded in classroom 1 in the ENERPOS building between September 2011 and August 2012. The grey columns indicate weeks where data are missing.

The data used to plot figure 3-22 are the temperature and humidity recorded in a classroom of the ENERPOS building (classroom 1 located in the north building, on the ground floor). It indicates that only two weeks during the year are critical in terms of thermal comfort (in February). This represents only 2% of thermal discomfort for all the hours of occupancy of the building (from 6 a.m. to 6 p.m.) over the year as it is shown in figure 3-23.

The difference between the comfort zone defined by Givoni and the new proposed area corresponds to 60 extra hours of comfort during one year (between 8 a.m. and 6 p.m.) for these data taken as a concrete example. Suggesting this new comfort zone allows to better optimise the building envelope for a passive building.

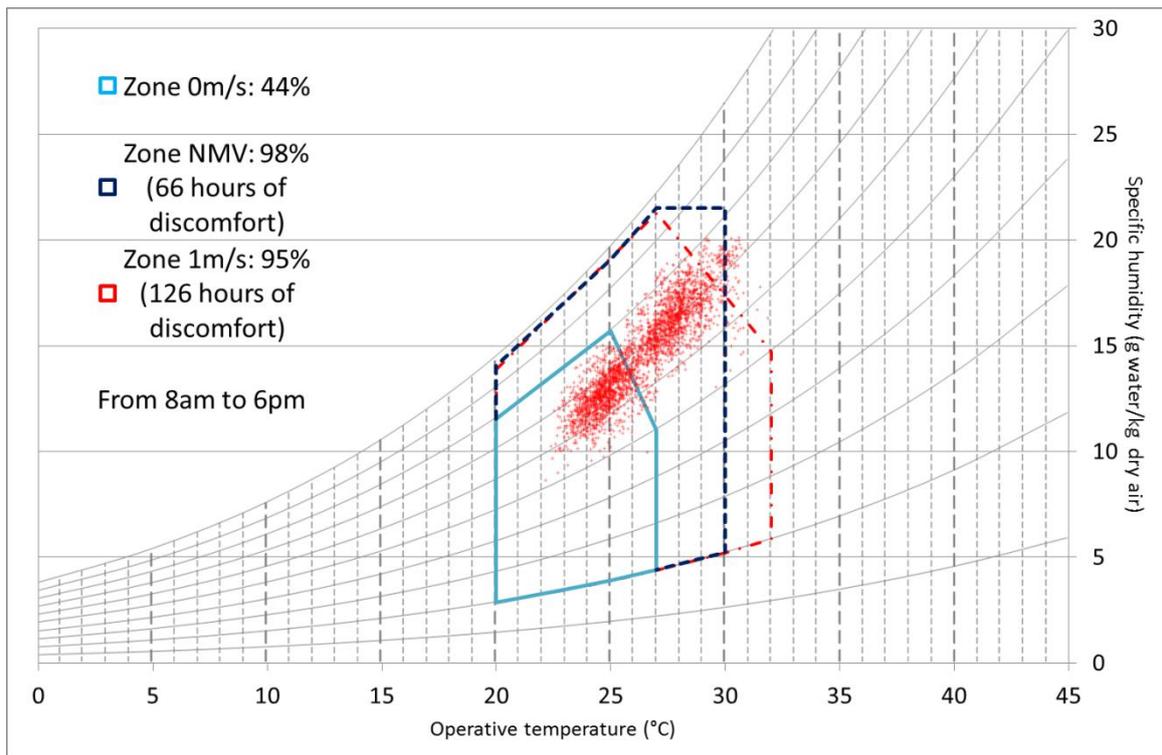


Figure 3-23. The same temperature and humidity data as represented in figure 3-22, plotted on the psychrometric chart with the comfort zones defined by Givoni and the new comfort zone NMV.

3.3. THE IMPACT OF THE OCCUPANTS ON THERMAL COMFORT

3.3.1. MEASUREMENTS OF THE IMPACT OF THE INTERNAL LOADS IN A CLASSROOM

In this experiment, the goal is to measure the thermal impact of internal loads on the temperature of a classroom. In order to do so, temperatures were measured in two classrooms on the first floor of the south building of ENERPOS (classrooms 5 and 6, see figure a- 2). One of the rooms was occupied from 8 a.m. to midday and from 1.30 p.m. to 5.30 p.m. by 28 students.

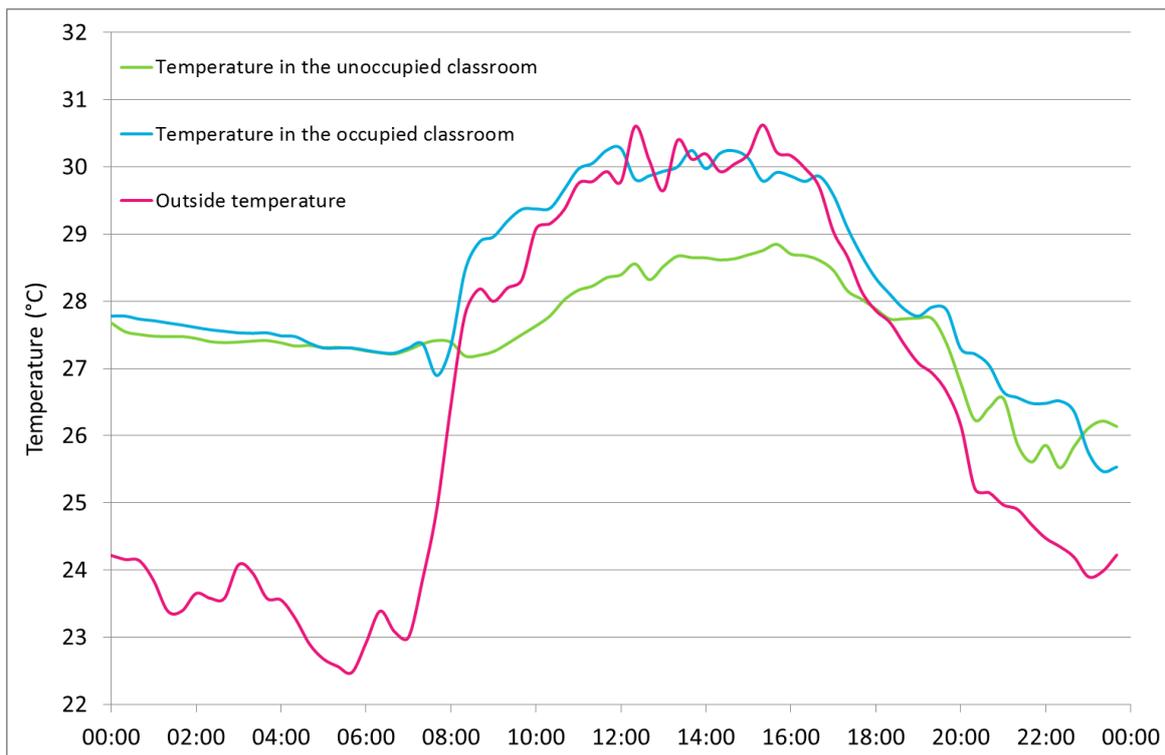


Figure 3-24. Temperature of both occupied and unoccupied rooms compared to the outside temperature.

In paragraph 1.5.2, in which the impact of natural ventilation on the temperature of a classroom has been shown, it was noted that the temperature of the naturally ventilated room remained below the outside temperature during the hottest hours of the day. This result is still visible in this experiment where the temperature of the unoccupied room is almost 2°C lower than the outside temperature.

The result is different for the room occupied by 28 students. The room temperature is very similar to the outdoor temperature. The impact of internal loads in a naturally ventilated classroom is approximately 2°C more than in an unoccupied classroom.

3.3.2. SCENARIOS OF USE

OBJECTIVES AND METHODOLOGY

The purpose of these experiments is to compare measurements of temperature and relative humidity of the air, under various configurations of the opening of louvres in the classrooms on the first floor of the south building at ENERPOS. The temperature sensors are placed on the desks at a height of 0.80 m, which corresponds to the height of the trunk of a seated student. Measurements were taken on a summer day (19th of March).

The objective was to compare the temperatures and the relative humidity in the three scenarios of use that are given in table 3-1.

Table 3-1. Configurations of the classrooms.

Classroom	Scenario
Classroom 5	Louvres open
Classroom 6	Louvres open from 10 a.m. until 6.45 p.m.
Classroom 7	Louvres closed

RESULTS

In terms of weather conditions, the measurements were done on a day with heavily overcast sky. The direct solar radiation on a horizontal surface was 1.3 kWh/m².day. The average temperature was 23.8°C which is rather cold for a summer day, but the average humidity ratio was 84% which is close to the upper limit of relative humidity in Saint-Pierre.

Figure 3-25 shows the evolution of the four temperatures recorded. First it is to be noted that the temperature of classroom 5 (where the louvres are open) follows the outside temperature, with a difference ranging from 0.5°C during the day to 2°C at night. The thermal delay only lasts for a few minutes. The definition of a bioclimatic building is founded on this principle as the inside temperature follows that of the outside.

Secondly, classroom 7 whose louvres are closed all day long is the hottest room. The temperature in this classroom is greater than the outside temperature with a difference of 1°C to 3°C.

In classroom 6 the louvres are open from 10 a.m. until 6.45 p.m. i.e. during class schedule. The temperature from midnight to 10 a.m. follows that of classroom 7 whose louvres are also closed. When the louvres are opened at 10 a.m., the temperature decreases for 2 hours to be on a par with that of classroom 5 whose louvres are open.

This result is important in guiding people on the use of the building. Indeed closing the louvres at night leads to the loss of two hours of comfort in the morning. Therefore it is of no great importance if the louvres remain closed at night, given that in the majority of cases the temperature in the morning is not critical for comfort.

The same phenomenon occurs with the humidity of the classrooms. It must be pointed out that the humidity level drops at about 5 p.m. This is explained by a change in the wind direction.

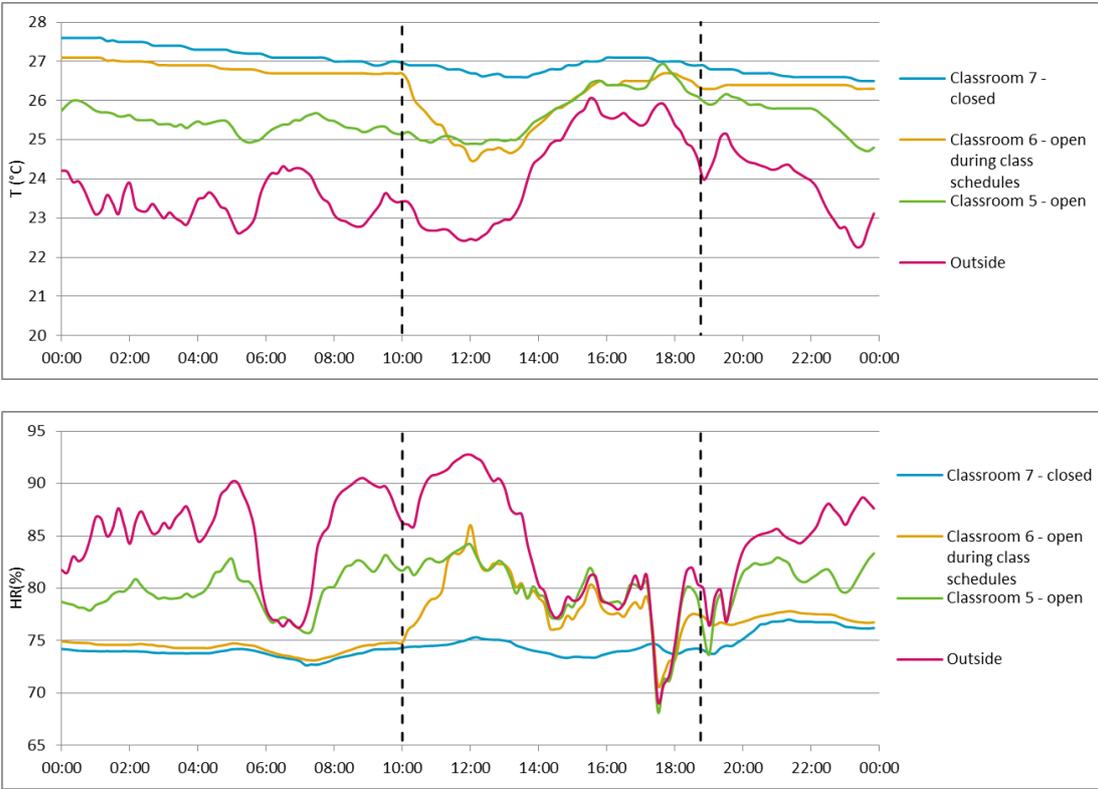


Figure 3-25. The evolution of temperatures and relative humidity in the three classrooms compared to the outside temperature.

3.4. THE INTEREST OF CEILING FANS

The introduction of ceiling fans in a naturally ventilated building has the advantage of being able to consider a comfort zone that is wider than when the air speed is zero. Even if the energy use of ceiling fans per square metre is at least ten times less than that of the air conditioning, it still represents a sizeable percentage that is interesting to study.

3.4.1. AIM OF THE STUDY

This study aims to analyse the use of ceiling fans in the ENERPOS building depending on the outside temperature. The use of ceiling fans inevitably depends on the occupancy of the classrooms and offices.

A dimensionless number representing the utilisation rate of the ceiling fans in the occupied rooms will be calculated with the measured power for all the ceiling fans of the building and the maximum theoretical power assuming that when a room is occupied, the occupant uses all the ceiling fans of the room at their maximum speed. In principle, the utilisation rate is between 0 and 1, but it can be greater than 1 if the ceiling fans are left turned on in an unoccupied room. This utilisation rate is calculated for several days and compared to the outside temperature.

3.4.2. RESOURCES AND ASSUMPTIONS

THE MEASURED POWER OF THE CEILING FANS

The ENERPOS building is equipped with 55 ceiling fans. All 7 classrooms have 6 ceiling fans each and there are altogether 13 ceiling fans in offices and the meeting room. The BMS is composed of an energy metre that records the energy and power load of the 55 ceiling fans of the building. This metre also records the energy used by the building management system as well as the automatic watering system. It is possible to assume that the energy required for the automatic watering system will not interfere with this study as it is rarely in operation during the occupancy hours of the building. The power load of the building management system (measured when the circuit breakers of all the ceiling fans and the automatic watering system are cut out) is estimated between 10 and 15 W. Therefore, 15 W will be subtracted from the measurements of the ceiling fans' power.

The power demand of one ceiling fan was measured and the values are close to the data given by the constructor (70 W). At the maximum speed, the demand of one ceiling fan is approximately 64 W. It is 40 W at medium speed and 20 W at low speed.

OCCUPANCY DATA

Two sources of information are available to assess the occupancy of the ENERPOS building: the presence detectors of the BMS that are placed in every classroom and office as well as the schedules of the classrooms that are entered in the room scheduling software of the University. Presence detectors are triggered every five minutes and do not detect the presence of a user when the user is

sitting still (especially in individual offices). As for the schedule, it cannot always be considered as a reliable source because some rooms can be booked without being occupied and vice versa.

To calculate the occupancy of the building, the presence detectors data are used for all offices and classrooms, except for classroom 3 whose detector is defective. In this case, the schedules will provide occupancy data.

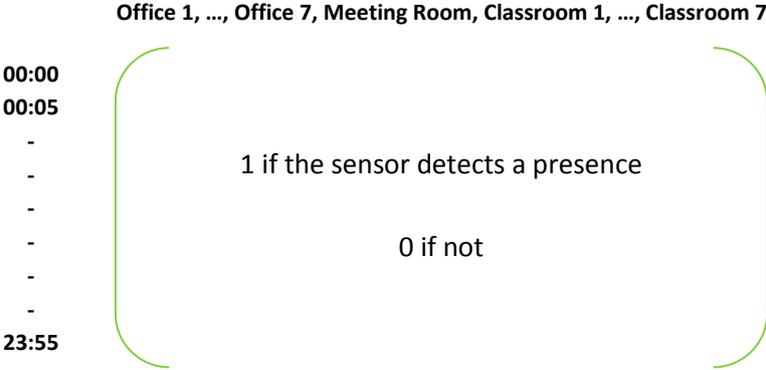


Figure 3-26. Occupancy matrix.

THEORETICAL MAXIMUM POWER

To calculate the theoretical maximum power, it is assumed that all ceiling fans are turned on at full power. The power demand of one ceiling fan is determined as the one given by the constructor (70 W). The vector of maximum powers is defined as the maximum power of all ceiling fans for each room of ENERPOS (figure 3-27). The occupancy matrix is multiplied by the vector of maximum power in order to obtain the theoretical maximum power every 10 minutes.

Maximum Power

Office 1	0.14 kW
Office 2	0.14 kW
Office 3	0.7 kW
Office 4	0.7 kW
Office 5	0.7 kW
Office 6	0.7 kW
Office 7	0.7 kW
Meeting Room	0.7 kW
Classroom 1	0.28 kW
Classroom 2	0.42 kW
Classroom 3	0.42 kW
Classroom 4	0.42 kW
Classroom 5	0.42 kW
Classroom 6	0.42 kW
Classroom 7	0.42 kW

Figure 3-27. Vector of maximum powers.

3.4.3. RESULTS FOR A MODERATELY HOT SUMMER DAY

The results presented are those from a moderately hot summer day (November 16th 2011). The average temperature between 8 a.m. and 6 p.m. is 27°C and the maximum attained is 27.9°C (figure 3-28).

During the occupancy period (8 a.m. to 6 p.m.), the curve of the measured power of the ceiling fans follows the trend of that of the maximum power of the ceiling fans (theoretical curve based on the occupancy data) but remains lower. The average utilisation rate for that day is 63% from 8 a.m. to 6 p.m.

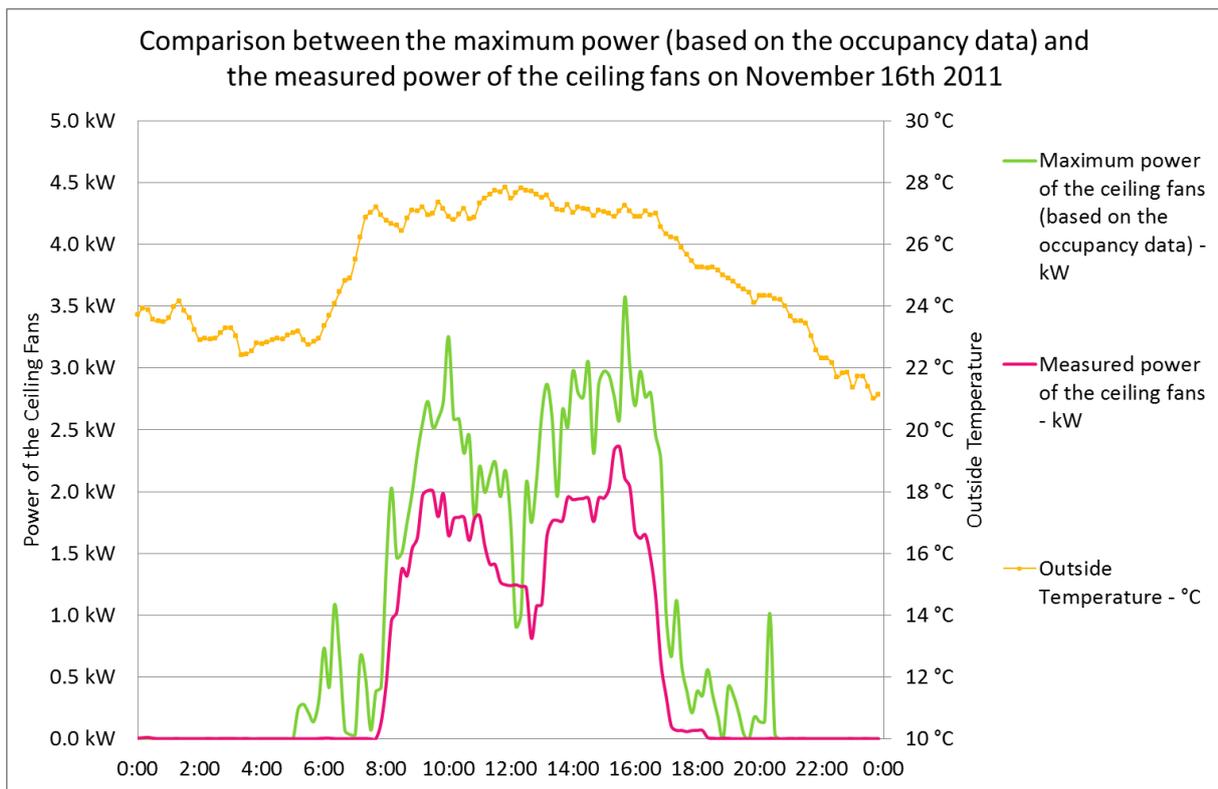


Figure 3-28. Comparison between the maximum power of ceiling fans (based on the occupancy data) and the measured power on November 16th 2011.

3.4.4. THE UTILISATION RATE OF THE CEILING FANS IN RELATION TO THE OUTSIDE TEMPERATURE

By carrying out the same calculations for several days, it is possible to plot the utilisation rate against the outside temperature (figure 3-29).

The percentages between 0 and 1% are eliminated and those greater than 100% (meaning that the ceiling fans were left turned on in an empty room) are brought back to 100%. In order to avoid

unnecessary energy consumption caused by ceiling fans left turned on when the room is unoccupied, the use of presence detectors to switch off the fans automatically could be a wise choice.

The data between midday and 1 p.m. are also excluded.

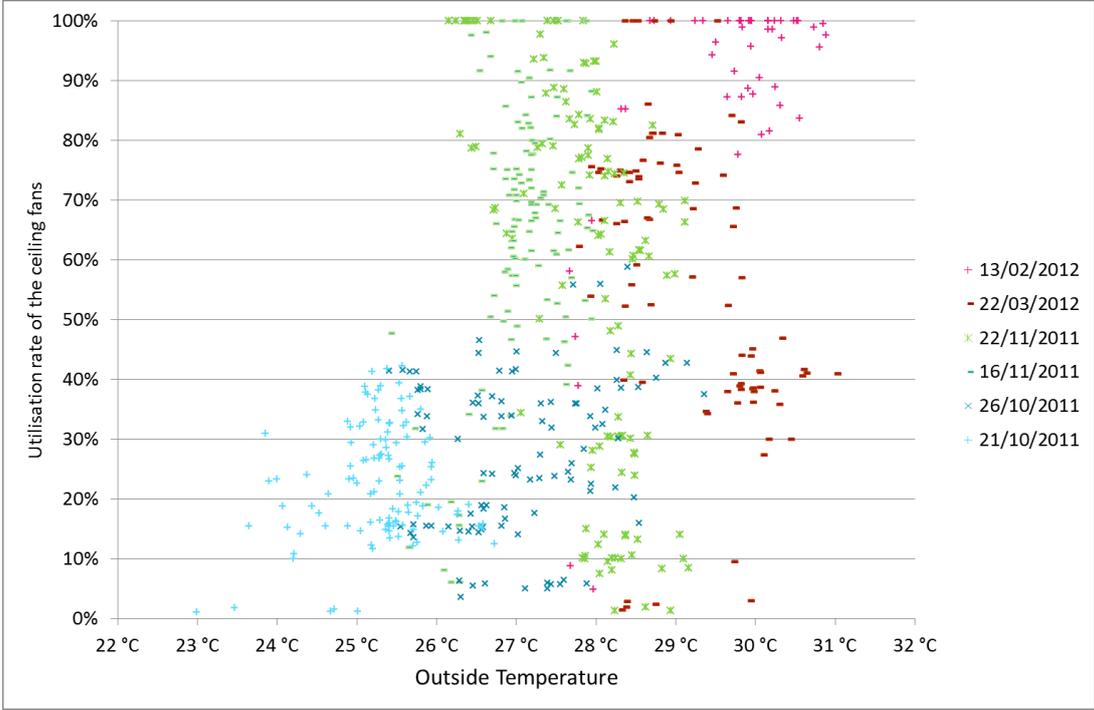


Figure 3-29. The utilisation rate of the ceiling fans plotted against the outside temperature.

It is challenging to establish a direct relationship between the utilisation rate of the ceiling fans and the outdoor temperature. It would be interesting to make a comparison with the indoor temperature, but since the ENERPOS building only has one energy metre for all the ceiling fans, this study is not feasible.

A trend can be observed between the utilisation of the ceiling fans and the outdoor temperature. According to the data of figure 3-29, the users begin to turn on the ceiling fan when the temperature is above 24°C. However, between 24°C and 26.5°C, the utilisation rate is relatively low, on average 23%. Between 26.5°C and 27°C, the utilisation rate appears to be distributed between the values of 10 to 100% with an average of 49%. Between 27°C and 29°C, the average utilisation rate is slightly higher at 57%. Above 29°C, ceiling fans are used at high rates of 71% on average.

The work presented in this chapter constitutes the first field study of thermal comfort conditions in a net zero energy building in a tropical climate. The results of the thermal comfort surveys reveal that the comfort zones defined by Givoni can be slightly extended in terms of the humidity level but that the temperature should be kept below 30°C which is a critical limit for thermal comfort when the building is naturally ventilated and when ceiling fans are available.

The experimental study on the natural ventilation scenario provides us with valuable information about the use of the building. The first conclusion is that in an unoccupied room, the temperature can be 1.5°C lower than that of the outside. This is due to the thermal mass of the building that keeps the walls cooler than the air during the day. The measurements considered give the same temperature for the room occupied with approximately 30 students and that of the outside. This result obviously depends on the number of occupants in the room and on the previous conditions of the room. However, it can be speculated that in a low thermal mass building (made of wood for instance), the temperature of an occupied room would be of the same as that of the outside even when naturally ventilated. Another conclusion is that in tropical climates, night ventilation has a low impact on the temperature of the room the following day. Indeed, when the louvres are opened in the morning, within two hours the temperature of the room follows the trend of one that remained open all night long. This is explained by the small temperature difference between nights and days in the tropics.

The study of the use of ceiling fans in the building shows that the limit of 26°C indicated by Givoni on the comfort zone when there is no ventilation appears to be consistent with the results. The calculation of the utilisation rate leads to the conclusion that the use of ceiling fans is necessary when the temperature is above 26°C. Below this limit, their use is more uncertain.

The new comfort zone proposed based on the results from the thermal comfort survey (named NMV zone) will be applied in the following chapter which will present a method to optimise the design of a building and particularly that of solar shading taking both thermal and visual comfort into account.

Chapter

4

OPTIMISATION OF THE BUILDING DESIGN

Each building is unique and is a complex system in which the conditions are dependent on the climate, orientation, surroundings, geometry, typology but also the people using the building. In a passive building and even more so in a net zero energy building, the aim is to limit the sources of discomfort in order to minimise the need for energy-consuming systems. Compromises must be made during the entire building design process.

This chapter proposes a methodology using simulations to help optimise the design of passive buildings using a comfort approach. The study will concentrate on the design of solar shading that plays an extensive role in tropical climates and that has a direct impact on the thermal and the visual comfort of building users. Parametric studies on the type and dimensions of solar shades are developed with regard to their impact on the percentage of thermal comfort and the availability of daylighting in the room. The methodology, based on a multi-physics approach, is innovative, as it involves the coupling of both thermal and visual comfort conditions.

Essentially, all models are wrong, but some are useful.

GEORGE E. P. BOX

4.1. UNCERTAINTIES DURING THE BUILDING DESIGN PROCESS

4.1.1. DESIGN PROCESS AND MODELLING

The use of simulation is decisive in the design process of new buildings. It evaluates several alternatives in terms of energy performance and occupant comfort. It is an essential tool for decision support. A satisfactory model should be a useful one. Modelling is not intended to be an accurate reflection of the reality on the ground, but to provide an image of it, retaining only the relevant features given the expectations raised. The model must be constructed and evaluated taking the intended use into account. The development of a model is motivated by a set of questions that the model should provide answers for. Thus, modelling results from a long series of decisions and choices that are guided by the initial questions. A large number of assumptions are made in the construction process of the model.

The question of the reliability of simulation codes should not be overlooked. Increased energy efficiency of buildings could undermine modelling assumptions generally accepted for standard buildings, because of the prevalence of new physical phenomena which were previously neglected or inadequately addressed. The question is not whether a model is correct or not - all models are wrong - but its principle function is to assess its contribution to the process of understanding the building and its behaviour.

The example of the ENERPOS building is rather relevant in order to point out both difficulties and challenges that can arise with the use of simulation in the design process. The case study of ENERPOS was used to test new methods and tools for the design of Net Zero Energy Buildings in hot climates. This was carried out within the framework of a French national research project also named ENERPOS, that involved three French university research laboratories, two HVAC practices and the architect himself (Garde et al., 2011). Some models were run during the designing to evaluate the performances of the building, with tools such as Codyrun (Boyer et al., 1996) or Design Builder for the thermal performances and Dial Europe for daylighting (Garde et al., 2006). However, the models were not used by the architect to design and even less so to optimise the building and its envelope, but only to check the performances.

Expert rules and common sense were more effective in this case, considering the state of research in the field of building simulation at that time, particularly in 2005 when work commenced on the design of the building. This type of approach is well-suited to simple buildings like ENERPOS. This building has low internal loads. Its location is close to ideal in terms of natural ventilation, with no major noise sources or high buildings at close proximity. Consequently, it has been possible to choose the orientation in order to take advantage of the cooling breezes, making the concept of natural ventilation straightforward. Even though the design and operation were based on numerous assumptions, its performances in terms of energy and comfort are more than satisfactory.

Building simulation is not required for simple buildings but in the case of more complex buildings, either because of their size or type; simulation is necessary to design, understand and optimise the building and its operation. The impact of natural ventilation and inertia then becomes dominant in the simulated performances of the building.

Building simulation is still at the research and development stage. It is still rather rarely used by design offices that prefer expert rules as well as their own professional experience.

In some cases, the simulation is not useful. For instance wind roses and solar diagrams are very effective to understand the climate and to design natural ventilation and solar shading in the initial phase of the building sketch. In other cases, simulation is very useful and reliable in terms of results, for example when representing the shadows created on a façade by solar shading with 3D-CAD tools. Finally, there are still a large number of concepts that are difficult to describe physically. Inertia (Chahwane, 2011), the effect of sunspots, natural ventilation (Stephan, 2010) and direct and diffuse radiation are some of the concepts that are not well described in the tools currently available while their impact on the thermal behaviour of the building is predominant, particularly in passive buildings in tropical climates. Daylighting is also poorly described in the simulation tools currently available and the results are not reliable for complex buildings with several reflections.

At the present stage of knowledge, a methodology is proposed to optimise passive building envelopes. This methodology has not been fully accomplished yet but it allows the introduction of lines of thinking about the appropriate approach to improve and optimise the design of a building. In this case, the simulation tools are not used in order to size the systems of the building but rather to optimise the building envelope. Therefore, instead of choosing outputs related to the energy consumption of the building, the aim is to minimise the percentage of discomfort (thermal and visual) in order to optimise the passive operation of the building.

Ultimately, the ideal would be to run inverse simulations where, for instance, from a specific result in terms of energy performance or comfort, it is possible to obtain the optimal design of a building.

4.1.2. SOURCES OF UNCERTAINTIES AND THE RELIABILITY OF THE MODELS

Given the complexity and the intricacy of the building system, it is almost impossible to find a direct relationship to link the variables and the cost function for optimisation purposes. The cost function cannot be evaluated, but approximated numerically. In this case, optimisation is an interesting approach in order to reduce the cost function previously chosen.

Some tools can be considered reliable, that is to say, they represent reality adequately, this being the case for instance of the representation of shadows created by the solar shading using Google SketchUp (figure 4-1). Google SketchUp makes it easy to assess the impact of solar shading on the windows of a building and is a user-friendly tool for design offices and architects throughout the design process.



Figure 4-1. Comparison between a picture of the ENERPOS building (November 26th at 5 p.m.) and the SketchUp Model with projected shadows of shading at the same time.

However, many uncertainties exist in the models that are developed during the design. Some of these are caused by the modelling assumptions retained for the performance simulation:

- The weather data: Buildings are simulated using a weather file which is either an average of several years of data or that of a specific year. In both cases, this weather file will never represent the reality of the climate. For daylighting simulations, the choice of sky model and the illuminance data available have a large impact on the results. The sky characteristics are changeable and sunlight cannot be disregarded;
- The shading masks might not be taken into account in the modelling whether it is for buildings that are constructed afterwards or vegetation whose shade varies seasonally and over time;
- The construction of the building itself: Material and construction quality is considered optimal in the model but there may be construction defects. Moreover, the building will deteriorate over time, a factor which is not necessarily heeded in the performance simulations;
- The modelling assumptions on occupants: Occupancy of the building (number of users, age, schedules), window-opening or equipment use, have a direct impact on the energy used by the plug loads;
- The settings of HVAC: Assumptions put forward to describe the use of HVAC in the building simulations, for instance the thermostat set points or the schedules.

4.1.3. COMPARISON OF MODEL PREDICTION WITH MEASUREMENTS FOR ENERPOS

The example of the ENERPOS building is taken to illustrate the uncertainties that can appear in the models developed during the design of a building. As stated in paragraph 4.1.1, several models were developed during the design process of ENERPOS but those models were used to assess and support the expert rules used to design the building rather than to optimise the envelope or the use of the systems operating within. Two comparisons are proposed in this paragraph. The first of these is the comparison between the energy use predicted during design and the measurements available following two years of monitoring. The second evaluation concerns the thermal comfort in the building

with the comparison of the model and the measurements for the annual temperature profile of an office. The use of ceiling fans scheduled during the design is also discussed.

ENERGY USE

The methodology used by the design office (Garde et al., 2011) to forecast the energy consumption of the building in the design phase is rather basic, but simple to establish. It consists of listing all the equipment, appliances and systems installed in the building, using an assumed-use scenario (number of hours of use per day and number of days per year) and multiplying by a diversity factor that takes into account the fact that all equipment is not used at the same time and is not using the maximum load. In this method, there are several sources of errors that are linked to the equipment installed, the use scenario, or even to the diversity factors based predominantly on the previous experience of the design office. The aim of this section is to explain the erroneous calculations carried out during the design phase when predicting the energy consumption of the building.

Figure 4-2 and table 4-1 present a comparison between the energy use that was predicted during design by end-uses and the measurements taken in the building while in operation over two years (June 2010 – May 2011 and June 2011 – May 2012). The ratios are given for the net floor area and final energy (electricity). Overall consumption has been largely over-estimated during the design predictions (45 kWh/m².y instead of 13-14). The major errors made during the design phase to predict the energy consumption of ENERPOS were in relation to the split air conditioning systems used to cool the two technical rooms, the air conditioning system (AC), the air treatment unit (ATU) and the plug loads.

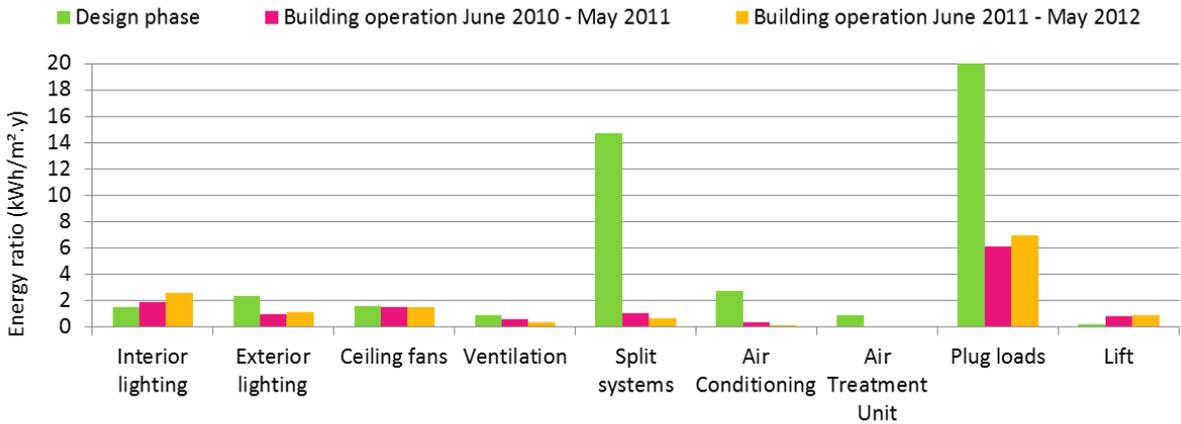


Figure 4-2. Energy consumption for the ENERPOS building. Comparison between the design phase calculations and measurements during the first two years of occupancy of the building.

Table 4-1. Energy ratio (kWh_{FE}/m².y) by end-uses: calculation during the design phase and measurements over two years.

	<i>Interior lighting</i>	<i>Exterior lighting</i>	<i>Ceiling fans</i>	<i>Ventilation</i>	<i>Split systems</i>	<i>AC</i>	<i>ATU</i>	<i>Plug loads</i>	<i>Elevator</i>	<i>Total</i>
Design phase (kWh _{FE} /m ² .y)	1.6	2.4	1.6	0.9	14.7	2.8	0.9	20.0	0.2	45.1
Building operation (June 2010 – May 2011)	1.9	1.0	1.5	0.6	1.1	0.4	0.0	6.2	0.8	13.4
Building operation (June 2011 – May 2012)	2.6	1.2	1.5	0.4	0.7	0.2	0.1	6.9	1.0	14.5

The air conditioning system (AC, VRV group) and air treatment unit (ATU) are installed in offices and in the two computer rooms. During the design phase, a dynamic thermal model of the building was developed using the DesignBuilder simulation tool. The offices were assumed to be air-conditioned for 1.5 months and the computer rooms for three months (15 days in December and from early February to mid-April, which represents 42 working days). The energy index due to air conditioning was thus assumed to be 2.8 kWh/m².y. In fact, it was revealed that after three summer seasons, the air conditioning in the offices was practically not used at all (about one week/year).

The purpose of the two split air conditioning units (one of 1780 W and the second one of 700 W) was to cool the two technical rooms equipped with computer hardware. In fact, only one technical room houses switchgear cubicles, thus only one split system (700 W) is turned on for cooling purposes.

During the design phase, it was proposed to set up an uninterruptible power supply (UPS), particularly for the two computer rooms. However, there is presently no UPS in the building. Moreover, the two computer rooms were not equipped with desktop computers up to August 2012. Students came to the building with their own portable computers. With regard to the offices, the use of laptops and nettops instead of desktop has been encouraged which decreases considerably the energy use of plug loads. This change between the design phase and the current situation explains the significant difference in the energy consumption of the plug loads (20 kWh/m².y on the basis of the design as compared to approximately 6-7 kWh/m².y from the measurements).

To conclude this comparison between the model predictions and the measurements for the energy use of ENERPOS, it is to be noted that the difference in assessing the result is not due to the model accuracy, but because the real building operation differs from that expected during the design.

THERMAL COMFORT

During the design phase, a dynamic thermal model of the building was developed using the DesignBuilder simulation tool. Figure 4-3 shows the annual temperature profile of an office in ENERPOS. Based on the seasonal variations in the temperature of the office, it was possible to predict the different operational periods of natural ventilation, ceiling fans or air conditioning, throughout the year. The transition from natural ventilation to ceiling fans was carried out partly based on the experience and knowledge of the site and climate by the design office team, but also on the basis of a maximum average resultant temperature above 28°C. The move from ceiling fans to air conditioning was made when the resultant temperature exceeded 30°C. Design studies indicated that an office

required active cooling from January to mid-March and that natural ventilation and ceiling fans were considered sufficient for the rest of the year.

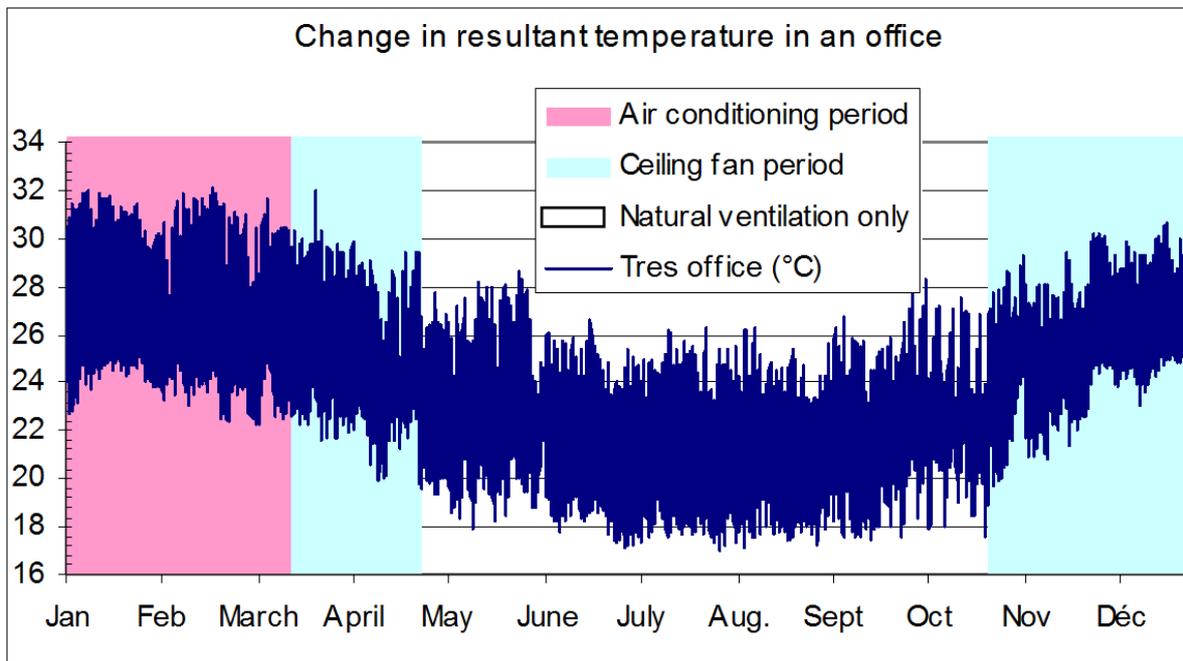


Figure 4-3. Annual temperature profile of an ENERPOS office simulated using the DesignBuilder software and the determination of the different operational periods of natural ventilation, ceiling fans or air conditioning. Source: (Garde et al., 2007).

Figure 4-4 shows the measurements of the indoor air temperature in an ENERPOS office as well as the energy used by the ceiling fans of the building during the three-year period from 2010 to 2012. The comparison between the temperature profiles of the model and the measurements shows that the model was rather accurate in terms of maximum temperature during summer (between 30 and 32°C). However, the minimum temperature in summer was close to 24°C in the model whereas the measured values do not fall below 28°C. In the model, the assumption was made that the louvres would stay open at night to ventilate the building. In reality, the users close their louvres when leaving their office in the evening to avoid rains.

The same observation can be made for the winter period where the maximum temperature according to the model was close to 24°C. The measurements show that the true temperature of the office is closer to 26°C. It was based on the assumption that the louvres would remain open during winter which is usually not the case.

These hypotheses should not have a large impact on the determination of the different operational periods as the maximum air temperature of the model building in summer is close to the measured values. However, by looking at the energy use of ceiling fans over three years, the real period of use can be identified. As stated previously, air conditioning is practically never used in the building. The period of use of the air conditioning defined during design (January to mid-March) is therefore

substituted by a period where ceiling fans are used. It can be observed that the real period of use of the ceiling fans is a little longer than the one predicted during the design (the ceiling fans are still used in early May).

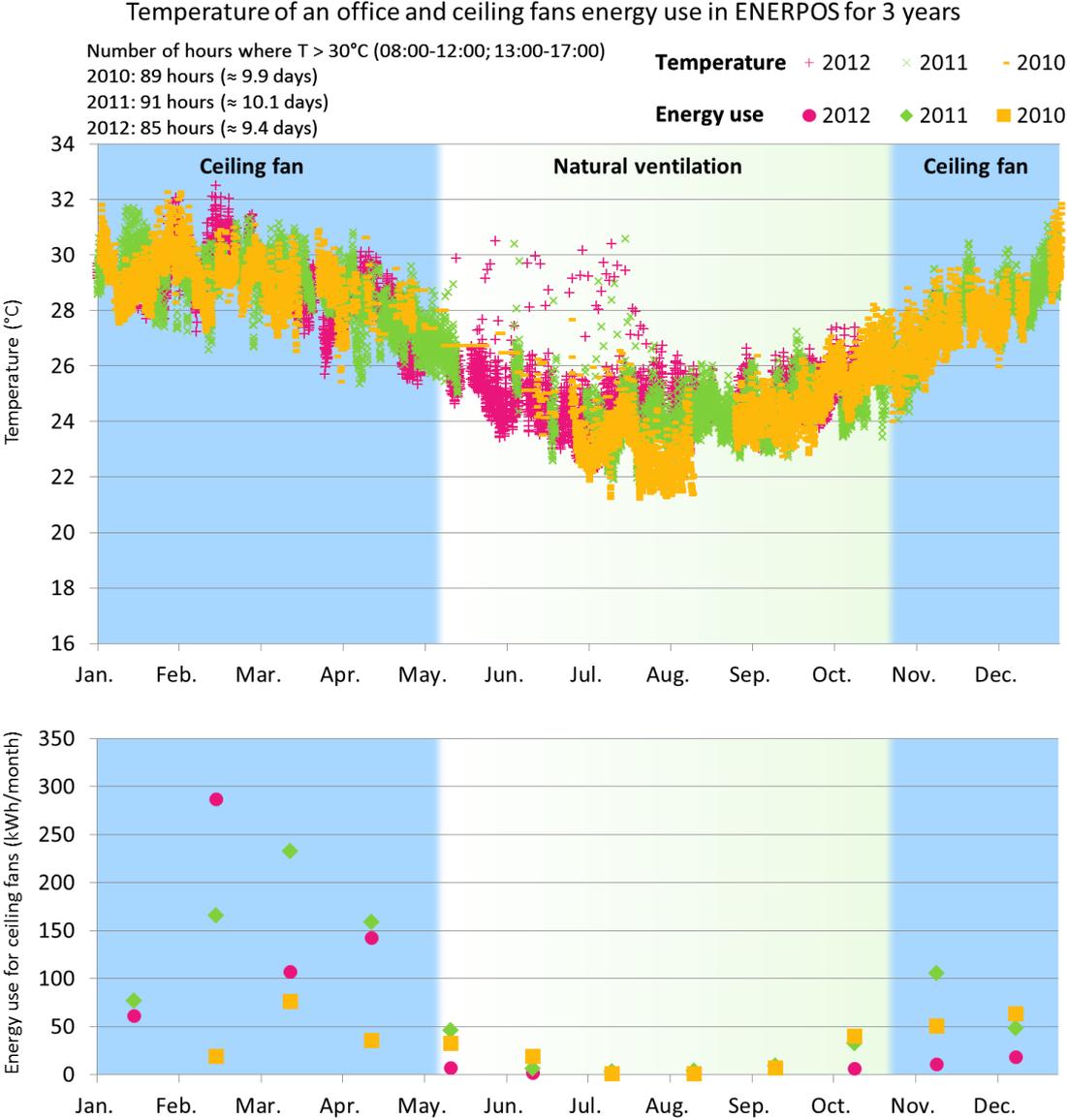


Figure 4-4. Measurements of the temperature of an office and the energy use of ceiling fans in ENERPOS for three years.

These observations on ENERPOS show that several risks of uncertainties can appear during the design and in the models. User behaviour remains the main challenge for the building performance simulations. Based on the findings about the thermal comfort developed in chapter 3, a methodology is presented below to evaluate the impact of solar shading on the passive operation of a building, in terms of thermal comfort and the availability of daylighting.

4.1.4. TOWARDS A COUPLED APPROACH TAKING BOTH VISUAL AND THERMAL COMFORT INTO ACCOUNT

As stated in the first chapter (paragraph 1.5.2), there is a need for an approach which takes both thermal and visual comfort into account when designing the envelope of buildings. Currently, solar shadings are designed only to improve the thermal conditions or to reduce the cooling loads of the buildings, but very often no attention is paid to daylighting. In some cases, over-efficient solar protection can result in the use of artificial lighting inside, which in turn leads to an overconsumption of electrical lighting. A compromise must be found between effective solar protection and suitable natural lighting. A combination of both of these objectives to reduce the overall consumption of the building is not always obvious.

There is a real need to develop a sound methodology combining thermal and daylight simulations so as to assess the impact of solar shading on both thermal and visual comfort. An innovative approach is proposed in this chapter, taking into account the passive behaviour of the building (as opposed to the conventional approach with regard to the energy use) both in terms of thermal comfort and the availability of daylight.

4.2. PRESENTATION OF THE SIMULATION METHODOLOGY

4.2.1. OBJECTIVES OF OPTIMISATION

To achieve optimisation of the building envelope, two methods can be used, either a parametric study or by coupling an optimisation software programme to the building models. Knowing the complexity of the problem, a parametric study could be difficult to realise. Indeed, in such parametric studies, we usually set all but one variable and try to optimise a function with respect to the unfixed variable. However, any change made to a variable makes all the other variables become non-optimal and therefore these variables need to be readjusted. This manual procedure can be extremely time-consuming, often impractical for more than two or three independent variables and only a limited improvement can be achieved (Wetter, 2000). As an alternative, an optimisation algorithm can be useful to reduce the number of required resolutions while ensuring a better convergence to a global minimum.

Usually, a lot of time is spent in generating the input files for a simulation model, but once this is done, the user generally does not determine the parameter values that lead to optimal system performance. This can be due to the lack of time left to carry out the tedious process of changing input values, running the simulation, interpreting the new results and deducing how to change the input for the next trial. The the system being analysed can become so complex that the user is just not capable of understanding the nonlinear interactions of the various parameters. However, using mathematical programming, it is possible to carry out automatic single or multi-parameter optimisation with search techniques that require only little effort (Wetter, 2001).

4.2.2. SELECTION AND PRESENTATION OF THE SIMULATION TOOLS

A division exists within the building simulation community regarding the problem of daylight in energy simulations (Jakubiec et al., 2011). The “single model” group utilises only energy models to account for daylight, thermal and energy analysis. This is probably warranted in situations where electric lighting is not a large component of the total building loads such as in residential programmes. The “hybrid model” group predicts daylighting and thermal consequences in two separate models which share lighting and shading schedules (Torcellini et al., 2010). This method accounts for a more accurate representation of the reality. However, it also takes more time to run such a two-model simulation along with a concerted effort to organise and transfer data from one simulation environment to another. The method presented in this chapter proposes a more integrated approach to this problem.

In this chapter, the models presented are hybrids and composed of a thermal model using EnergyPlus software as well as a daylighting model using Daysim software that relies on the calculation methods of Radiance software. A comparison between the daylighting calculation methods of EnergyPlus and Daysim will be performed to clarify this choice.

ENERGYPLUS – ENERGY AND HEAT

EnergyPlus is a whole building energy performance simulation tool developed by the US Department of Energy (Crawley et al., 2000; Crawley et al., 2001). This next generation tool is under constant development and offers advanced simulation capabilities. It is primarily a simulation engine – there is no formal user interface. The EnergyPlus simulation results are generated in different formats, mainly HTML and CSV files.

The software is a free, open-source tool that allows third-party graphical user interfaces (GUIs). For example, the Legacy OpenStudio Plug-in for SketchUp makes it straightforward to create and edit the building geometry in the EnergyPlus input files (Ellis et al., 2008). SketchUp is a popular tool among architects and designers and it offers an easy-to-use interface that can make building energy simulation more accessible for both architects and designers during the design process.

DAYSIM – DAYLIGHTING

DAYSIM is a free, standalone, daylight calculation software that combines the backward ray tracing software, known as Radiance developed at the Lawrence Berkeley National Laboratory (Ward, 1994), with the Daylight Coefficient (DC) method for rapid calculation of the diffuse and direct components of daylight in a space over every daylight hour over a year.

In calculating the diffuse component, the daylight coefficient approach allows for the use of non-uniform, more realistic skies that vary hour by hour. The DC method divides the sky into 145 individual patches, and pre-calculates the percentage of contribution each patch of sky has on a reference point inside a space. Then, for each hour, the sky luminance value of each individual patch is multiplied by the solid angle constant and the DC; the summation of the illuminance contribution of each sky patch provides the equivalent of the sky component, the external reflected component, and the internal reflected component (Laouadi et al., 2007).

Daysim uses the Perez All Weather Sky Model to account for the ever-changing sky conditions that are expected to occur in the real world. Daysim can accurately simulate complex geometry and complex fenestration systems, and can accurately calculate the daylight level in any location of the room. The direct component is calculated from actual sun positions.

ENERGYPLUS OR DAYSIM: A COMPARISON FOR DAYLIGHT SIMULATIONS

Both EnergyPlus and Daysim allow us to calculate the annual hourly illuminance data as well as the visual comfort indicators. However, the calculation methods used are completely different.

EnergyPlus utilises the split flux method based on a representation of complex geometries in plans when predicting interior daylight levels. This kind of calculation works best in rooms where the ratio of width to depth to height is 1:1:1 which almost never occurs in reality, and thus such calculations often result in substantial inaccuracies (Jakubiec et al., 2011). Daysim, on the other hand, employs a reverse ray tracing algorithm based on the physical behaviour of light in a volumetric, three-dimensional model which should represent the reality in a most accurate way (Ward, 1994). Daysim uses a daylight coefficient method to generate an annual illuminance profile at each point of interest.

The contribution for each daylight coefficient is then determined by using the Perez All Weather Sky distribution based on values from the TMY data. Furthermore, Daysim considers direct sunlight entering a space whereas EnergyPlus does not.

The above discussion establishes a significant reason to use Daysim for the generation of the distribution of natural light in a space when compared to EnergyPlus and other split-flux methods.

GOOGLE SKETCHUP – GRAPHICAL USER INTERFACE

Google SketchUp has been used to draw the geometry of both thermal and daylighting models. The OpenStudio plugin of SketchUp makes it straightforward to create the geometry of the EnergyPlus model. The geometry is then exported as a 3ds file that can be imported into Daysim.



Figure 4-5. Use of Google SketchUp as a graphical user interface to create the geometry of both thermal and daylight models.

GENOPT

GenOpt, developed by Michael Wetter, was first introduced in 2000 (Wetter, 2000; Wetter, 2001). GenOpt is an optimisation software programme, to help find the independent variables that produce the best performance of complex systems involving several independent variables, where the cost

function is computationally expensive, and its derivatives are not available. GenOpt can be coupled to any simulation programme that reads and writes INPUT/OUTPUT to text files. It is divided into a kernel part that reads the INPUT files, calls up the simulation programme, and stores the results; as well as an optimisation part that contains the optimisation algorithms.

To perform the optimisation, GenOpt automatically generates input files for the simulation programme. These files are based on input templates for the particular simulation programme. GenOpt then launches the simulation programme, reads the function value being minimised from the simulation result file, checks possible simulation errors and then determines a new set of input parameters for the next run. The whole process is repeated iteratively until a minimum value of the function is found.

The literature on this subject provides many examples of GenOpt being used with the simulation tools EnergyPlus or TRNSYS. This coupling to EnergyPlus as well as Daysim, undertaken in this study, was never before realised. Furthermore, GenOpt is normally used for the purpose of minimising the energy use of a building, whereas optimisation on the passive performances of the building has been rarely explored.

4.2.3. SIMULATION WORKFLOW

Figure 4-6 shows the principle of coupling GenOpt with the thermal and daylighting simulation tools. The inputs of both models are created by GenOpt by varying the parameters selected depending on the previous outputs recovered from EnergyPlus and Daysim. Once the input files have been created by GenOpt, it automatically launches both simulations and waits until the end of the simulations to recover the results and launch a new pair of simulations.

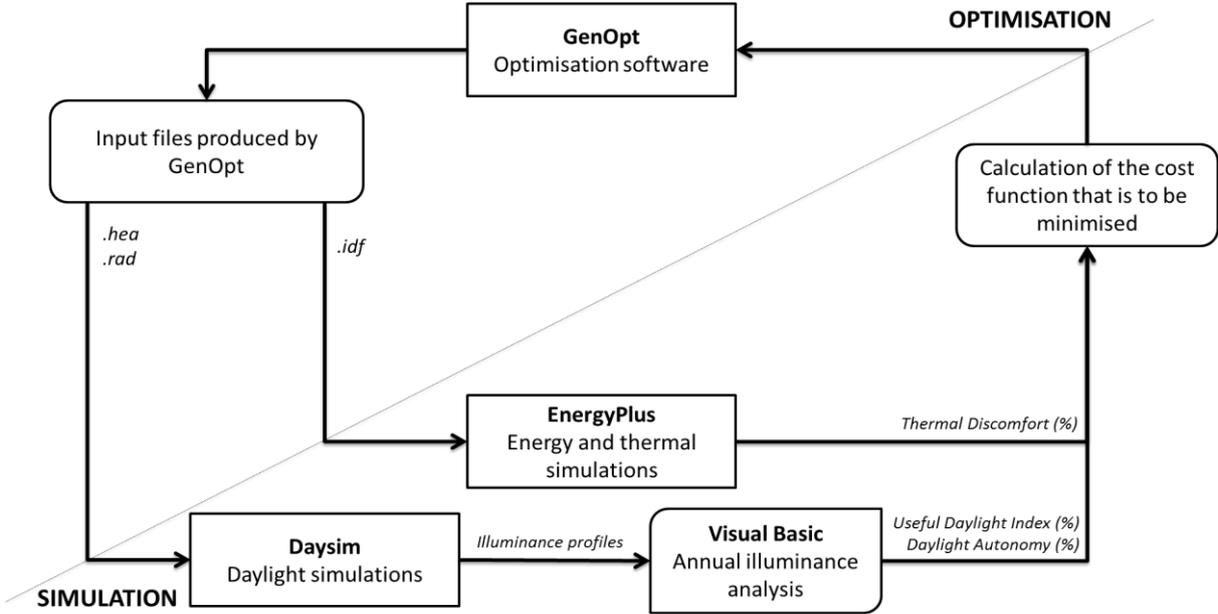


Figure 4-6. The coupling principle of the simulation tools Daysim and EnergyPlus with GenOpt.

4.3. CRITERIA AND OUTPUTS TO ASSESS THERMAL COMFORT AND DAYLIGHTING

4.3.1. PERCENTAGE OF THERMAL COMFORT

In this study, thermal comfort is evaluated according to the NMV zone on the psychometric chart that was defined in the previous chapter (figure 3-21). It is based on the assumption that the occupants have adaptive opportunities and play an active role in ensuring their own comfort, using window openings and ceiling fans wisely, taking advantage of a range of options to dress appropriately. The number of uncomfortable hours (between 8 a.m. and 5 p.m.) that is outside the NMV zone is counted to calculate the percentage of comfort for each simulation. Table 4-2 provides the conversion of the percentage of thermal discomfort into a number of hours, days or weeks of discomfort.

Table 4-2. Conversions of the percentage of comfort into a number of hours, days and weeks of discomfort.

Percentage of comfort	20%	40%	60%	80%	85%	90%	95%	100%
Hours of discomfort	1829 h	1372 h	914 h	457 h	343 h	229 h	114 h	0 h
Days of discomfort (9 hours / day)	203.2 d	152.4 d	101.6 d	50.8 d	38.1 d	25.4 d	12.7 d	0 d
Weeks of discomfort (5 days / week)	40.6 w	30.5 w	20.3 w	10.2 w	7.6 w	5.1 w	2.5 w	0 w

4.3.2. DAYLIGHTING INDICES

In the daylighting simulations, the mapping is defined by modelling the illuminance on a desk plan (0.8 m high) every 0.5 or 1 metre. Only the working hours are considered (8 a.m.-5 p.m.).

With regard to the offices of the study, a hybrid indicator is used that takes into account the daylight comfort zones defined in paragraph 2.4.2. The daylight comfort zone is located close to the window leaving a gap of 0.5 m to reduce the risks of glare and sunspots. In this area, represented by the green dots in figure 4-7, the illuminance values have to be between 300 Lux and 8,000 Lux. The Useful Daylight Index UDI (300-8000) is calculated on those spots. As for the area located close to walls, the need for lighting is lower as the space should be mainly used for storage and as passage. The illuminance in this area needs to be greater than 100 Lux and the indicator in this case is the Daylight Autonomy with a lower limit of 100 Lux (purple dots). Depending on the spot considered, the indicators are calculated over the year and then averaged for the whole office. The final indicator that will be used in this study is named UDI_{office} .

This indicator does not claim to solve all problems linked to visual comfort such as the glare. It reduces the risk of sunspots on the desk plan that often leads to the use of curtains or blinds cutting off natural ventilation and daylighting and causing the need for active systems (air conditioning, ceiling fans or artificial lighting) to address the comfort issues.

In the case of the classroom, the mapping is defined in figure 4-7. Two parallel strips close to the windows are taken to be unoccupied because the risk of sunspots and glare is high. The illuminance is simulated every metre and the average useful daylight index (UDI 300-8000) is calculated.

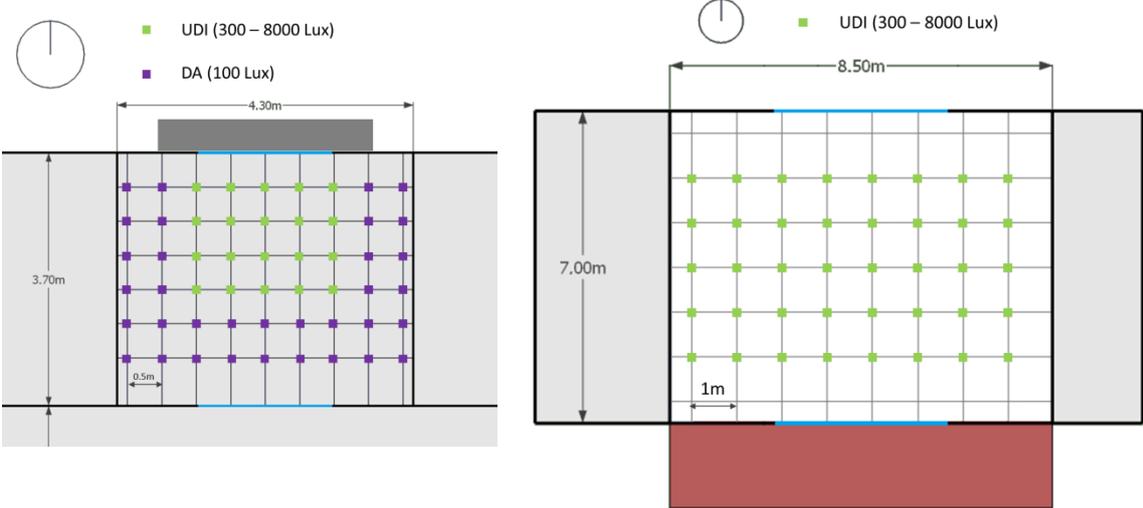


Figure 4-7. Left: Daylight mapping of an office and definition of the useful daylight index for an office (UDI_{office}) that takes into account the daylight comfort zone. Right: Mapping of a classroom.

4.3.3. DEFINITION OF THE COST FUNCTION

One of the main difficulties of this task is the definition of the cost function. The aim is to take both thermal and visual comfort in the optimisation process into consideration. In terms of human behaviour and preferences, it is very complicated to assess whether users prefer thermal or visual comfort. However, what must be kept in mind in the process of optimisation is that the energy challenges are very different when seeking to alleviate the problems associated with thermal or visual discomfort. The energy consumption associated with the possible solutions to comfort issues is presented in table 4-3.

Table 4-3. Energy consumption associated with the possible solutions to comfort issues.

Type of discomfort	Thermal discomfort	Thermal discomfort	Visual discomfort (lack of light)	Visual discomfort (sunspots or glare)
Possible solution	Air conditioning	Ceiling fans	Artificial lighting	Curtains
Energy ratio	100 kWh/m ² .y	2 kWh/m ² .y	12 kWh/m ² .y	/
Installed load	80 W/m ²	7 W/m ²	4-15 W/m ²	/
Comments		Possible solution if the air temperature and humidity are in the comfort zone NMV		Cuts off natural ventilation and daylighting

4.4. APPLICATION OF THE METHODOLOGY TO AN OFFICE AND A CLASSROOM

4.4.1. DESCRIPTION OF THE SIMULATED BUILDING

WEATHER DATA

The weather file used to run the simulations was produced with the measured data of the weather station located on the university campus of Saint-Pierre, approximately 100 metres away from the ENERPOS building. The weather station complies with the technical specifications of World Meteorological Organization (WMO).

The period of measurements used was from November 2010 to October 2011. The climate of Saint-Pierre is oceanic which means that the monthly average air temperature follows that of the ocean. Climate variability is relatively low in the tropics and especially when the climate is oceanic. Therefore, the choice of one year of measurements rather than an average of several years does not have a high impact on the weather data obtained.

OFFICE AND CLASSROOM GEOMETRY

The optimisation methodology is experimented on a test cell including an office and a classroom using the example of the ENERPOS building. The investigated building is composed of two typical cellular offices, which can be occupied by one or two persons and that are separated by a corridor. The outside window orientation is north-facing. The offices are naturally cross ventilated with interior openings between the corridor and the two offices. On the first floor, a naturally ventilated classroom with two openings on two opposite façades is north-south orientated. The offices and the classroom are assumed to be surrounded by rooms with a similar temperature on the east and west walls.

The height of the window sill is usually 1.1 m but to improve natural ventilation of the seated users of an office or a classroom, it is useful to lower the height of the window sill to 0.8 m. This choice was made for the test cell.

Table 4-4. Office and classroom dimensions.

	Office	Classroom
Width (façade)	4.3 m	8.5 m
Room depth	3.7 m	7.0 m
Room height	2.7 m	2.7 m
Height of the window sill	0.8 m	0.8 m
Height of the window	1.8 m	1.4 m

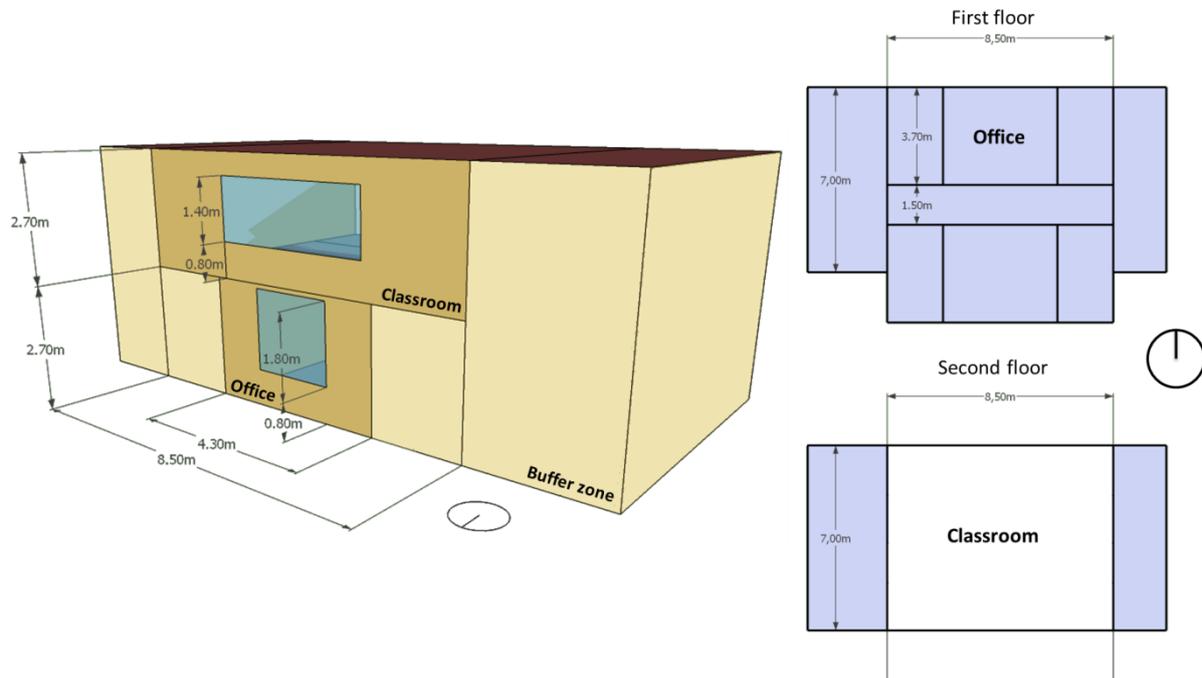


Figure 4-8. Perspective and cross section of the investigated rooms.

CONSTRUCTION MATERIALS AND THERMAL MASS

The building envelope is composed of 18 cm of concrete for the exterior walls and plasterboard for the interior walls. The exterior roof incorporates the following layers: 1.5 mm of bitumen, a 10-cm layer of expanded polystyrene, 20 cm of concrete, an air space and acoustic tiles. The thermal resistance, the heat loss and the solar factor values of the envelope are given in table 4-5.

Table 4-5. R-values, U-values and S-values of the roof and the walls of the base case test cell.

	R-value (m ² .K)/W	U-value W/(m ² .K)	S-value	S-value required by PERENE
Insulated roof	2.86	0.33	0.015	0.02
Exterior wall	0.10	3.33	0.1	0.05

WINDOW AREA AND GLAZING

Windows are required to achieve natural cooling through ventilation which is of primary importance in a tropical climate. An optimised window design plays a vital role in the building envelope to maximise both thermal and visual comfort. The PERENE label for high-efficient buildings in Reunion Island gives a minimum value of 20% of WWR. Another aspect is occupant satisfaction with the window area of their room in terms of the quantity and quality of the view, privacy and daylight distribution. Field studies lead to the conclusion that occupants would accept a minimum window area of 20-30% (Galasiu et al., 2006). In the ENERPOS building, a porosity of 30% was chosen to enhance natural ventilation and daylight availability. A similar choice was made in the test cell.

The type of glazing used for the building simulations is a single clear glass. The U-value is assumed to be $0.9 \text{ W}/(\text{m}^2\cdot\text{K})$. The glazing is colour-neutral in order not to affect the view. The solar factor of the glazing is 0.8 when the window is closed and approximately 1 when the window is open for natural ventilation.

SHADING, DAYLIGHTING AND VIEW

For this investigation, all windows are considered not to be shaded by either opposite buildings or neighbouring ones. This might not be realistic for all inner city locations, but it results in higher solar heat gains and is therefore a safe assumption regarding the evaluation of thermal comfort.

For the baseline model, the building does not contain any solar shading for the windows. Shading is added in the process of optimising the building in order to determine the impact of shading devices on thermal and visual comfort. The investigated shading devices for the rooms are:

- an outside overhang that stands on top of the opening;
- an outside overhang with two side fins on each side of the window;
- horizontal slats with a constant gap of 0.3 m.

The parameters being modified in the optimisation process are related to the geometry of the overhang, the side fins or the horizontal slats as the case may be. The parameters defined in the PERENE label are used to describe the dimensions of the solar shading studied. For an overhang, the d/h ratio represents the ratio of the length of the overhang (d) and the height of the opening (h), as illustrated in figure 4-9. As for horizontal slats, the angle of incidence (θ), described in figure 4-9, depends on the length of the slats and the height between two following slats.

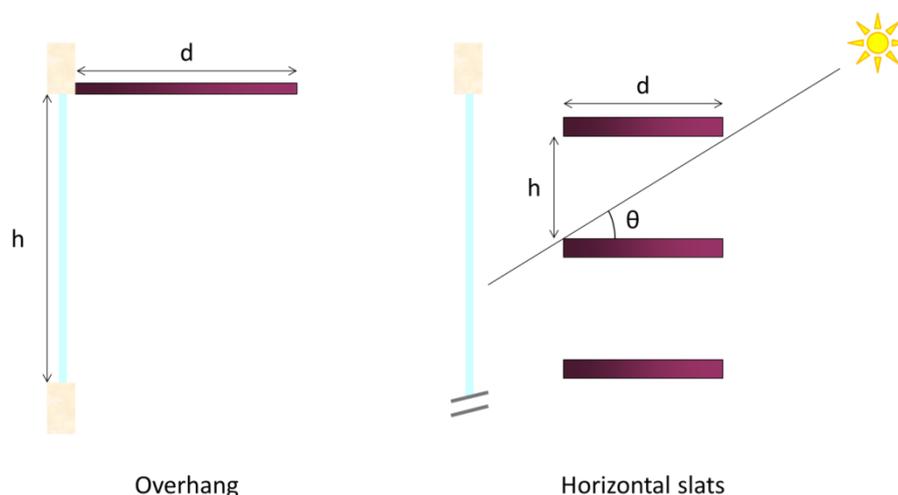


Figure 4-9. Definition of the ratio d/h for an overhang and of the angle of incidence θ for horizontal slats.

VENTILATION AND AIR EXCHANGE RATES

Usually for thermal comfort simulations air exchange rates are considered constant during occupancy as well as at night or during weekends. When the building is not naturally ventilated, the air infiltration rate is supposed to be one air change per hour (ACH). With natural cross ventilation, air exchange rates are typically higher, in the range of 50 ACH. This value will be used when simulating natural ventilation of the office or the classroom.

Another important aspect of natural ventilation by manually operated windows is the window opening behaviour of the occupants. The first goal of this investigation is to optimise the building envelope assuming that the occupants are using the building properly. Consequently, it will be assumed that the air exchange rates are constant throughout the year using the values indicated in two paragraphs below.

OCCUPANT DENSITY AND PROFILES

Usually the occupant density in an office is based on hierarchies and/or task. Often employees in a higher hierarchical position have single rooms and more square metres per person than those in lower hierarchical positions. Additionally, some specific tasks might require single occupancy in order to provide privacy or not to disturb colleagues. The number of persons working in a room is linked to the related office equipment and influences internal heat load in offices.

In this study, as a first step and in order to optimise the building envelope as such, the building will be considered to be free of occupants, electric equipment, lightings and ceiling fans. In the second phase, the internal loads will be added to the simulation in such way as to calculate the percentage of thermal comfort as well as the annual electric consumption. The floor area used in the simulation is 8.5 m²/person in the office and 2.4 m²/person in the classroom. For the thermal comfort simulations, the occupancy profile used is that of a typical office building. This is shown in figure 4-10.

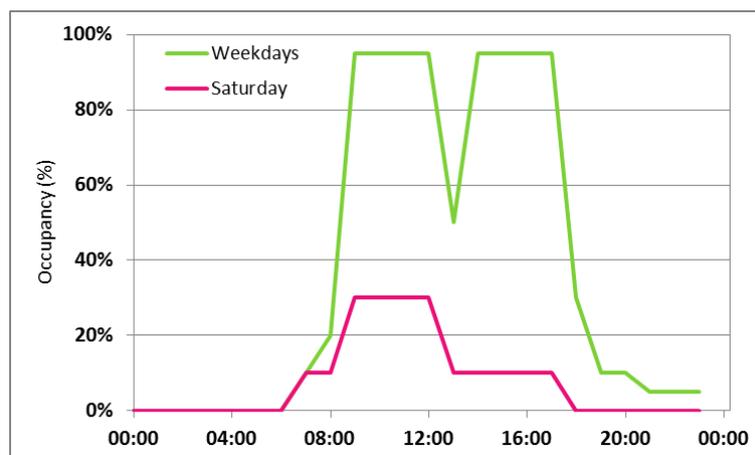


Figure 4-10. Occupancy profile of an office.

OFFICE EQUIPMENT, CEILING FANS, ARTIFICIAL LIGHTING AND CONTROLS

With regard to the installed power, it is always a question of the combination of lighting features such as lamps and ballasts, and therefore a broad variety of possibilities exists, each resulting in a different type of energy consumption.

With the Daysim software, it is possible to define active or passive users for lighting controls. Active users are assumed to switch the light on or off or to dim it according to the daylight illuminance, and passive users are assumed neither to switch off nor to dim the light if there is adequate daylight. The latter may result in lighting being switched on for the entire day. Daysim also provides the option of choosing a combination of the passive and active user. This scenario will be taken as a hypothesis.

The use of equipment in offices is strongly dependent on the performed task, therefore not only one configuration is applicable to all office environments. In this study, the installed load of electric equipment in the office was assumed to be 8.5 W/m². No electric equipment is taken into account in the classroom. Copiers and servers, although highly energy-consuming, have not been considered in these configurations. Due to their negative effect on indoor air quality, it is not recommended to place them in the office.

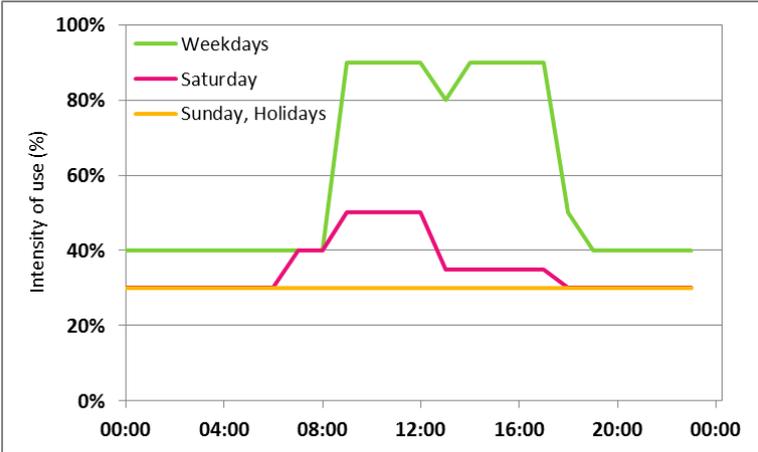


Figure 4-11. Intensity of use of electrical office equipment.

The office is equipped with one ceiling fan whose load is 70 W. The classroom is equipped with six ceiling fans; the overall installed load is 420 W. A simplified fan schedule assumes that the fans are only used from November to April, from 8 a.m. until 5 p.m. at 70% of their maximum load.

4.4.2. SIMULATION RESULTS FOR AN OFFICE

NORTH-FACING OFFICE

For the north-facing office, the solar shading studied is an overhang that stands on top of the opening. Three parameters vary and are described in figure 4-12 and in table 4-6.

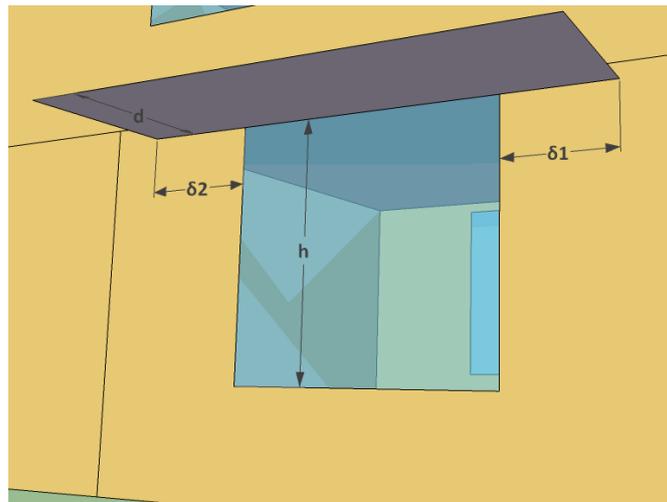


Figure 4-12. Definition of the parameters of the overhang (d , δ_1 , δ_2 and h).

Table 4-6. Variation of the geometrical parameters of the overhang.

	Minimum value (m)	Maximum value (m)
d	0.01	3
δ_1	0	3.2825
δ_2	0	3.2825

The impact of the geometry of the solar shading on thermal and visual comfort is estimated by plotting several outputs obtained using the thermal and daylighting simulations. Figure 4-13 shows the percentage of thermal comfort (NMV), the daylight autonomy with a lower limit of 300 Lux (DA300), the useful daylight index defined for an office in paragraph 4.3.2 (UDI_{office}) and the useful daylight index with 300 Lux as a lower limit and 8,000 Lux as upper limit ($UDI_{300-8000}$).

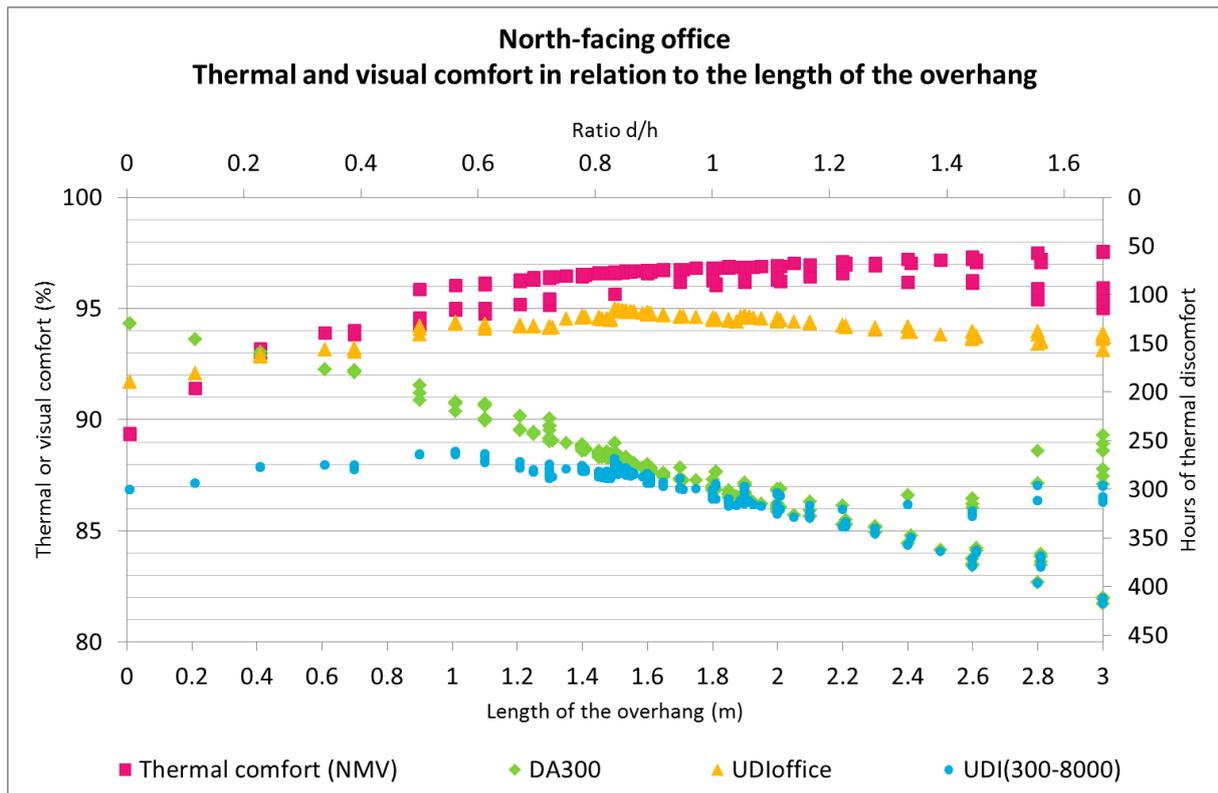


Figure 4-13. Thermal and visual comfort variations in relation to the length of the overhang.

Logically, the percentage of thermal comfort increases with the length of the shade. This can rise by 8% which represents approximately 190 hours of thermal discomfort and reaches a plateau when the ratio d/h is greater than 1. The slight fluctuations of thermal comfort for a similar length of the overhang correspond to the variation of δ_1 and δ_2 .

With regard to daylighting, the variations are less noticeable than for thermal comfort. By looking at the daylight autonomy (DA300), it is to be noted that the percentage decreases when the length of the overhang increases from 93% to 81%. When the ratio d/h is approximately 1.6, the calculation of the daylight autonomy can produce several results, due to the variations of δ_1 and δ_2 . The variations of the useful daylight index (UDI 300-8000) are different from the daylight autonomy. However, when the ratio d/h is less than 1, the UDI increases slightly. Indeed, the occupants of the office are protected from direct sunlight by the solar shading when the ratio d/h increases from 0 to 1. This reduces the number of hours when the illuminance is greater than 8,000 Lux. Afterwards, when the solar shading has a ratio d/h greater than 1, the UDI starts decreasing which signifies that the number of hours when the illuminance is below 300 Lux rises. The UDI curve follows the trend of that of the DA when the ratio d/h is greater than 1.5, meaning that from this value, there will be almost no values of illuminance greater than 8,000 Lux in the office and therefore that the risks of sunspots in the office is low.

The UDI_{office} indicator is less restrictive than the two other daylighting indices. In the case of a north-facing office, the UDI_{office} increases with the length of the overhang by approximately 5% and reaches a plateau when the ratio d/h is greater than 1.

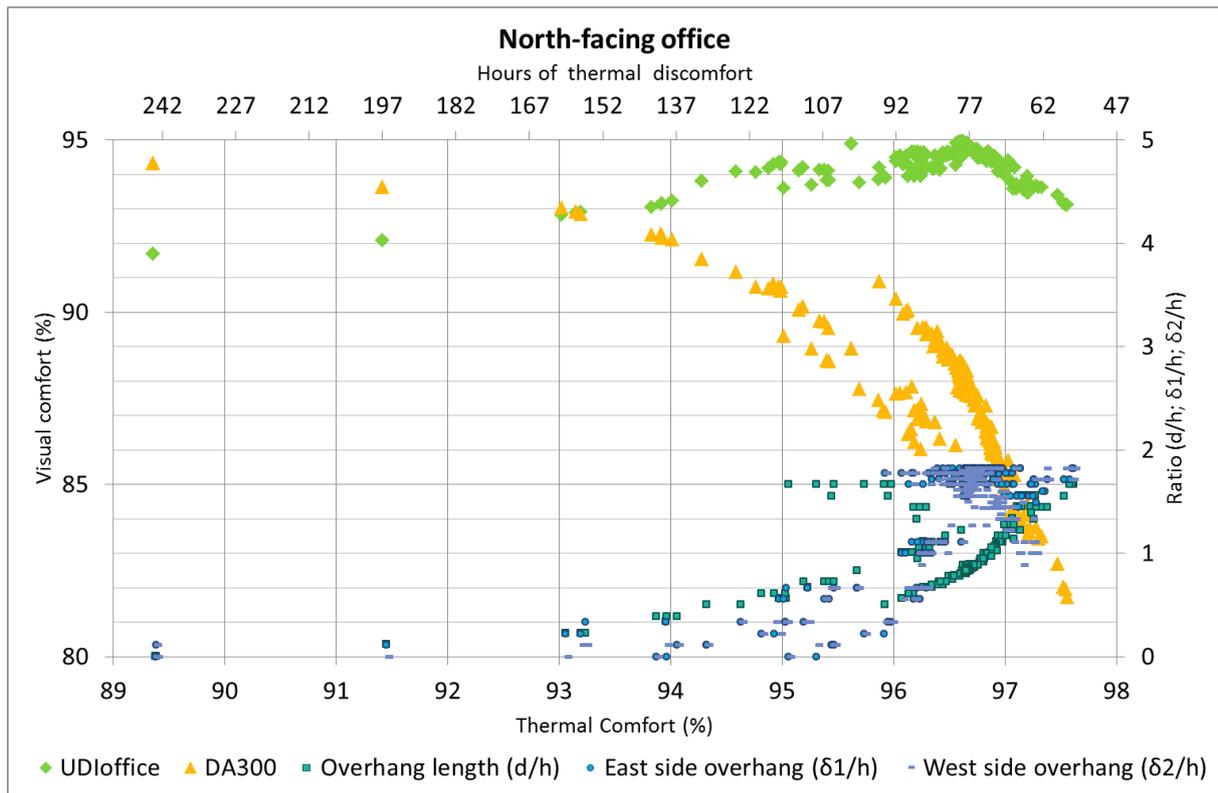


Figure 4-14. Variations in the visual comfort with regard to the thermal comfort when the geometry of the overhang varies.

Figure 4-14 presents the variation of the visual comfort (UDI_{office} and DA300) with regard to the percentage of thermal comfort. As one would have expected, the thermal comfort increases when the daylight autonomy decreases and vice versa, but as noted earlier, the variations of thermal comfort are greater than that of the daylight autonomy. Finding the optimum geometry for the overhang is not straightforward. Even though there is almost a common maximum for the UDI_{office} and the percentage of thermal comfort, it can be noted however, that the daylight autonomy decreases notably when the percentage of thermal comfort is greater than 95%. If one thinks in terms of human preferences, the solution is not necessarily simple, however it might lean towards thermal rather than visual comfort as the heat is more difficult to tackle using passive means.

In order to study more in-depth the thermal and visual comfort for a particular geometry of the overhang, the thermal and daylight simulations are launched again. An arbitrary choice is made for a percentage of thermal comfort of approximately 96% and a daylight autonomy of 91%. The parameters corresponding to this case are given in table 4-7.

Table 4-7. Chosen parameters for an overhang on a north-facing window.

d/h	d	δ_1/h (East)	δ_1	δ_2/h (West)	δ_2
0.5	0.9 m	1.78	3.2	1.78	3.2

The internal loads (people, lights and office equipment) and the natural ventilation (modelled by a mechanical ventilation of 50 vol/h) are added to the thermal simulation. The operative temperature and the relative humidity of the office are plotted on the psychrometric chart in figure 4-15. With the internal loads and the natural ventilation, the percentage of thermal comfort is approximately 99% which corresponds to 49 hours of discomfort per year (approximately 5.4 week days).

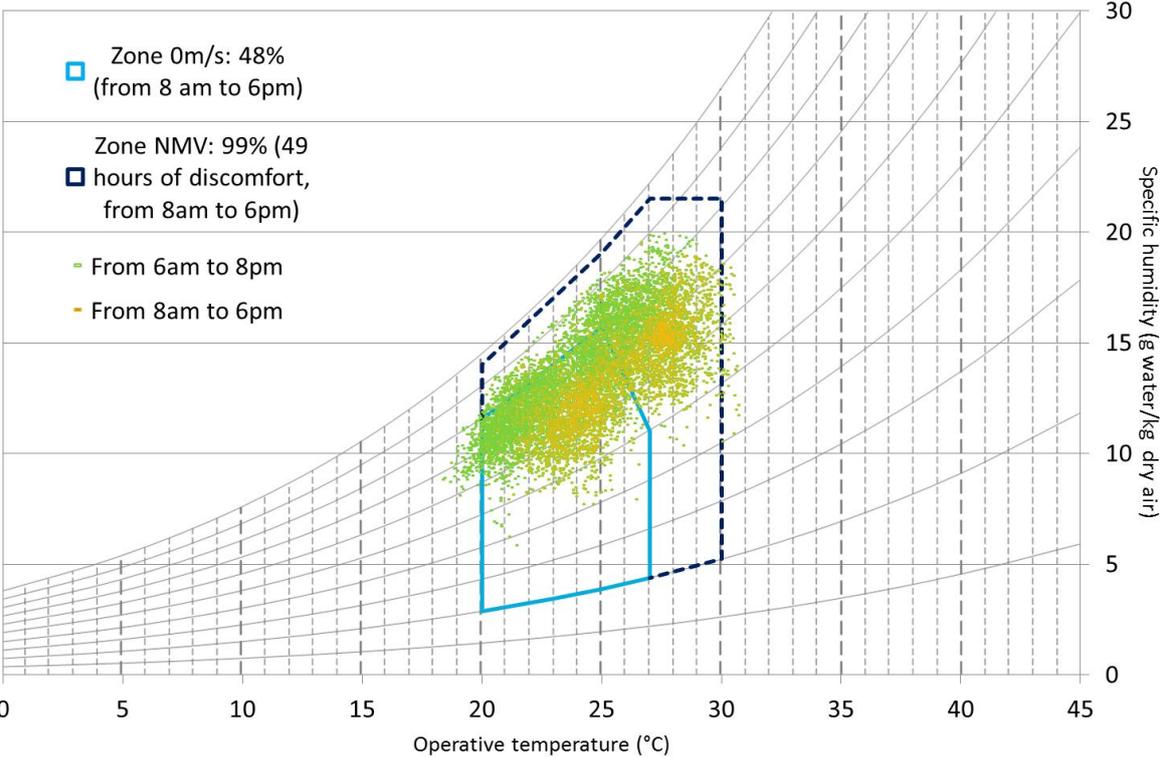


Figure 4-15. Psychrometric chart illustrating the simulation results of a north orientated office with an overhang as described in table 4-7.

The daylight model is also launched again with the parameters chosen in table 4-7. The useful daylight index for the office (UDI_{office}) is 94.2% and the daylight autonomy (300 Lux) is 90.9%.

The illuminance map of the office is demonstrated in figure 4-16. On average, the illuminance remains greater than 500 Lux over the whole surface of the office which is a very interesting result as it means that artificial lighting is only rarely needed. On the area of the work plane, the illuminance values are high, on average from 3,000 Lux to 7,000 Lux. An examination of the illuminance values during winter and summer (figure 4-17) makes it possible to assess that the highest values will appear during winter (as the sun is mainly in the south during summer). This is a satisfying observation because even if the users are tempted to close their potential internal blinds or curtains to remedy visual discomfort; in winter, the natural ventilation is often not required to ensure the thermal comfort of the occupants.

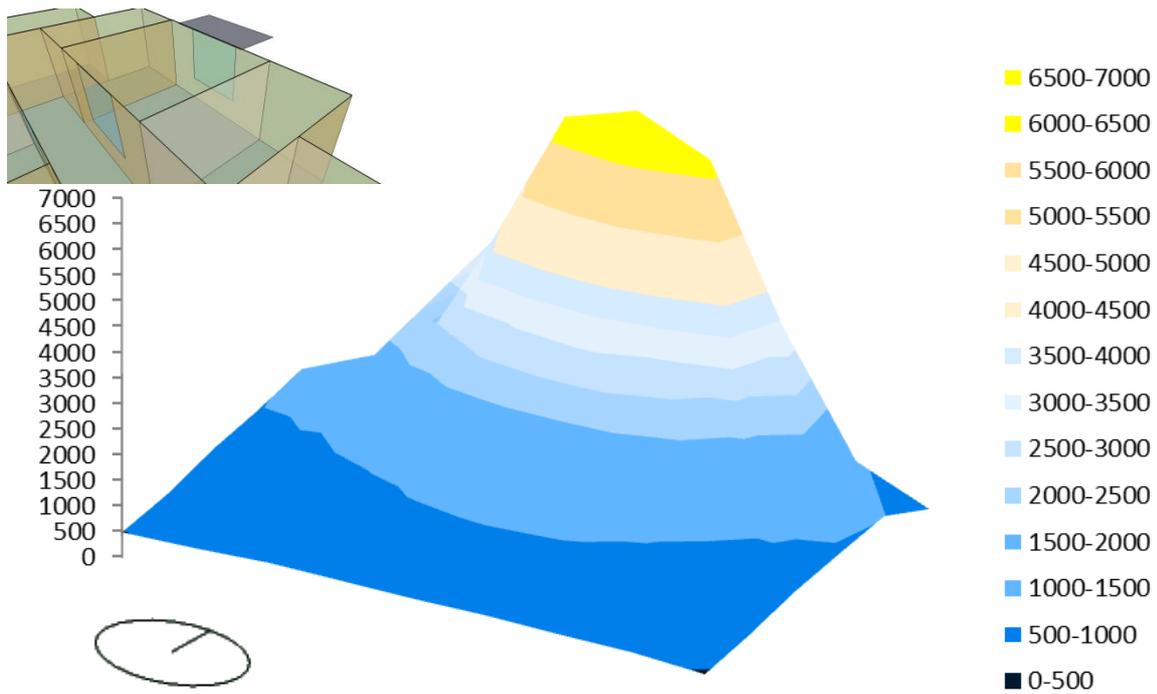


Figure 4-16. Annual average illuminance map of the north-facing office.

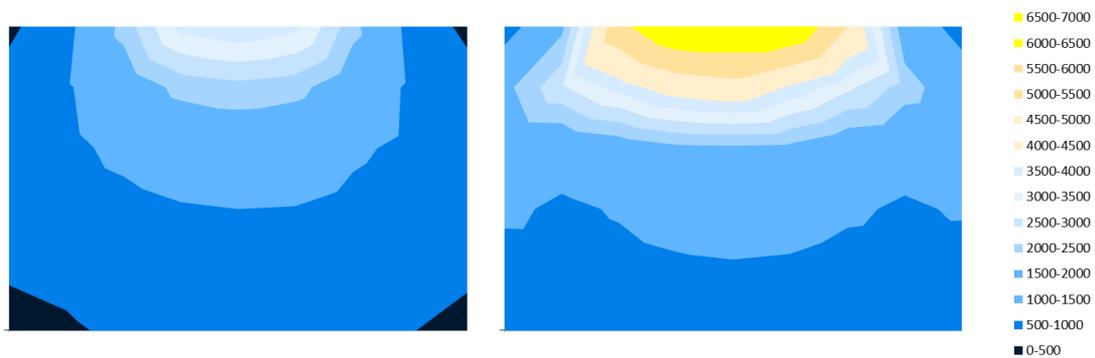


Figure 4-17. Average illumination map during summer (left) and winter (right).

Daysim can also evaluate the energy use for artificial lighting with the results of the illuminance map. It assumes that the users are a combination of active (users who operate the electric lighting in relation to ambient daylight conditions) and passive users (users who keep the electric lighting on throughout the working day). For an installed load of 4.7 W/m² in the office, the energy index is expected to be 1.18 kWh/m².y.

SOUTH-FACING OFFICE

For the south-facing window, the solar shading studied is composed of an overhang with two side fins. Three parameters vary from 0.01 m to 3 m (figure 4-18):

- the length of the overhang d_1 ;
- the side fin on the left-hand side (West) d_2 ;
- the side fin on the right-hand side (East) d_3 .

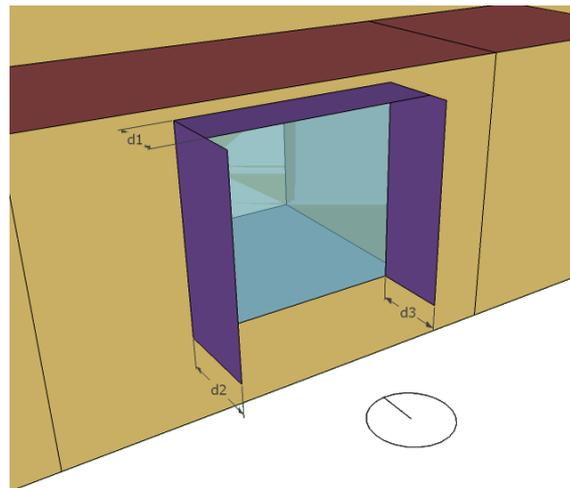


Figure 4-18. Overhang and side fins for the south-facing window.

The percentage of thermal comfort varies from 87% (292 hours of discomfort), when the length of overhang and the side fins are close to zero, to 96% (93 hours of discomfort) when the length of the overhang is the largest. The variations are not very significant because the south-facing window only receives direct solar radiations for three months in the year. However, those three months (November, December and January) are amongst the hottest of the year, and thus, it is essential to shade south openings.

Figure 4-20 illustrates the changes in visual comfort in relation to thermal comfort when the geometric parameters of the shading vary. First, the increase in the percentage of thermal comfort from 87% to 90% does not have a significant impact on the daylight autonomy and the useful daylight index of the office. However, the increase in the percentage of thermal comfort from 90% to 96% induces a drop in both visual comfort indices (by approximately 25% for the useful daylight index and by 60% for the daylight autonomy). Any intentions to bring about a significant decrease in the number of hours of thermal discomfort of the office will adversely affect the availability of daylight in the office for the whole year.

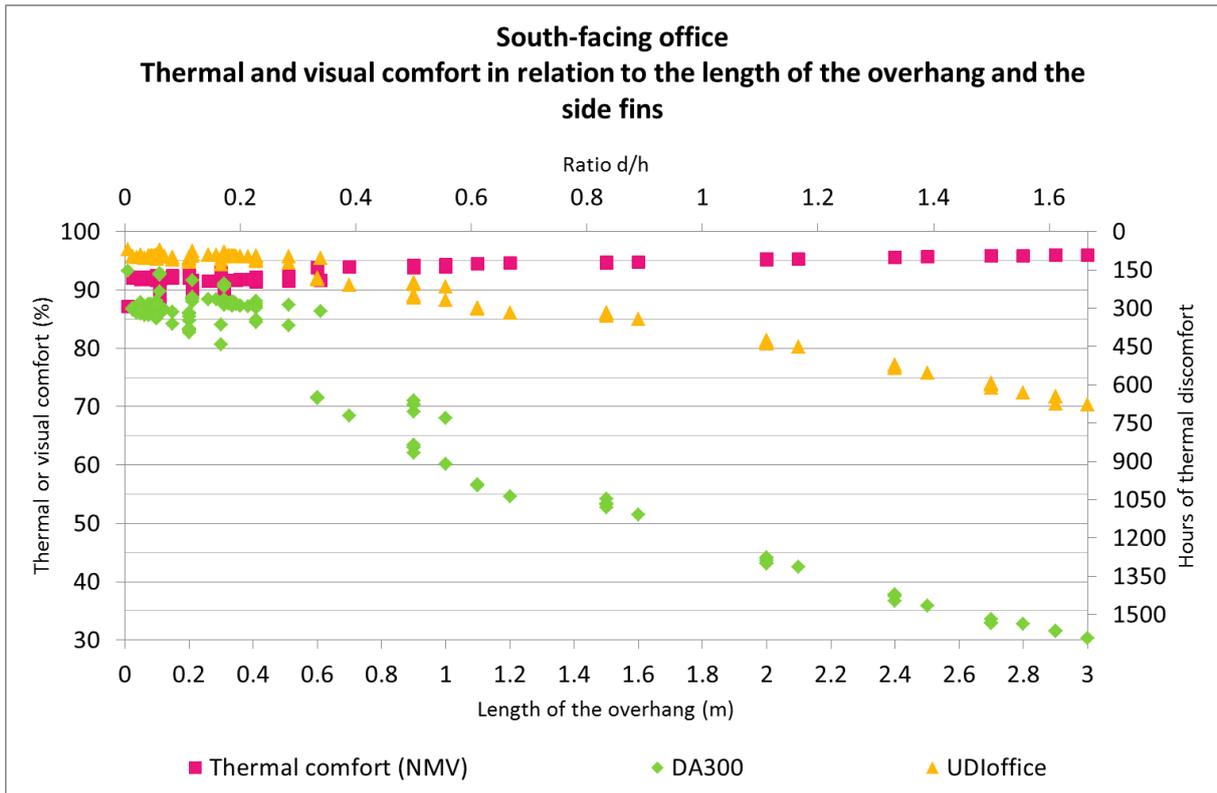


Figure 4-19. Thermal and visual comfort variations in relation to the length of the overhang.

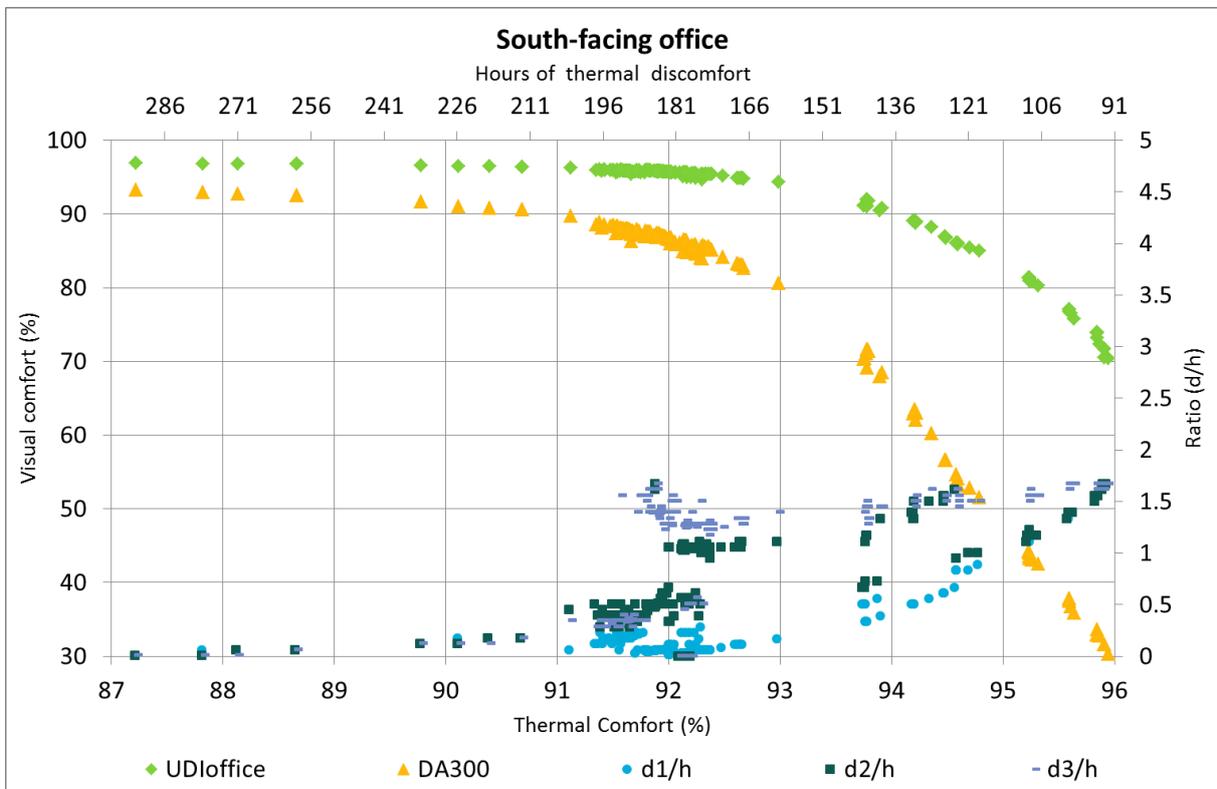


Figure 4-20. Variations of the visual comfort with regard to the thermal comfort when the geometry of the overhang and side fins varies.

EAST ORIENTATION

In the case of an east-facing window, an overhang does not constitute a suitable form of shading because in the morning the sun is almost horizontal and direct radiation will enter the office causing high risks of glare and sunspots. The solar shading studied is in the form of horizontal slats in front of the window as shown in figure 4-21. The impact of the number of horizontal slats is studied by comparing the thermal and visual comfort with 4 or 6 slats in front of the office.

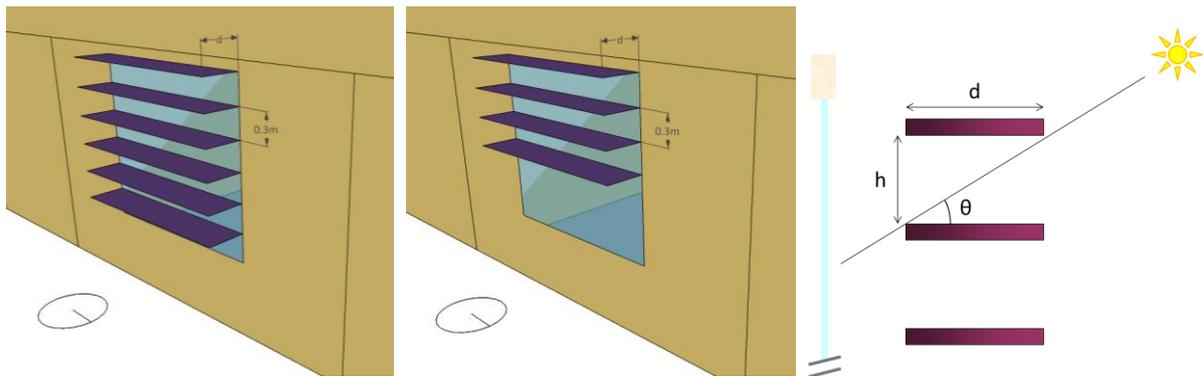


Figure 4-21. East-facing window - comparison between 4 and 6 horizontal slats and definition of the angle of incidence θ .

The angle of incidence θ varies from 15° to 88° which corresponds to a variation of the length of the slats (d) of 0.01m to 1m. Figure 4-22 shows the changes of thermal and visual comfort when the angle θ varies. It is noticeable that the percentage of thermal comfort decreases when the angle of incidence increases which means that the slats are smaller and the shading is not as efficient. Variations of the percentage of thermal comfort range from 60% (914 hours of discomfort) to 80% for 4 slats (457 hours) or 85% for 6 slats (343 hours).

With regard to visual comfort, the daylight autonomy (DA300) varies considerably in the case of 6 slats. It ranges from 35% to almost 95%. In the case of 4 slats, the variations are less significant as the minimum is 60%. It is very interesting to observe the variations of the useful daylight index for the office in both cases. Indeed, in the case of 4 slats, UDI_{office} remains nearly constant with the angle of incidence. By contrast, UDI_{office} in the case of 6 slats has a variation of 20% depending on the angle of incidence.

Since the percentage of thermal comfort does not change significantly when comparing the two types of shading (the difference is less than 5% corresponding to approximately a hundred hours of thermal discomfort), choosing a type of solar shading composed of 4 horizontal slats could be particularly beneficial for visual comfort and daylighting without having a substantial impact on thermal comfort. Moreover, 4 slats in front of the window instead of 6 increase the occupants' view towards the outside. Even if there is no widely accepted scientific agreement as to what the benefits of having a work place with a view are, it is conceivable that a view overcomes the feeling of loneliness of building occupants.

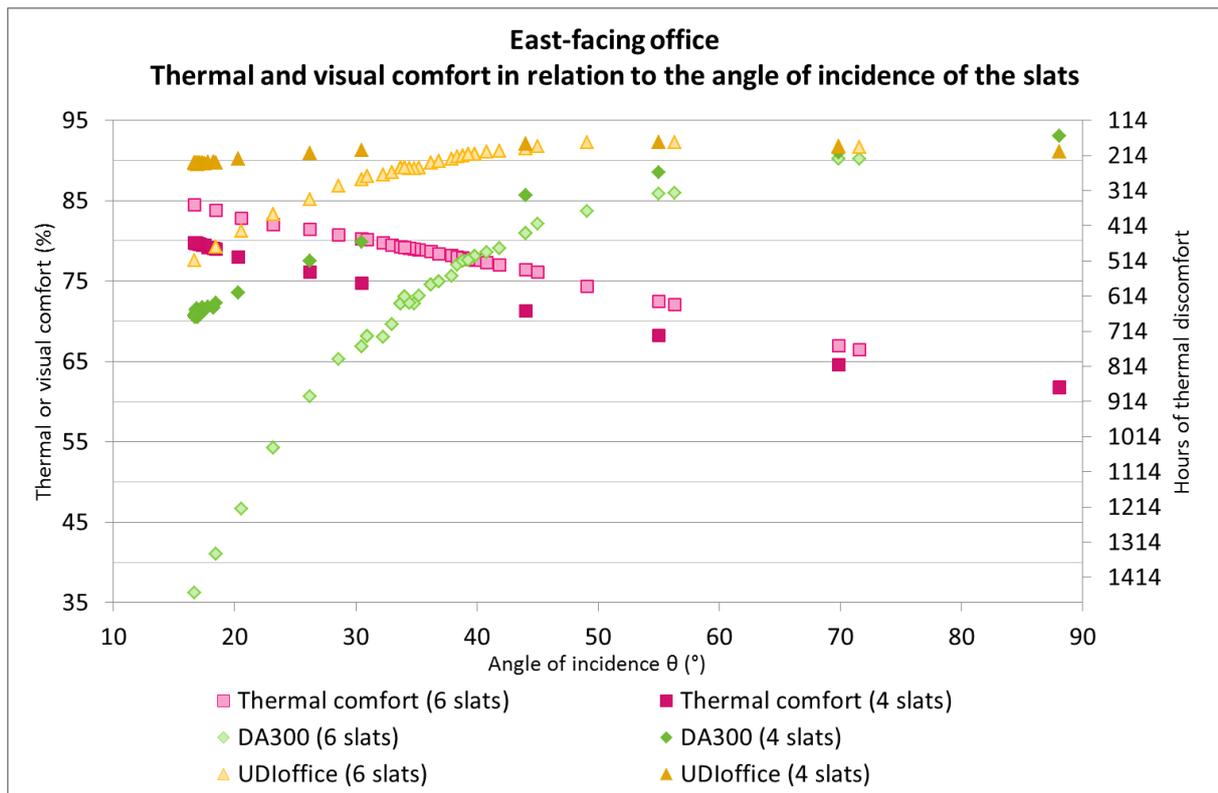


Figure 4-22. Thermal (percentage of hours) and visual (UDI_{office} and DA300) comfort function of the angle of incidence (θ) of the slats for the east-orientated office.

The solar diagram of Reunion Island (given in Appendix B -) indicates that the angle of incidence of the sun is 30° in March. To be effective during the summer season, the angle of incidence of the horizontal slats must be below this value.

Considering an angle of incidence of 30°, figure 4-22 indicates the percentage of thermal comfort for both cases. With 6 slats, this percentage is approximately 80% (457 hours of discomfort) whereas it is 75% with 4 slats (572 hours). The difference in terms of daylight autonomy is more significant as the daylight autonomy is approximately 66% for 6 slats and 80% for 4 slats. The loss of thermal comfort is 5% (114 hours) when the two slats at the bottom are removed, while the gain in daylight autonomy is close to 15%. This difference is less visible on the useful daylight index for the office as this indicator is less restrictive on the lower limit of illuminance. A gain of a few per cent of the useful daylight index UDI_{office} is still noticeable when the angle of incidence is 30°.

Several indicators assessing visual comfort are plotted in relation to the percentage of thermal comfort in figure 4-24 for the two case studies.

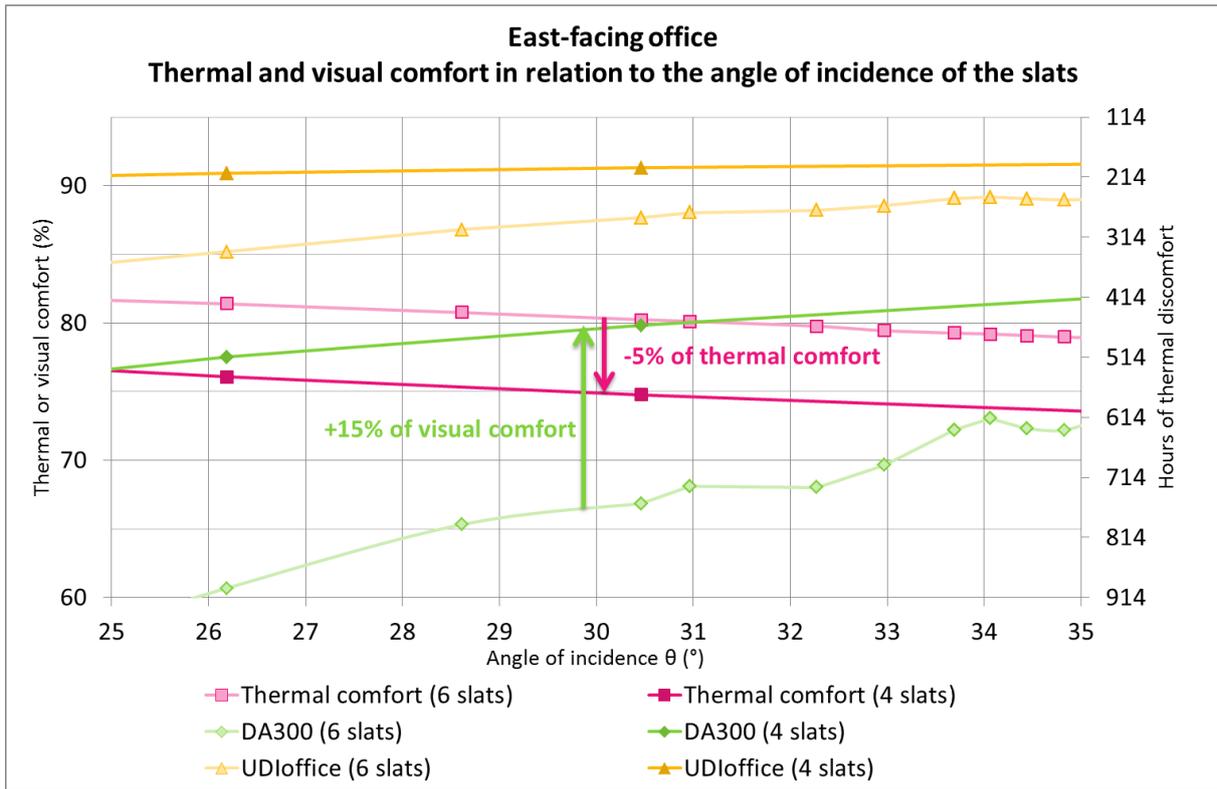


Figure 4-23. Gain and loss in terms of thermal and visual comfort when the two lower slats are removed.

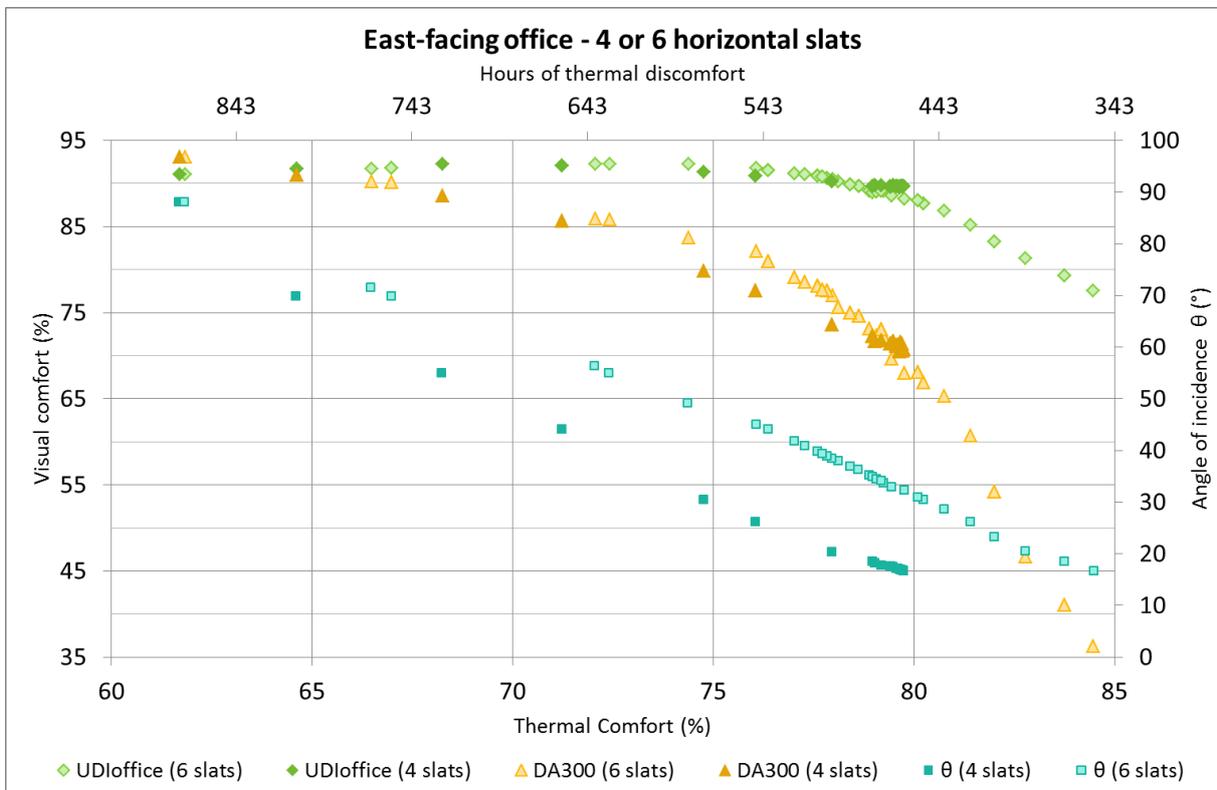


Figure 4-24. Visual comfort in relation to thermal comfort for the two case studies of an east-facing office.

WEST ORIENTATION

The study of the west-facing window is similar to that of the east-facing one except that the discomfort issues are more likely to appear in the afternoon than in the morning.

The results are presented in figure 4-25 and are quite similar to the one for the east-facing window. The percentage of thermal comfort varies from 75% in both cases to 87% for 4 slats (297 hours of discomfort) and 89% for 6 slats (251 hours of discomfort). As for the daylight autonomy, the minimum value is approximately 40% for 6 slats when it is 76% for 4 slats.

Facing west, an efficient solar shade should have a maximum angle of incidence of 20° in order to be efficient until 5 p.m. in March. Figure 4-25 gives the percentage of comfort associated with this angle of incidence. In terms of thermal comfort, when the two lower slats are removed, the loss is reduced from 93% (157 hours) to 91% (205 hours) i.e. a loss of 50 hours of thermal comfort. In contrast, the gain in daylight autonomy is from 52% to 78%. The useful daylight index increases by 10% from 83% to 93% when the two lower slats of the solar shading are removed.

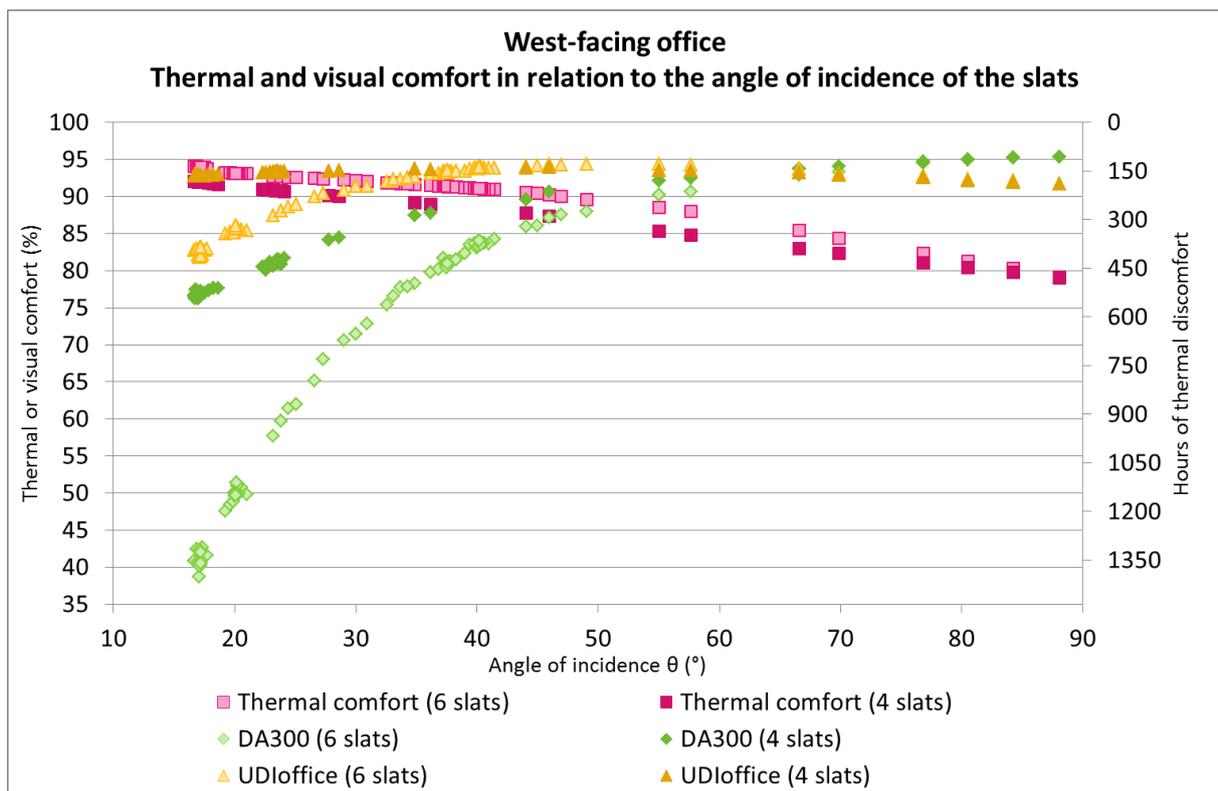


Figure 4-25. Thermal (percentage of hours) and visual (UDI_{office} and DA300) comfort in relation to the angle of incidence (θ) of the slats for the west-orientated office.

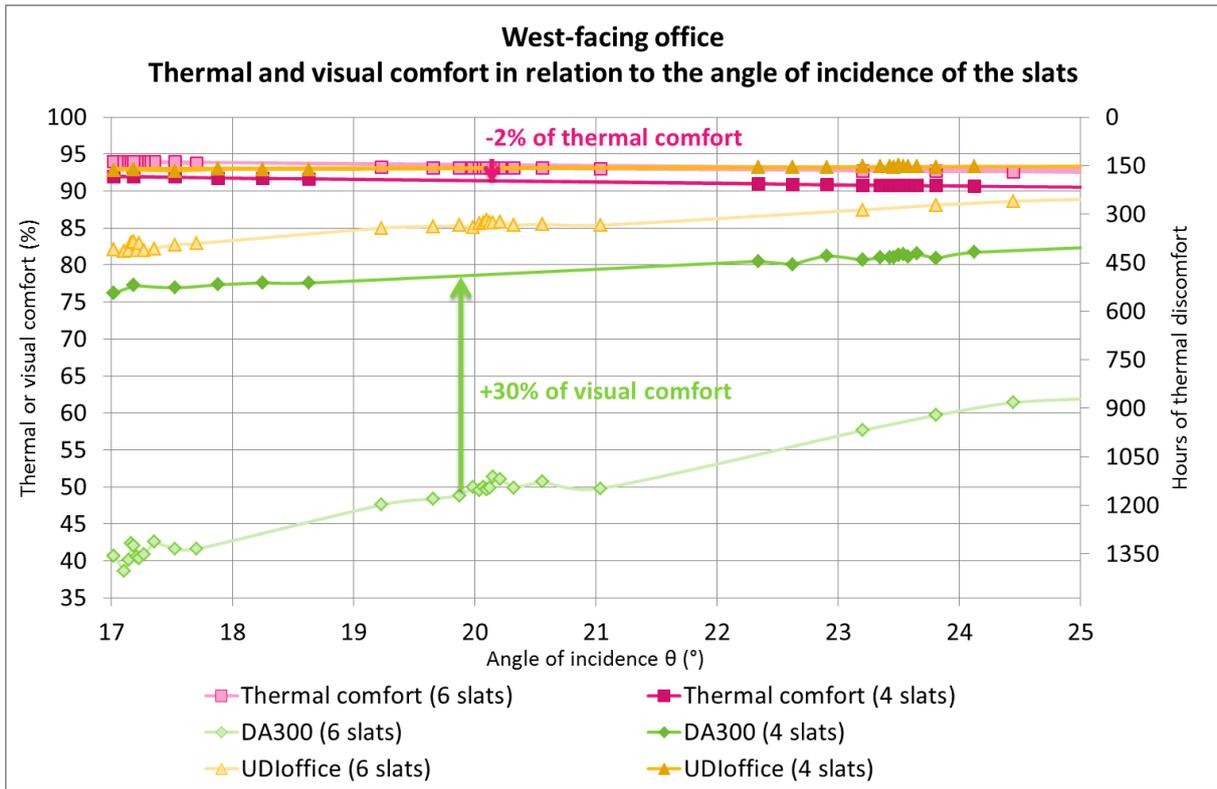


Figure 4-26. Gain and loss in terms of thermal and visual comfort when the two lower slats are removed.

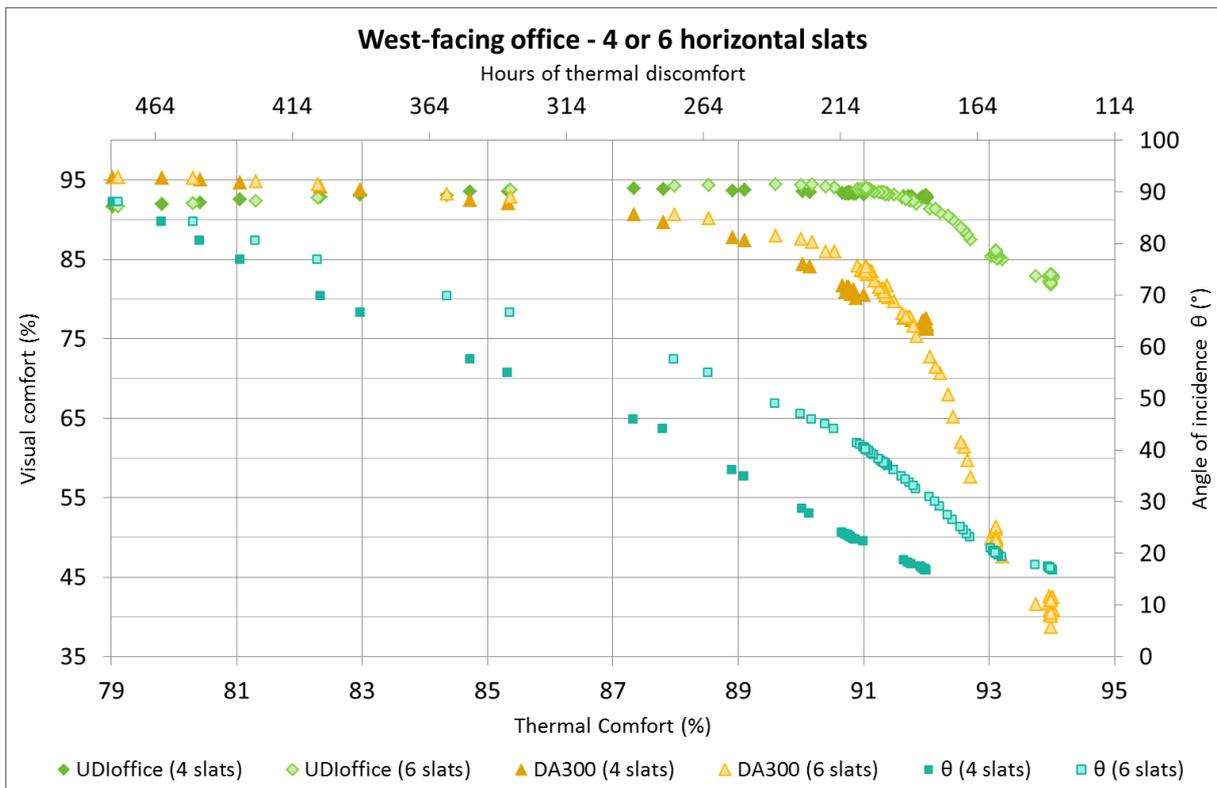


Figure 4-27. Visual comfort in relation to thermal comfort for the two case studies of a west-facing office.

4.4.3. SIMULATION RESULTS FOR A CLASSROOM

In this study, the classroom is considered north-south orientated. The two opposite facades include openings (with a 30% porosity) in order to enhance the natural ventilation of the room.

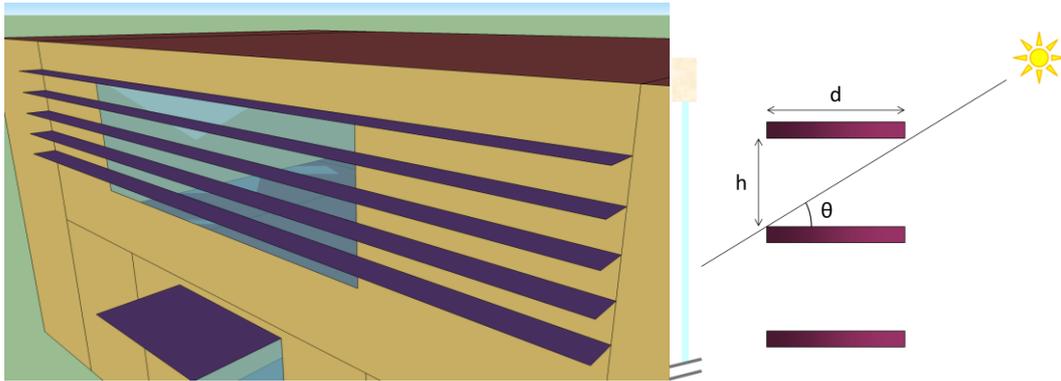


Figure 4-28. Solar shading of the classroom and definition of the angle of incidence (θ).

Solar shading is provided by horizontal slats for both windows. The parameters that vary in the optimisation process are the angle of incidence of the south slats (θ_1) and that of the north slats (θ_2). Figure 4-29 and figure 4-30 shows the thermal and visual comfort indices in relation the angles of incidence of the slats (θ_1 and θ_2). Several observations can be made looking at the graphs.

Concerning thermal comfort, the percentage of thermal comfort decreases from approximately 95% to 82% when the angles of incidence of the slats increase. It corresponds to an increase of 98 to 400 hours of discomfort over one year. The changes of the indices for visual comfort are more significant. Both have a minimum of approximately 30% for an angle of incidence of 15° . The maximum is 89% for the UDI and 93% for the DA. It is to be noted that both indices have the same values when the angles of incidence are lower than 60° , while there is a difference of a few per cent between the UDI and the DA when the angles of incidence are higher than 60° . This difference is due to the values of illuminance that are higher than 8,000 Lux. It means that when the horizontal slats have an angle higher than 60° , there is almost no risk of values of illuminance greater than 8,000 Lux.

According to figure 4-29 and figure 4-30, an acceptable compromise between thermal and visual comfort appears to be for an angle of incidence of the north and south slats between 50° and 60° . This allows a percentage of thermal comfort of approximately 90% and a UDI somewhat below 90%.

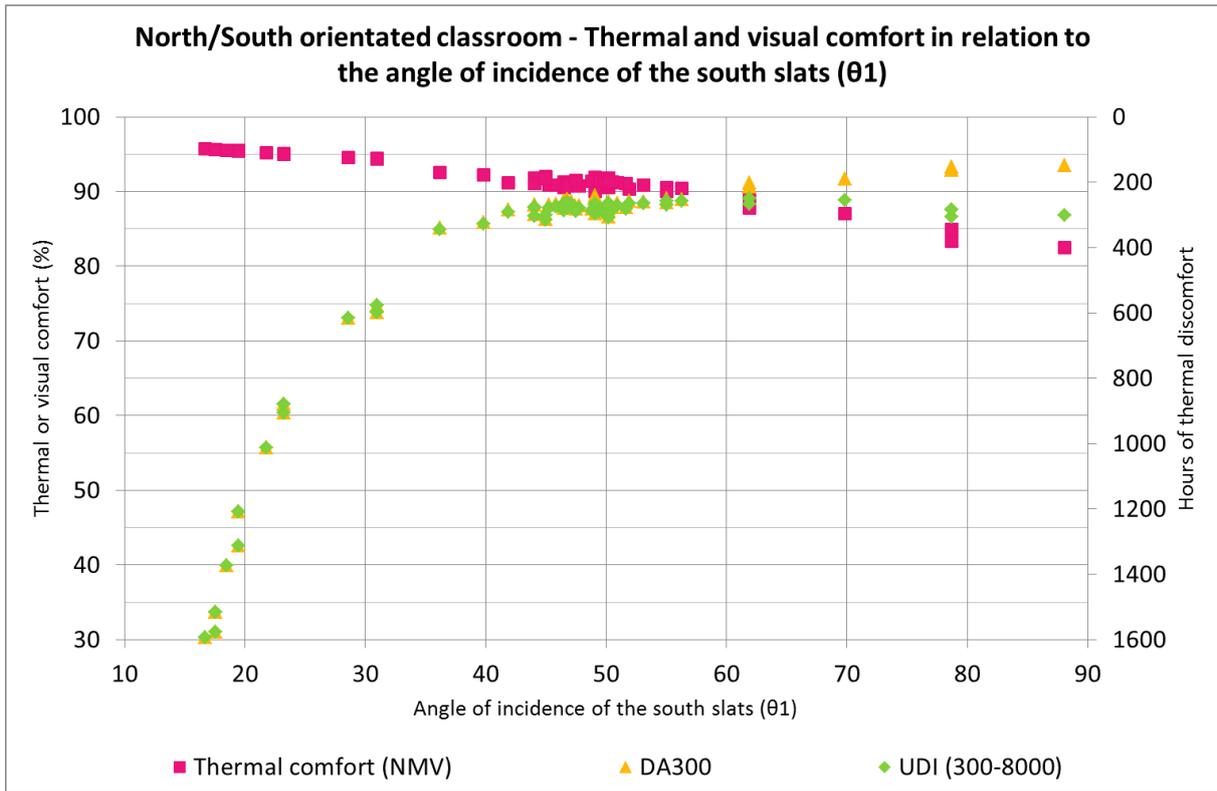


Figure 4-29. Thermal and visual comfort in relation to the angle of incidence of the south slats for the north-south orientated classroom.

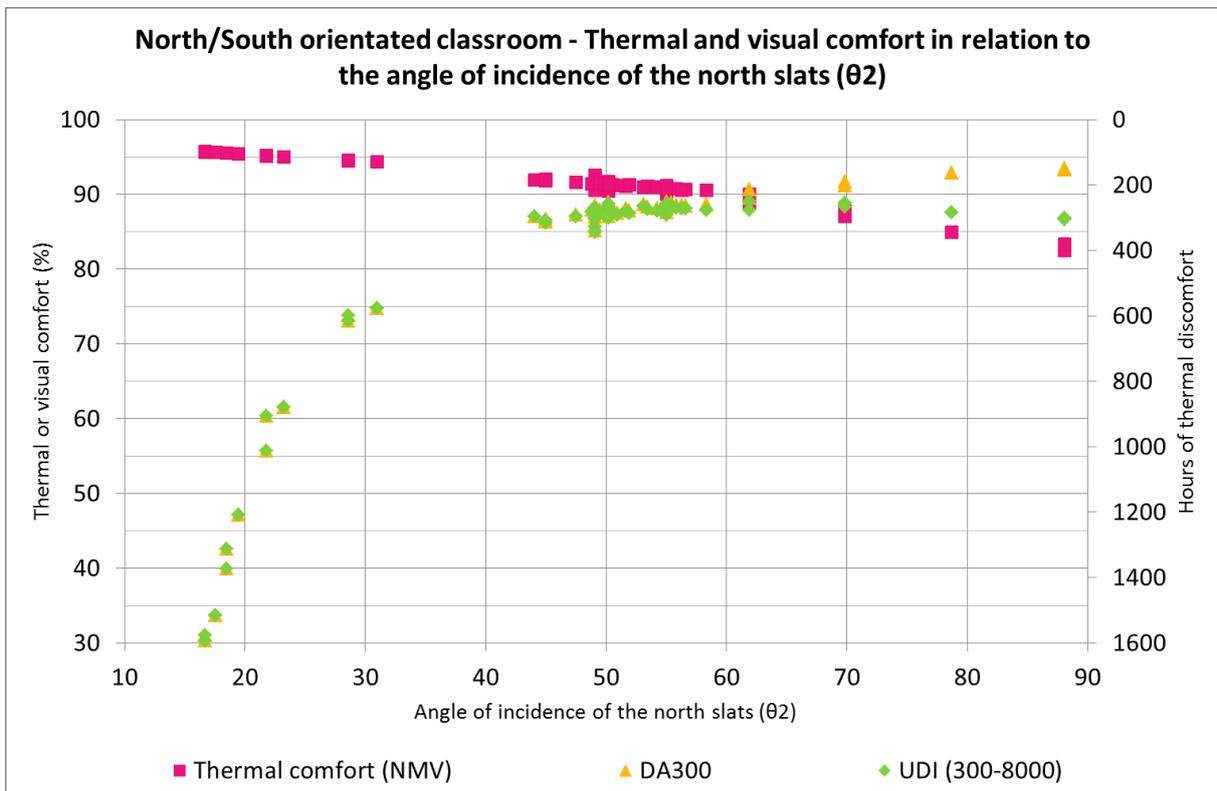


Figure 4-30. Thermal and visual comfort in relation to the angle of incidence of the north slats for the north-south orientated classroom.

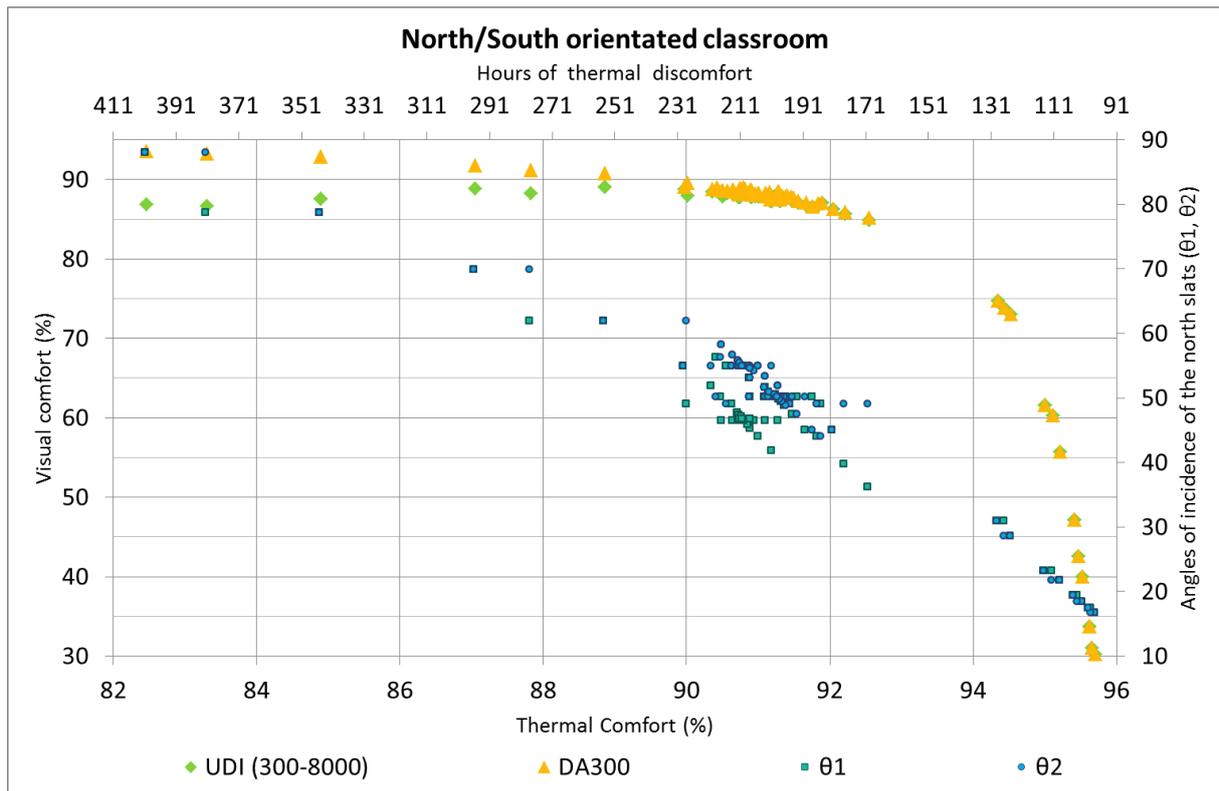


Figure 4-31. Visual comfort in relation to thermal comfort for the north-south orientated classroom.

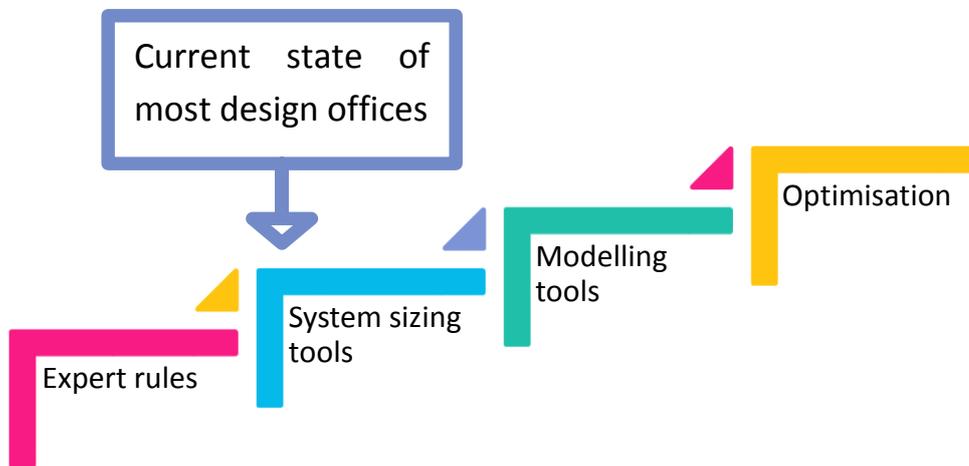


Figure 4-32. Four levels of requirements for the design of buildings.

This chapter addresses a multi-physics challenge in building design as it integrates physical issues i.e. thermal design, airflow, daylight and energy but also human behaviour that is difficult to describe mathematically (thermal and visual comfort, building occupancy, equipment use). The innovative methodology that is proposed focuses on comfort to design buildings rather than the conventional approach incorporating energy use. A parametric study is suggested for the dimensions of solar shading. The outputs of the model are defined as the percentage of thermal comfort, considering the natural and mechanical ventilation comfort zone defined in chapter 3, and the daylight autonomy or the useful daylight index.

Although this methodology raises specific issues which require further thought in terms of building design, there are also limitations to be taken into account. GenOpt has been used to launch both thermal and daylight models. This tool does not have a graphical user interface and its implementation is not straightforward. Currently, it is unsuitable for design offices that lack technical abilities to use such tools. In addition, although the maximum number of independent variables is not restricted with GenOpt, it is preferable not to exceed 10 variables. This is a limiting factor if the methodology is to be applied to an entire building. The simulation times are also prohibitive since the simulation takes approximately 2 hours when only one parameter varies and approximately half a day is required when 3 parameters vary. Another limitation is the single cost function that makes it very complicated to optimise several outputs.

Figure 4-32 illustrates, in our view, the steps needed to achieve an improvement in the building design process. Four levels of design are identified. The first one is the sole use of expert rules such as that proposed by the PERENE label to size solar shading. The second step is the use of tools to size the systems (air conditioning and electrical lighting for instance). Most design offices currently stand between level one and level two. The use of modelling tools to simulate the passive behaviour of buildings is the third step. Some design offices use such tools to assess thermal comfort or daylighting performances. However, no coupling is achieved between the thermal and the daylight simulations. The simulation tools are currently employed more to develop expert rules rather than to simulate and optimise buildings. The optimisation methodology proposed in this chapter, that represents the fourth stage of this process, is far removed from current practice. However, we estimate that it is necessary to move towards this direction.

OPTIMISATION OF THE BUILDING OPERATION

Although the design phase aims to optimise the building envelope, many parameters are still uncertain. Modelling the impact of natural ventilation on the indoor environment, climate and occupant, for instance, is very difficult to achieve.

Today's non-residential buildings are complicated structures, and, unlike cars or electronics, two buildings are rarely alike, making quality control difficult. As a result, problems such as installation errors, malfunctioning equipment, equipment degradation, and inefficient control strategies often go unnoticed (Mills et al., 2004; Mills et al., 2005). These deficiencies can lead to compromised indoor air quality and comfort, to unnecessarily elevated energy use or under-performance of energy-efficiency strategies. Fortunately, strategies - known as building commissioning - exist to address operational problems in buildings, detecting and remedying most deficiencies. The energy consumption of non-residential buildings can be reduced by 15% with improved operation and maintenance (Mills et al., 2004).

This chapter ends by presenting a methodology to optimise performances of buildings in operation through measurements, control actions and occupant surveys. This methodology is based on different levels of monitoring that can be proposed for a building and on the post-occupancy evaluation (POE) of the building. Results of monitoring and POE are presented for a case study, the ENERPOS building.

If you can not measure it, you cannot improve it.

LORD KELVIN

5.1. INTERESTS AND ISSUES RELATED TO MONITORING BUILDINGS FOR ENERGY SAVINGS AND COMFORT

A methodology to track the building energy use and comfort is proposed in this chapter along with actions to be taken to correct or optimise the building performance after completion.

5.1.1. THE INTERESTS OF BUILDING MONITORING

A number of issues and challenges of monitoring buildings and post-occupancy evaluation (POE) are listed here. The interests of monitoring buildings are:

Mastering the energy use of the building after its completion: A well-designed building does not necessarily guarantee low energy consumption. It has been shown that there is a gap between the consumptions calculated during design and the measured energy use of an occupied building. The differences can be related to the climate, the conditions of occupancy, the management of equipment and the behaviour of users.

Optimising the operating costs while preserving satisfactory comfort conditions: Energy management must not be at the expense of the users' comfort. Monitoring should also assess or even improve the overall users' comfort in the building, in terms of thermal, visual and acoustic comfort as well as indoor air quality. Satisfactory thermal comfort conditions lead to the increase of productivity in non-residential buildings.

Raising the awareness of the users about decreasing energy consumption, while maintaining equal or higher comfort conditions: The aim is to make users as active as possible so that they can participate in improving the indoor environment and thus the level of comfort in the building. It is necessary to inform users after the completion of the building, to explain the operation of the latter and their required involvement for it to perform correctly. Building monitoring is a valuable tool for users. Monitoring results will confirm or refute the usage scenario initially assumed. If malfunctions are found, the exchanges with users enable readjustments that are understood and shared amongst the occupants. The attention given to users facilitates the optimisation of the energy consumption, because they share the knowledge and the characteristics of the building they occupy.

Table 5-1. Interests of building monitoring for the building manager, the users and the environment.

Interests for	
Building Manager	<ul style="list-style-type: none"> - Knowing the specific energy consumption by end-uses; - Reducing the risk of rising consumptions due to inappropriate use of the building; - Ensuring the return of investments on the costs linked to the management of the energy demand; - Educating users regarding energy conservation; - Improving the comfort of users and their productivity; - Checking the correct operation of equipment; - Setting set point temperatures and sensors; - Alerting failures and making corrections.
Users	<ul style="list-style-type: none"> - Managing and optimising thermal, visual, acoustic comfort and indoor air quality; - Evolving healthy and comfortable environment; - Understanding the characteristics and operation of the building.
Environment	<ul style="list-style-type: none"> - Saving energy and resources while reducing environmental impacts; - Limiting global warming.

5.1.2. ENERGY MONITORING TO IMPROVE OVERALL BUILDING PERFORMANCE

The first year of occupancy and use of a building is crucial because most of the problems and dysfunctions observed are to be solved during that year. Several types of dysfunctions can be seen in a building, either related to the equipment, to a lack of maintenance or management and to incorrect assumptions about the use of the building. A list of examples is given in table 5-2.

Table 5-2. Examples of the dysfunctions that can be noticed in a building.

Dysfunctions related to equipment	<ul style="list-style-type: none"> - Defects in the installation or in the connections of some equipment, e.g. defective metres, wiring problems or omissions, uncontrolled use of lighting in lifts; - Time-control programme settings that need to be adapted to the real use of the building, e.g. set point temperatures, schedules; - Addition of non-performing equipment e.g. desk lamps or individual air-conditioners.
Lack of maintenance or management	<ul style="list-style-type: none"> - Dirtying of ventilation filters; - Poor or non-use of the Building Management System.
Incorrect assumptions about the use of the building	<ul style="list-style-type: none"> - Incorrect use of mobile shading; - Misuse of natural ventilation (during day or night); - Poor maintenance of the vegetation around the building that helps to improve comfort conditions inside the building; - Incorrect usage or occupancy scenarios e.g. higher internal loads depending on the number of people in the building.

These discomfort problems, even if they do not cause immediate overconsumption, can lead to complaints, sometimes solved by adding energy-consuming equipment (such as air-conditioners, fans, desk lamps, blinds or curtains that reduce the use of natural ventilation and natural lighting). Monitoring can analyse the sources of discomfort and can help to solve the problems in a more cost-effective way.

5.1.3. THE DIFFERENT PROPOSED LEVELS OF MONITORING

One of the actions of the Task 40 / Annex 52 consists in the monitoring analysis of the 30+ Net ZEBs of the database. Four levels of energy monitoring were defined by analysing the monitoring solutions of the 30+ Net ZEBs selected. These are described in table 5-3.

Table 5-3. Description of the four levels of monitoring defined in the framework of Subtask C of IEA SHC Task 40 / ECBCS Annex 52 by analysing a database of 30+ Net ZEBs.

Level	Description	Possible analysis with monitored data	Possible analysis with design data
Level 1	Annual energy balance	Energy balance	Measured / design comparison
Level 2	Monthly energy balance	Monthly mismatch	Measured / design comparison
Level 3	Monthly energy balance by end-uses	Evaluation of the performance of the solution sets	Measured / design comparison
Level 4	Daily / Hourly energy balance by end-uses Indoor air quality data: measurements campaign or fixed sensors Occupancy Weather station ...	Measured / design comparison for typical days Lessons learned from the solution sets Comfort analysis Identify energy leaks	

The inventory of the level of monitoring for each building is under way, but it has been already pointed out that only very few buildings were monitored at level 4. ENERPOS is one of the few buildings providing this level of monitoring. Paragraph 5.3 will illustrate the possible analysis given by each level of monitoring based on the ENERPOS case study.

5.2. OCCUPANT CONSIDERATION AND ENERGY EDUCATION

5.2.1. SUSTAINABLE BUILDINGS ARE THOSE THAT WORK WITH THE OCCUPANTS, NOT AGAINST THEM

The active and passive design approaches presented in the first chapter refer to two attitudes to user involvement during the operation of the building.

In the case of an active building, the user will be considered as passive. The operating system is automated and the occupants do not have to intervene in the building operation, they must adapt to indoor conditions controlled by automated systems.

In a passive building, occupants must be active and involved in the daily management of the building, either to improve their own comfort or to avoid unnecessary energy consumption. The occupant behaviour is seen as a passive conservation feature, as it does not cost anything for the users to change the way they use energy in buildings.

In both cases, if the design and the systems are not adapted to the expectations and the needs of the occupants, the risk of misuse or bypass is high. Upstream, the design must take into account the expectations and habits of users as much as possible. Downstream, the users must be informed and educated regarding the use of the building and the new systems.

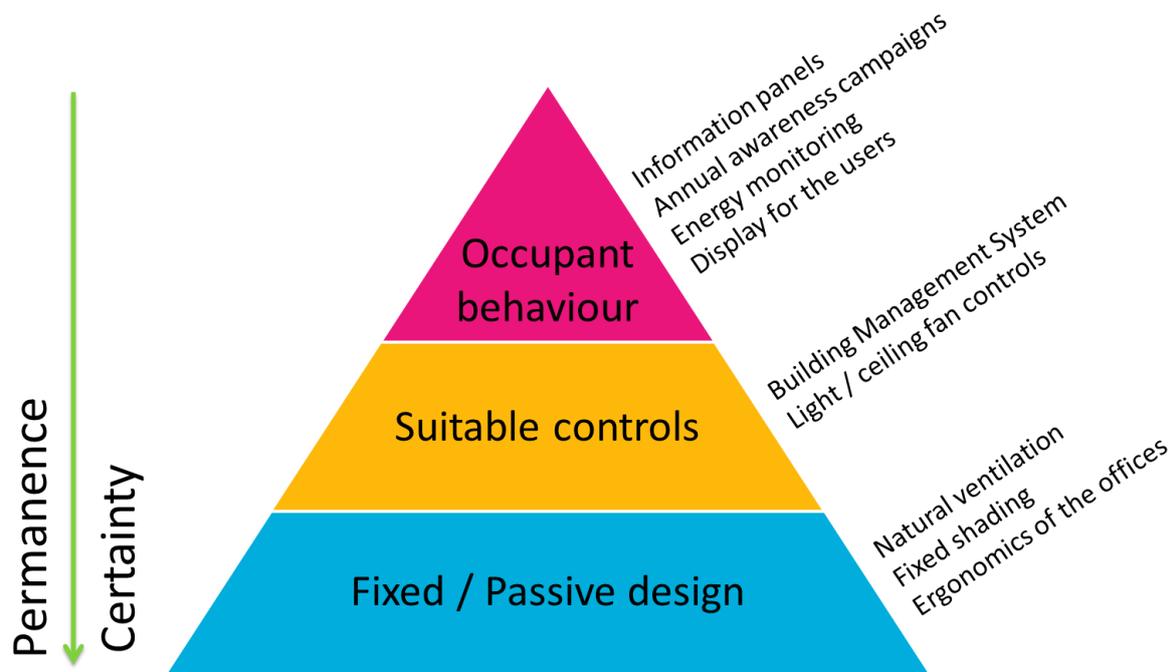


Figure 5-1. Occupant conscious design. Adapted from O'Brien (O'Brien, 2012).

Figure 5-1 adapted from O'Brien (O'Brien, 2012) provides a methodology to follow in order to reduce the risks of energy use or comfort drifts, due to incorrect occupant behaviour of the building and its systems. Once the first two steps have been completed, i.e. passive design of the building and good controls of the systems, occupant behaviour still remains a significant issue. Not only should the building be well designed, but also the occupants should be trained in how to use the building efficiently and to make a conscientious use of energy. There are several ways of educating the users, in order to raise their awareness about the operation of the building and the maintenance of an equivalent level of comfort, while limiting the energy consumption of the systems.

5.2.2. A SMART BUILDING WILL NEVER BE SMARTER THAN THE PEOPLE OPERATING IT

BARRIERS TO ENERGY SAVINGS

Several social, cultural and psychological factors prevent users from making energy savings. These barriers to energy efficient behaviour are linked to several issues (Thollander et al., 2010), some of which are listed here:

Lack of both awareness and information on energy consumption and cost: It may lead to cost-effective and energy efficient opportunities being missed, because people are not aware that they are wasting energy. Issues related to imperfect information may be counteracted with different forms of information campaigns.

Inertia: Individuals and organisations are, in part, creatures of habits and established routines, which may make it difficult to create changes to such behaviours and habits.

The rebound effect: Energy savings can be reduced because it leads to additional activity through either greater use of the same product or for another energy-using action, such as driving a more efficient car further, or leaving lights on because the bulbs are energy-saving.

The symbol of energy: In developing countries, using energy can be a symbol of progress and wealth. Social recognition can come from consumption, which clashes with saving energy. In the developed countries, it is a commodity that is taken for granted and its insignificance can lead to thoughtless waste.

It is very difficult to remove those barriers to energy savings but it is certain that communicating simple and relevant information is a crucial step to any changes in the behaviour of the building occupants. Enhancing the awareness of the occupant on how to use the building efficiently offers several advantages.

ADVANTAGES OF ENHANCING OCCUPANT AWARENESS IN RELATION TO ENERGY AND COMFORT

Reduction of the energy consumption: Information given to the building occupants is necessary to help them to understand the issues related to energy consumption, as well as to inform them about possible energy-saving actions. More visibility is needed in the passive design of the building, in building control systems and in the benefits of users' actions in the building energy use, because people are more committed if they know what is happening and why. People alter their behaviour if they know that their behaviour is having an effect on the energy they are using. For instance, most people

tend to drive more economically if they set the display in their car to show the gas consumption of their vehicle. Similar systems in buildings can display real-time energy usage and also let people know when the energy use increases or decreases depending on their actions.

Increase in comfort: One of the keys for the users to understand the benefits of energy savings is to realise their own interest in terms of comfort. Energy only makes sense when it provides a service and should not be presented as being disconnected from everyday life.

Technical devices to measure energy consumption and provide immediate feedback help the building users to decrease their energy consumption. Direct and immediate feedback reveals the link between the actions and their impacts. Well-informed consumers choose actions to save energy with minimal impact on their comfort. Perceptions of comfort are important; there must be a balance between the energy-saving value and any perceived loss of comfort.

EXAMPLE OF THE ENERPOS BUILDING

The ENERPOS building favours passive solutions rather than active energy-consuming systems to reach comfortable conditions for the occupants. Thermal and visual comfort is partly in the hands of the users who can open or close louvres, turn on or off ceiling fans or the electrical lighting. This strategy comes with substantial risks. If users are misinformed or insensitive to the energy issues, they can use the available systems incorrectly. For instance, it has been noted several times that the louvres of fully occupied classrooms remain closed while all the ceiling fans are turned on. A more positive form of behaviour would be to first open all the louvres and, if necessary to turn on ceiling fans. This decreases the energy consumed in the building. Communication to the building users plays a decisive role in improving the building performances.

COMMUNICATION METHODS

The key to the success of effective communication is to tailor messages to the intended audience as well as to the type of building. For instance, in housing, money can be considered as a driving force towards behavioural change. This argument is more sensitive in an office building where health, comfort or the well-being of employees can be promoted to convey the message of reduced energy consumption. Messages should be as concrete as possible and based on the usage rather than technical performances. A prior audit can help target end-users who have the greatest impact, in order to avoid overload of information.

Awareness tools can take many different forms: posters or panels around the building, screen displays with measured data, booklets given to the occupants or dedicated websites.

EXAMPLE:

High-school “Saint-Benoit IV” in Reunion Island

In “Lycée Saint-Benoit IV”, a high school located in Reunion Island, information panels are placed around the schoolyard to raise students’ awareness about the use of the building and the environmental challenges of the island.



Figure 5-2. Examples of information panels concerning daylighting (left) and photovoltaic energy (right) at “Lycée Saint-Benoit IV”.

Research Support Facility - NREL in Denver, Colorado

The main principles featured in the RSF building in Denver, Colorado are explained on stone information panels around the building. In the main entrance, a screen displays the energy consumed by all end-uses during the previous day and year, as well as the energy produced by the photovoltaic panels placed on the roofs and on the car park. Building occupants and visitors can thus be informed about the use of the building upon entering.



Figure 5-3. Information panels and screen with the energy used and produced at RSF, Denver, Colorado.

5.3. CASE STUDY: THE ENERGY PERFORMANCE OF ENERPOS

5.3.1. THE ANNUAL ENERGY BALANCE – LEVEL 1 MONITORING

The question of the time frame for energy balance is raised in the definition of a Net Zero Energy Building. The yearly balance is the most common and often implicit choice (Sartori et al., 2010). The PV production measured over the first year of monitoring (June 2010 – May 2011) was 75,213 kWh (101.8 kWh/m²_{NFA}) for an overall consumption of 9,908 kWh (13.4 kWh/m²_{NFA}). Over the second year of monitoring (June 2011 – May 2012), the PV production was 78,333 kWh (106.0 kWh/m²_{NFA}) and the energy use was 10,712 kWh (14.5 kWh/m²_{NFA}). During the two years in question, ENERPOS has produced approximately seven times its own electrical consumption. This proves that the building is net zero on an annual basis.

The energy index for the building is approximately 14 kWh/m²_{NFA}.y. The 2012 French Thermal Regulation RT2012, not applicable in Reunion Island because it is not adapted to tropical climates, defines an energy index of 50 kWh_{PE}/m².y (primary energy) for low energy buildings (referred to as *Bâtiment Basse Consommation* or *BBC* in French). To compare this goal with the consumption of the ENERPOS building, the final energy (electricity) must be converted into primary energy. In Reunion Island the ratio of primary energy to final energy is 3.3, whereas in mainland France, this ratio is 2.58. The index in primary energy is then 46.2 kWh_{PE}/m²_{NFA}.y which remains below the national goal for low energy buildings. This comparison is not fully accurate because the *BBC* index only includes the five end-uses defined by the Thermal Regulation (heating, cooling, ventilation, interior lighting and DHW) whereas the index defined for the ENERPOS building takes into account all the end-uses of the building, particularly the plug loads which represent approximately half the total energy consumed.

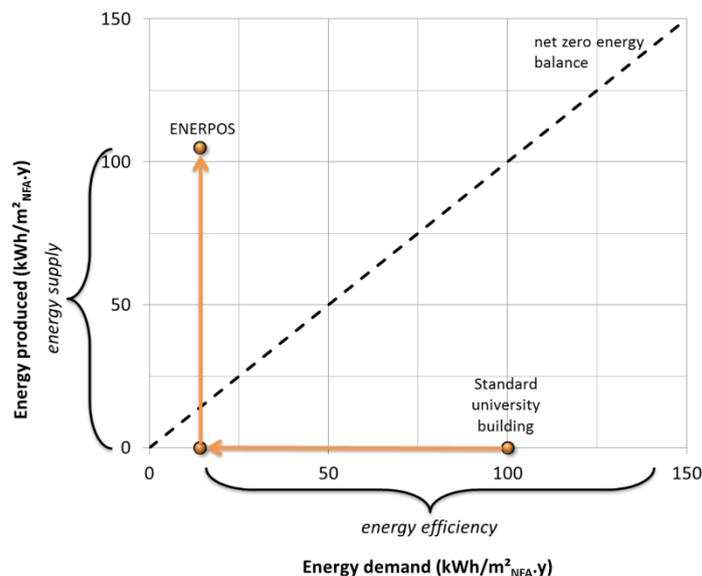


Figure 5-4. Representation of the net zero energy balance line for the ENERPOS building.

This index can also be compared with those outlined in the PERENE label in order to evaluate the consumption of ENERPOS with that of a standard building of the same type in Reunion Island. According to PERENE, a university building has an energy index of 100 kWh/m²_{NFA}·y (final energy). ENERPOS consumes approximately seven times less energy than a standard building.

In figure 5-4 the consumption of a standard university building in Reunion Island is plotted compared to the consumption and production of ENERPOS. This type of analysis is possible with Level 1 Monitoring (see table 5-3).

5.3.2. THE MONTHLY ENERGY BALANCE – LEVEL 2 MONITORING

Level 2 Monitoring (see table 5-3) corresponds to a monthly energy balance of the building. Figure 5-5 illustrates both annual electricity consumption and generation based on monthly data. ENERPOS is not only net zero on an annual basis but also on a monthly basis. The energy produced is 5 to 10 times higher than the energy used. The interaction between the building and the power grid will be discussed in the next paragraph.

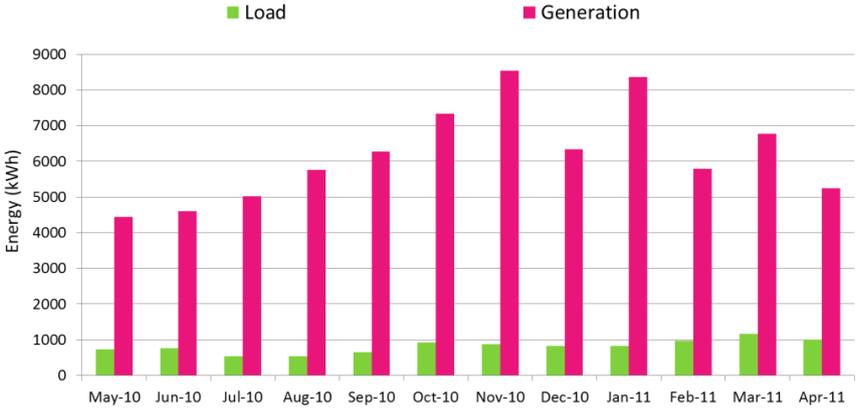


Figure 5-5. Annual electricity load and generation profile based on the monthly data.

5.3.3. THE MONTHLY ENERGY BALANCE BY END-USES – LEVEL 3 MONITORING

Figure 5-6 displays the distribution of all end-uses. It is to be noted that the plug loads represent the largest share of the energy consumed (46%). This is followed by the air conditioning that includes the split air conditioning systems in the technical rooms (8% of the 11%) as well as the VRV air conditioning system, air treatment unit and terminal units of the offices and computer rooms. The VRV air conditioning system has only been used for two days during the year, so it should not play such an important role in the energy consumed.

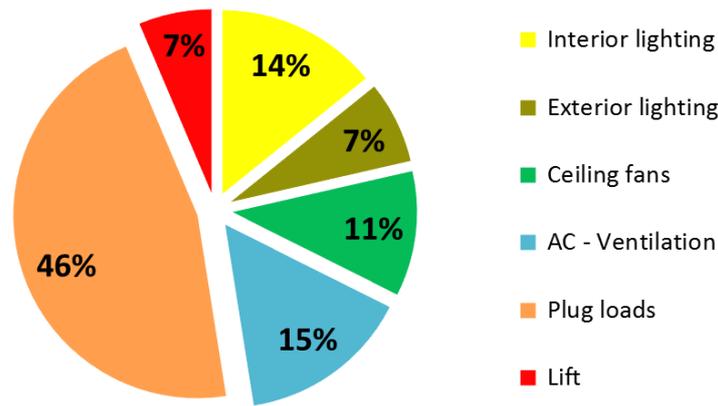


Figure 5-6. Distribution of all end-uses.

Table 5-4. Energy ratio by end-use (kWh/m²_{NFA}.y).

Use	Interior lighting	Exterior lighting	Ceiling fans	AC - Ventilation	Plug loads	Lift	TOTAL
Energy ratio (kWh/m ² _{NFA} .y)	2.0	1.0	1.6	2.2	6.7	0.9	14.4

Figure 5-7 represents the energy consumed for all end-uses on a monthly basis, as well as the energy produced by the BIPV roof. It can be noted that the energy use is lower during July and August which corresponds to the holiday period. The consumption of the plug loads remains more or less constant over the year. The end-uses that vary the most are those due to air conditioning (particularly the use of the split systems in the technical rooms), ceiling fans and interior lighting. The exterior lighting has a higher consumption during the austral winter (May to October except for July and August due to holidays). The ceiling fans and the air conditioning units are, on the contrary, used more often during the summer season (November to April).

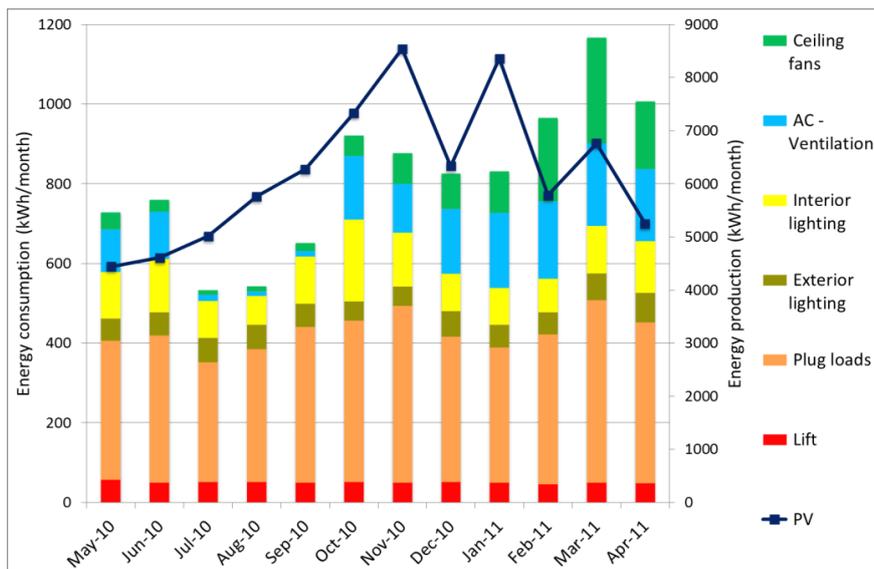


Figure 5-7. Energy by end-uses on a monthly basis for one year of occupancy.

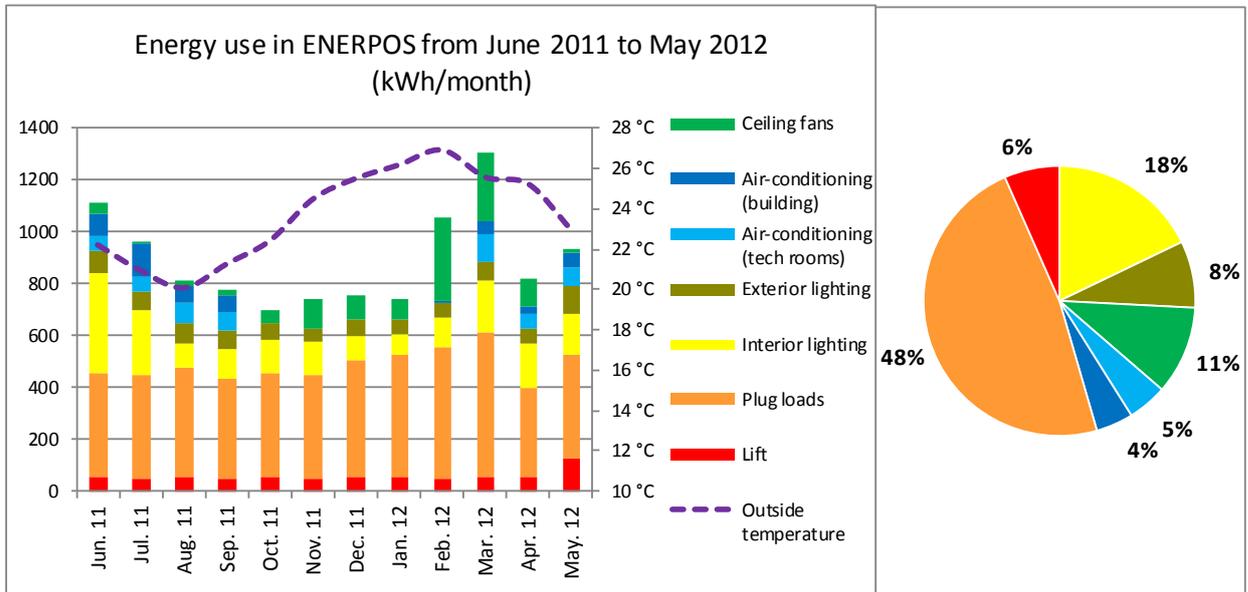
YEAR 2 : June 2011 to May 2012

Energy use

Annual energy use 10 712 kWh
 Energy index 14,5 kWh/m²_{NFA}

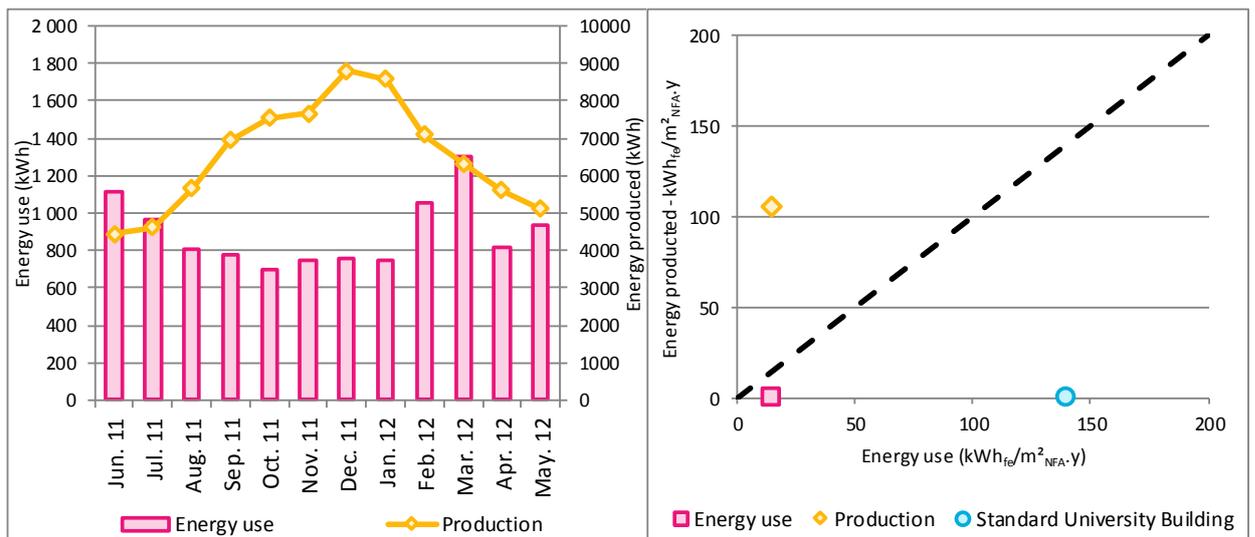
Production

Annual production 78 333 kWh
 Energy index 106,0 kWh/m²_{NFA}
 Productivity 1 674 kWh/kWp



	Jun. 11	Jul. 11	Aug. 11	Sep. 11	Oct. 11	Nov. 11	Dec. 11	Jan. 12	Feb. 12	Mar. 12	Apr. 12	May. 12
Ratio (kWh/m²_{NFA})	1,5	1,3	1,1	1,0	0,9	1,0	1,0	1,0	1,4	1,8	1,1	1,3

	Int. Lighting	Ext. Lighting	Ceiling Fans	Air-conditioning	Plug loads	Lift
Energy use	1909 kWh/y	856 kWh/y	1134 kWh/y	980 kWh/y	5129 kWh/y	704 kWh/y



Maximum load of the building 9,8 W/m²_{NFA}

Figure 5-8. Example of graphical data representation with the level 3 of monitoring.

5.3.4. THE LOAD CURVE OF THE BUILDING – LEVEL 4 OF MONITORING

The difference between Level 4 Monitoring and the three others is based on the time step of measurements. At ENERPOS, the energy data are recorded every minute, however, for ease of readings, this is averaged over 10 minutes. This time step corresponds to the synchronisation pulse defined by the national supplier of energy in France, *Electricité de France (EDF)*. With this kind of data, it is possible to reproduce the load curve of the building, which is useful to identify the possible improvements in terms of energy savings. This paragraph shows an example of a possible analysis with Level 4 Monitoring.

March 2011 was the month during which the building had the highest energy consumption in the year. Over this month, the 1st was a weekday when the consumption was the highest and the 9th another weekday when it was the lowest. The load curves of these days are given in figure 5-9 and the total energy consumption by end-use is given in table 5-5.

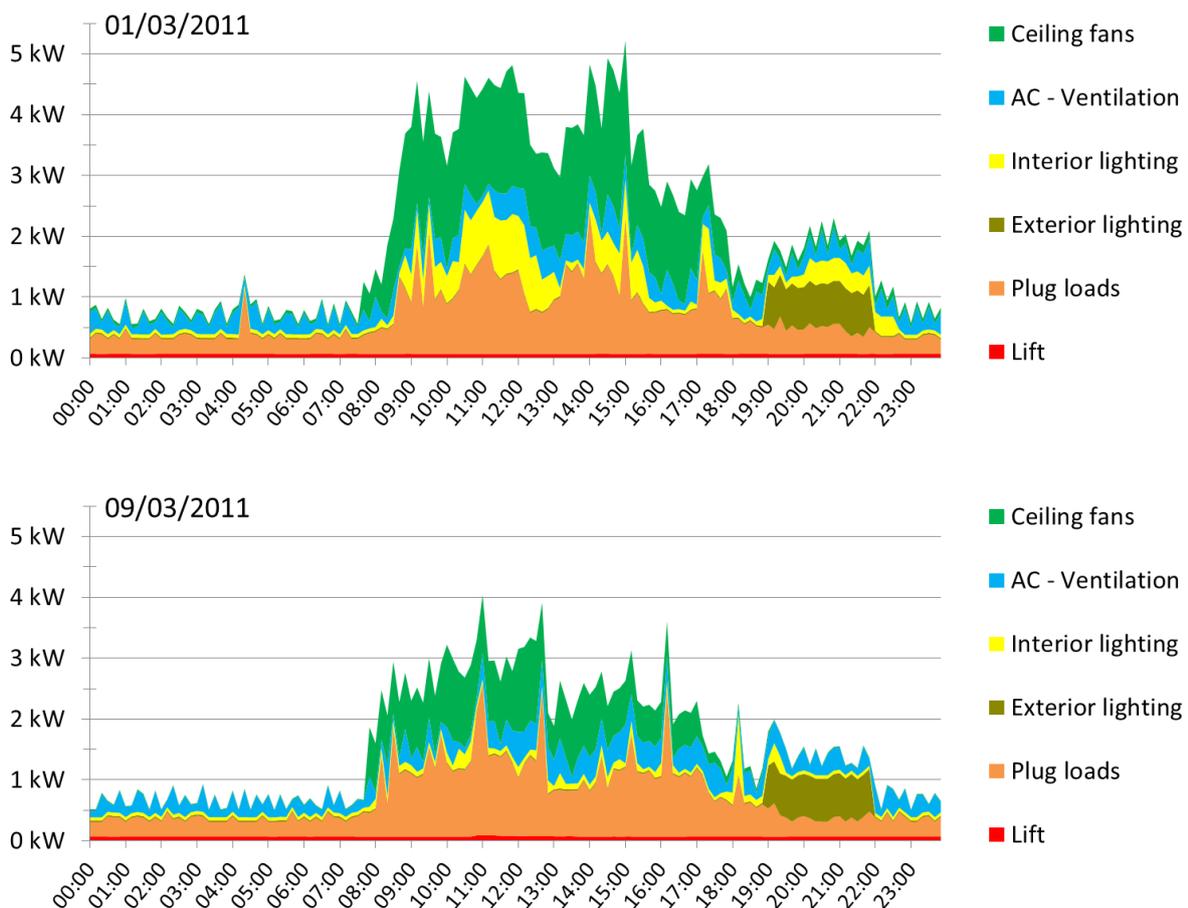


Figure 5-9. Load curves on March 1st and 9th 2011.

Table 5-5. Energy use by end-use for March 1st and 9th 2011.

Energy use (kWh)	Interior lighting	Exterior lighting	Ceiling fans	AC - Ventilation	Plug loads	Lift	TOTAL
01/03/2011	6.3	2.6	16.9	7.2	15.4	1.7	50.1
09/03/2011	2.2	2.6	8.8	7	15.7	1.7	38

A comparison of the energy consumption by end-use on those two days leads us to note that the major differences occur for interior lighting and ceiling fans. We can look for the influence of weather for these differences. Table 5-6 provides the weather conditions of the two days, which are rather similar with an average temperature during the day close to 30°C, a relative humidity of 60%. The solar radiation levels are also quite close. It seems that the weather does not provide the answer to the differences between March 1st and 9th.

Table 5-6. Weather on March 1st and 9th 2011.

Weather	Average daily temperature (8am-5pm)	Average humidity ratio (8am-5pm)	Direct solar radiation (horizontal)
01/03/2011	30.0°C	58%	5.5 kWh/m ²
09/03/2011	29.4°C	67%	5 kWh/m ²

It is then possible to look into the occupancy of the building during the two days. Based on the assumption that the occupancy of the offices is comparable during the two weekdays (this assumption is supported by the fact that the energy use for plug loads is similar on the two days), we can look at the presence detectors of the classrooms. On March 1st, the sum of occupied hours for the 7 classrooms was 31.6 hours, whereas it was 13.3 hours on the 9th. The occupancy of the building explains the differences noted in the consumption.

What is essential to note here based on the above measured data is the major importance of occupancy scenarios, particularly in buildings where the occupancy varies considerably throughout the year. It also shows the importance of monitoring in order to understand the dynamic energy consumption profile and variations.

5.3.5. ENERGY PRODUCTION

The PV energy production measured between April 2010 and March 2011 was 71,118 kWh which is about 8% less than the production expected during the design stage. Figure 5-10 gives a comparison between the measured PV production and the PV syst simulations. To compare the measured data with the simulations, the latter are carried out again integrating the solar radiation measured by the weather station located on the campus of the University of Saint-Pierre, very close to the ENERPOS building, as input data. The PV simulations, that were run during the design stage, integrated averaged data from weather files for the solar radiation. Using those new data, the simulations give a total of 70,614 kWh for the year April 2010 to March 2011, which is only 0.7% less than the measured data of the installation.

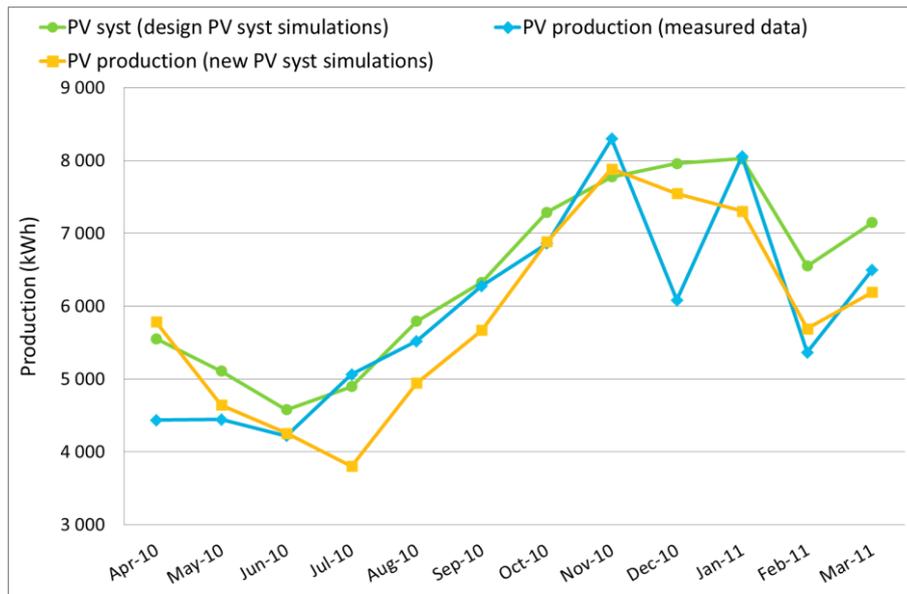


Figure 5-10. Comparison between the measured PV production and the PV-syst simulations (during design and new simulations with measured data for the monthly solar radiation).

Figure 5-11 gives a comparison of the production in kWh/kWp for the two parts of the roof. For 9 months, the northern roof produces more energy than the southern one, with a maximum deviation of 28% in June 2010. During November, December and January, the southern roof was a little more productive than the northern one, less than 2% more in December 2010. This result could be expected by studying the sun path in Reunion Island (given in Appendix B -). Due to the latitude of Reunion Island (21 °S), the position of the sun is mostly the north except from November to January when the sun is in the south.

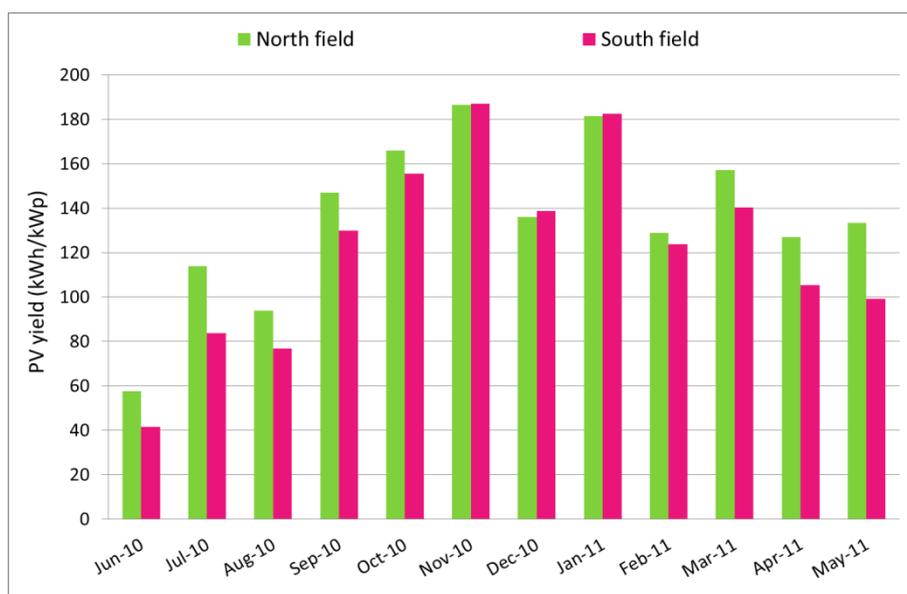


Figure 5-11. Comparison between the production of the North and South roofs.

5.3.6. LOAD MATCHING AND GRID INTERACTION

The underlying philosophy of ENERPOS is to balance the final energy consumption of all end-uses with the PV energy production and to reduce the time period within which the energy balance is reached. The advantage of the tropical climate is indeed that there is simultaneity between the peak consumption, that corresponds to the use of ceiling fans or air conditioning, and the maximum potential production, corresponding to the maximum solar radiation for the PV panels.

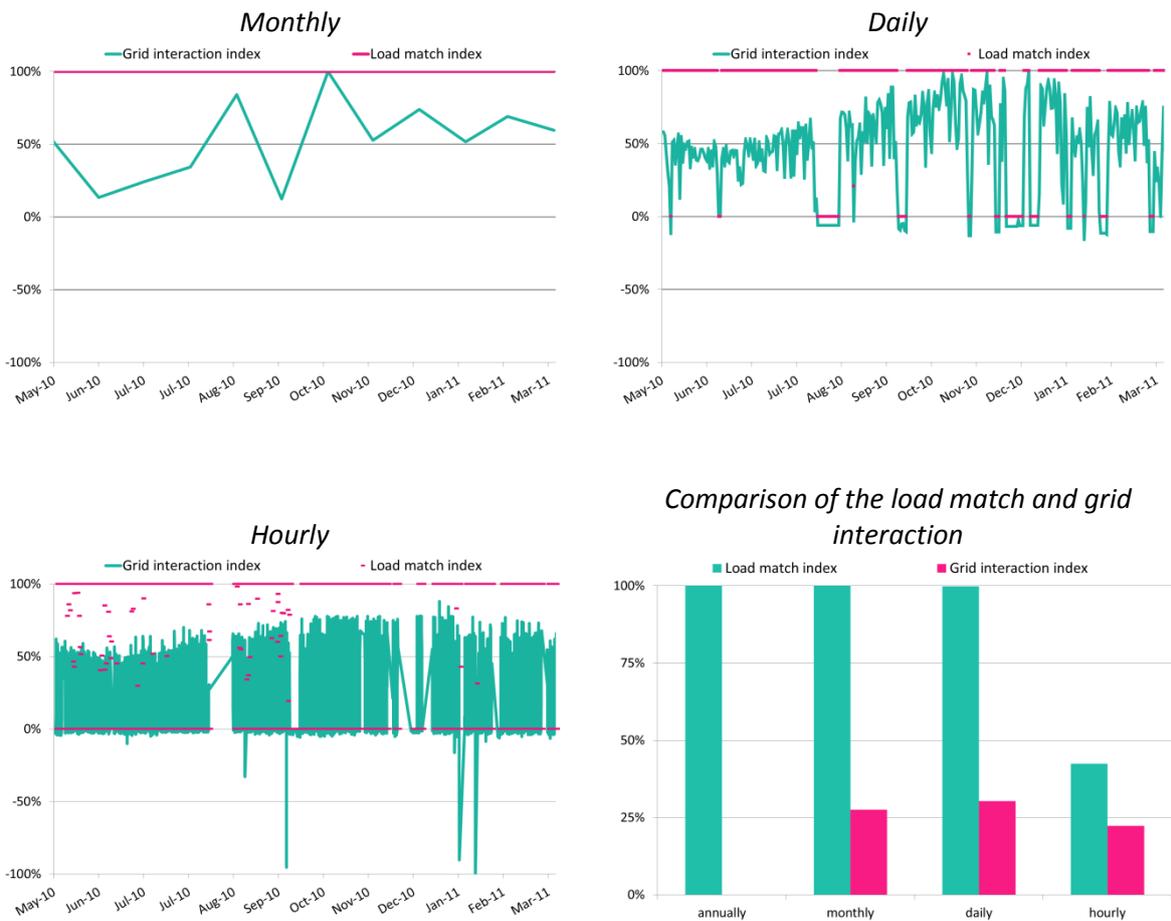


Figure 5-12. Load Match and Grid Interaction Indices (monthly, daily and hourly resolution). Comparison of the Load Match and Grid Interaction Indices.

The indices described in paragraph 1.3.4 are explained in this paragraph. They strongly depend on the time resolution considered; therefore they will be calculated for three time intervals: hourly, daily and monthly. The results are given in figure 5-12. On a monthly basis, the building is net zero (Load Match Index = 100% all year) and net exporting (the Grid Interaction Index is always positive). On a daily basis, it seems that the building is not net zero for a few days per year. It should be noted here that the zero values of the Load Match Index correspond to a loss of data. Indeed in the event of missing data, the total energy generation and use are not recorded for the day and the energy use can appear as higher than the production. Except for those few days where the missing data do not allow to make any

conclusion about the Load Match Index, all the other days of the year have a Load Match Index of 100% which means that ENERPOS is also net zero on a daily basis. An examination of the Grid Interaction Index makes it possible to assess that the building is also net exporting, except for the missing data days, on a daily basis as well.

The hourly results demonstrate that the building is obviously not net zero during night time. The Load Match Index is close to 100% when the PV cells are producing energy and 0% when they are not. The grid interaction index is an interesting criterion in this case because even if it becomes negative at night, it stays very close to zero which means that the building is not net exporting but does not require a lot of energy during the night.

The last graph of figure 5-12 gives the average of the Load Match Index over the year for the four time intervals (annual, monthly, daily and hourly) as well as the standard deviation of the Grid Interaction Index. The hourly average of the Load Match Index is 42% which is significantly high and close to the maximum possible average which is 50%. The Grid Interaction Index should be as close as possible to zero so that the building has a very low impact on the grid. The values for ENERPOS remain relatively high, close to 25%, which means that even though the building exports a considerable amount of electricity, it has a high impact on the grid.

5.3.7. CONCLUSIONS ON THE ENERGY MONITORING OF ENERPOS

The ENERPOS building has been monitored by end-users for its consumption and production since 2010. The monitoring results that are given in the previous section show that the building outperforms the objectives targeted during the design. ENERPOS proves that a building can reduce its energy consumption significantly because that of ENERPOS ($14.5 \text{ kWh/m}^2_{\text{NFA}\cdot\text{y}}$ from June 2011 to May 2012) is approximately 7 times less than that of a standard university building in Reunion Island (approximately $100 \text{ kWh/m}^2_{\text{NFA}\cdot\text{y}}$).

ENERPOS generates the equivalent of 7 times its own consumption with the 365 square metres of PV panels on the roof ($106 \text{ kWh/m}^2_{\text{NFA}\cdot\text{y}}$ from June 2011 to May 2012). It has been proven that the building is not only net zero on an annual scale, but also on a monthly and daily scale. Therefore, this example provides an opportunity to question the definition of a Net ZEB in a tropical climate. According to the generally accepted definition, a Net ZEB is a low-energy building that balances its low-energy consumption using on-site renewable energy on an annual basis. However, in tropical climates, the energy consumption and production are usually synchronized. The balancing period can be reduced to a week or even to a single day.

Beyond the energy aspect, it is essential to make sure that the users enjoy and understand the building and know how to operate it. To this end, a post-occupancy evaluation was conducted on the users of ENERPOS. The aim and the results are presented in the following section.

5.4. CASE STUDY: OCCUPANT COMFORT IN ENERPOS

The following section deals with the post-occupancy evaluation that has been conducted in ENERPOS. This work was presented during the Anzasca congress (Franco et al., 2011) and has been published in the architectural science review (Lenoir et al., 2012).

5.4.1. AIMS OF THE POST-OCCUPANCY EVALUATION

Unlike commissioning, which focuses on the operations of HVAC, electrical and water systems, a post-occupancy evaluation focuses on the people who inhabit the facility. Commissioning and energy monitoring are the best ways to develop strategies to reduce energy consumption, but they are not likely to reveal how the occupants feel about the facility or to give an idea of how the work environment affects their productivity. While reducing energy consumption is critical for many reasons, and significantly easier to quantify than productivity, it should be one focus - but not the only focus - of building operations.

Post-Occupancy Evaluation (POE) seeks to assess the building performances from the point of view of the building users. A POE is a survey that includes questions for building occupants about many aspects of the facility and operations, including thermal comfort, indoor air quality, lighting quality, cleanliness, the work environment, furniture and more. The goals of the post-occupancy evaluation should be to gauge employee satisfaction and identify modifications that will enhance comfort.

Putting the emphasis on the building users can be justified by the 1:10:100 rule often used by life-cycle analysis, considering that the ratio of the operating costs (1), to combined capital and rental costs (10), to total salary costs of the occupants (100), over the life of a building, makes it abundantly clear where the attention should be centred. There is indeed growing evidence of a significant connection between job performance and various physical attributes of the workplace. The costs to organisations are considerable if employees are performing below their full potential because their workplace does not fully meet their needs (Baird et al. 1996).

Most Building Sustainability Rating Tools (BSRTs), that certify low energy buildings, are based on the building design and its potential for low energy and sustainable operation. These tools focus on the technical aspects of building design (Cole, 2003). Even if indoor environmental quality is one of these criteria, this only concerns design data or measurements of temperature, humidity, air quality, sufficient lighting and appropriate acoustic conditions. The measurements of those physical factors are likely to provide insights into the thermal, visual and acoustic performances of the buildings but comfort can be evaluated only by the occupants (Baird, 2009; Baird et al., 2013).

One of the very few BSRTs that assess the environmental quality of the building once in operation, is the National Australian Built Environment Rating System⁸, which involves conducting a questionnaire survey of the building occupants. Two methods are recognised by NABERS for the survey: the Building Use Studies⁹, developed by the Usable Buildings organisation in London, UK and the one proposed by the Center for the Built Environment at the University of California, Berkeley, USA.

⁸ NABERS: National Australian Built Environment Rating System, <http://www.nabers.gov.au/>

⁹ BUS: Building Use Studies, <http://www.usablebuildings.co.uk/>

5.4.2. METHODOLOGY APPLIED TO ENERPOS

The aim here, using the Building Use Studies survey methodology, was to determine whether the occupants of ENERPOS recognised themselves to be comfortable and to identify modifications that would enhance comfort. The user survey was composed of a three-page questionnaire for the staff and a shorter one-page version for the students. Aspects investigated included building design, space, the image of the building, cleanliness, the availability of meeting rooms, storage capacity, the size of the offices, furniture, noise, thermal comfort depending on the seasons, productivity, health, control of heating, air conditioning, ventilation, lighting and the round trip journey from home to work. The vast majority of responses are on a 7-point scale, typically ranging from unsatisfactory to satisfactory or comfortable to uncomfortable.

Ten members of the staff and 127 students completed the questionnaires over a two-week period in April 2011. To obtain an overall view of the entire building, special care was taken to include students from all classrooms of the building.

5.4.3. USERS' PERCEPTION OF THE ENERPOS BUILDING

Overall responses: The average scores for each of the survey questions are listed in table 5-7. The number of staff working permanently in the building is relatively low (12 persons). Though all responded, given the relatively low number, the results should be interpreted with caution. For all of the interviewed staff, the building is their usual place of work. They work an average of 4.5 days per week in the ENERPOS building, 8 hours per day. Six persons were aged 30 and over, 5 had worked in the building for more than a year and 4 at the same desk or work area. The table also indicates those aspects of the building that the staff perceived as being significantly better, similar to, or worse than the benchmark and/or scale midpoint.

Overall, some 20 aspects were significantly better, 13 significantly worse, while the remaining 11 aspects had much the same score as the benchmark. The students' perception scores are also indicated in brackets. The student questionnaire includes only 14 variables. Of these 14 variables, 4 aspects (temperature, air, health and overall lighting) score significantly better than the benchmark, 7 significantly worse, while the remaining 3 aspects have approximately the same score.

Table 5-7. The ENERPOS building – Average staff scores for each factor and whether they were significantly better, similar to, or worse than the BUS Benchmarks (student scores in brackets).

	Score	Worse	Similar	Better		Score	Worse	Similar	Better
Operational factors									
Image (5.74)	6.2			•	Cleaning	4.8	•		
Space in building	5.6			•	Availability of meeting rooms	6.33			•
Space at desk: too little/much ⁴	4.9	•			Suitability storage arrangements	5.4			•
Furniture	5.8			•	Facilities meet requirements	5.2	•		
Environmental factors									
<i>Temp and air in winter</i>					<i>Temp and air in summer</i>				
Temp: overall (5.73)	4.86			•	Temp: overall	4.63			•
Temp: too hot / too cold ⁴	4.83	•			Temp: too hot/too cold ⁴	3.0	•		
Temp: stable / variable	4.2		•		Temp: stable/variable ⁴	3.75	•		
Air: still / draughty ⁴	5.0	•			Air: still/draughty ⁴	3.88		•	
Air: dry / humid ⁴	3.67		•		Air: dry/humid ⁴	4.63	•		
Air: fresh / stuffy ¹	2.6			•	Air: fresh/stuffy ¹	3.4			•
Air: odourless/smelly ¹	3.2		•		Air: odourless/smelly ¹	2.71			•
Air: overall (5.79)	5.0			•	Air: overall	5.33			•
<i>Lighting</i>					<i>Noise</i>				
Lighting: overall (5.39)	5.2		•		Noise: overall (4.42)	4.5		•	
Natural light: too little/much ⁴ (3.8)	4.2	•			From colleagues: too little/much ⁴	3.44	•		
Sun and sky glare: none/too much ¹ (3.41)	3.8		•		From other people: too little/much ⁴	3.89			•
Artificial light: too little/much ⁴ (3.8)	3.8	•			From inside: too little/much ⁴	3.56	•		
Artificial light glare: none/too much ¹ (2.58)	1.8			•	From outside: too little/much ⁴	4.44	•		
					Interruptions: none/frequent ¹	2.9			•
Control factors^b					Satisfactory factors				
Heating 0%	1.5	•			Design (5.74)	5.8			•
Cooling 25%	1.8	•			Needs (5.38)	5.78			•
Ventilation 50%	6.6			•	Comfort: overall (5.58)	5.6			•
Lighting 25%	6.4			•	Productivity % (+11.25)	+17.5			•
Noise 0%	3.7		•		Health (4.47)	4.22		•	

Notes:

(a) Unless otherwise noted, a score of 7 is 'best'; superscript 4 implies a score of 4 is best, superscript 1 implies a score of 1 is best.

(b) The per cent values listed here are the percentages of respondents who thought personal control of that aspect was important.

(c) Student scores are in brackets – the temperature and air scores cover all seasons.

Overall performance indices: Three indices have been used to assess the overall performance. These use standardised scores (also called z-scores) which put variables on a common scale with the mean equal to 0 and the standard deviation equal to 1. The Satisfaction Index, which is the average of the standardised scores for design, needs, health and productivity, is 0.65 for the staff and 0.57 for students. One notes that the midpoint on a -3 to +3 scale is zero. The Satisfaction Index is an indicator that shows whether people are pleased to work in this building. Overall, the staff and student indices indicate that both groups find the building to be satisfactory.

The Comfort Index is the average of the standardised scores for temperature in summer and winter, air in winter and summer, lighting, noise and overall comfort. This index is 0.57 for staff and 0.99 for students, showing that both groups find the environmental conditions comfortable. The Summary Index is the average of the Comfort and Satisfaction Indices, in this case, it was found to be 0.61 for the staff and 0.78 for the students. An additional forgiveness factor is a measure of tolerance, being the ratio of the score for overall comfort to the mean of the six other environmental variables. It is 1.14 (a factor of 1 being the midpoint on a scale that normally ranges from 0.5 to 1.5) for this building, which indicates that the staff is relatively tolerant of minor shortcomings in individual aspects such as changes in winter and summer temperatures (Baird 2010).

Figure 5-13 indicates the mean scores for the main overall variables for both staff and students. The green squares indicate scores that are better than the midpoint of the scale and the relevant benchmark (based on the scores for the previous 50 buildings surveyed), while an orange circle indicates a score that is not significantly different.

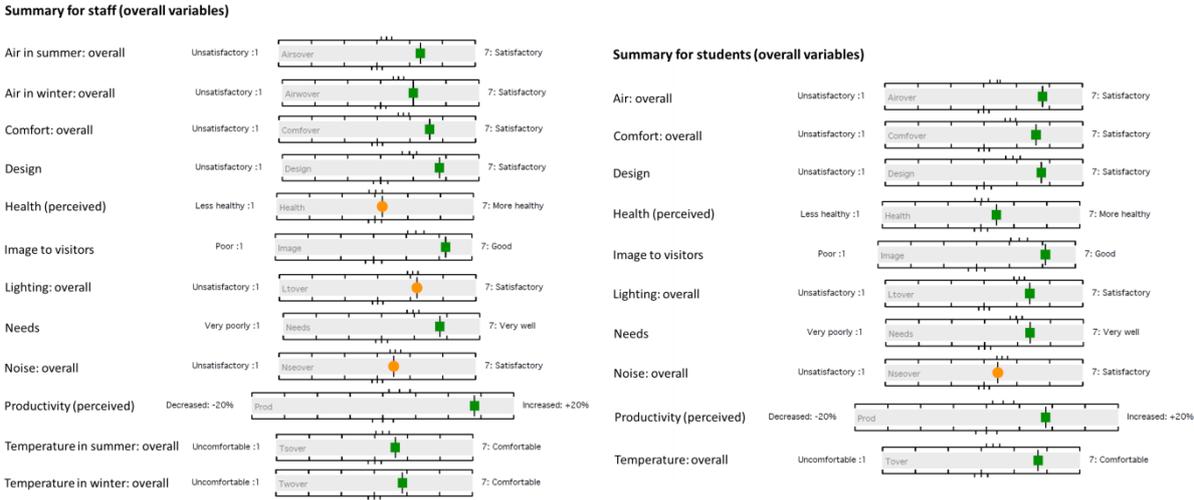


Figure 5-13. Overall variables for staff (left) and students (right).

Temperature: An average student score of 5.73 places the ENERPOS building at the 94th percentile (see figure 5-14) of the BUS benchmark. For the staff, there is very little difference in the scores for overall temperature between winter and summer (4.86 and 4.63, respectively). In both cases, the scores are significantly better than the average of other buildings surveyed so far. This is particularly encouraging, given that the air conditioning is not used in the classrooms and used rarely in the staff area (only 2 days during summer 2011). The passive cooling techniques rely on the use of natural cross ventilation by the occupants, thanks to the manual louvre windows and the ceiling fans. This building is therefore a positive example of what can be put into practice.

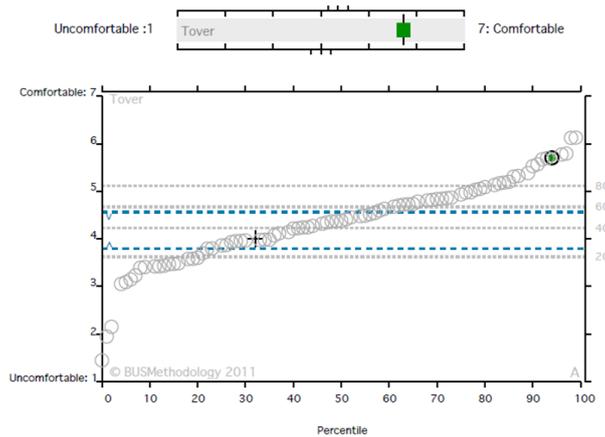


Figure 5-14. Temperature perception of the students.

Air: The staff scores for air overall were better than the benchmark in both winter and summer. The quality of the air was perceived to be odourless and fresh, relatively humid in summer and relatively dry in winter. However, one can note that during the winter, the building is particularly draughty. In any case, all the staff, even those who were reluctant at the beginning to work in a non-air-conditioned building, are very happy with their new environment and do not want to return to work in an air-conditioned building.

Noise: ENERPOS is an academic building where noise should be avoided so that students and staff can study and work in a pleasant environment. Particular attention should be given to this aspect because the building is naturally ventilated, thanks to a high number of openings. Therefore, noise could be a huge problem from one classroom to another, particularly during breaks thus increasing the acoustic discomfort of the occupants. In fact, for staff and students, the perception scores for overall noise were similar (4.50 and 4.42, respectively). In both cases, this score is within the lower limit of the average of the benchmark set for buildings.

Lighting: The perception of lighting in this building is highly dependent on the location of the room. In some rooms, the light is too bright to use a video projector, while in other rooms, it is slightly dark. Similarly, glare can be experienced at specific times (early in the morning or at sunset) in some rooms while in other rooms there is no problem of glare. As for artificial lighting, users do not complain about the glare effect. This is most likely because the artificial lighting is practically unused. During the construction of the building, special attention was given to maximizing the use of daylight. In addition, the building is equipped with type T-8 low-energy lamps that use indirect lighting (that dazzle less than conventional lighting). As a result, the ENERPOS building performs extremely well in relation to glare caused by artificial lights (see figure 5-15). Glare from the sun and sky scores approximately the average of the benchmark. This source of glare is mitigated by exterior wooden, large, solar blinds installed on the north and south façades.

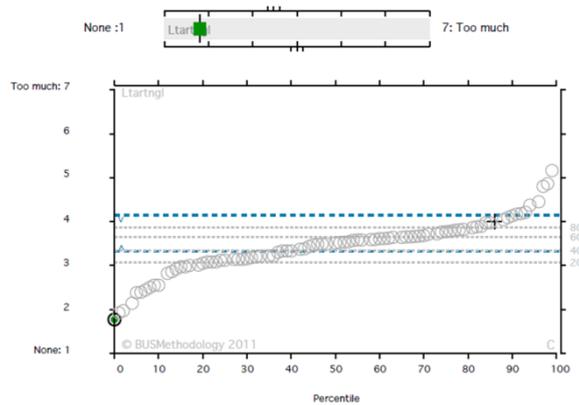


Figure 5-15. Glare from artificial lights (staff score).

Controls: The more people have the capacity to control their environment (light, ventilation, and temperature) the more comfortable they feel. Not surprisingly, 80% of the staff feel that they have no control on the air conditioning of their workspace. This percentage is important because air conditioning is not used in the offices. The same comment applies to heating control, 88% of the staff feel they have no control over it, as there is none in the offices. The climate of Reunion Island is tropical, the temperature in winter is pleasant and heating is not required.

Ventilation and lighting controls are the two highest rated parameters of the POE. Users have two options at their disposal to influence ventilation: manual control of the louvres and ceiling fans. Efficient ceiling fans were installed in each office to ensure the comfort of users in case the natural ventilation is not sufficient. Each ceiling fan covers an area of 10 square metres. As a consequence, in the offices, the staff members have their own ceiling fan which ensures individual control. This explains the high scores given by users (see figure 5-16). As for solar shading, large, fixed, wooden blinds were installed on the outside façades of each block. The users cannot control the blinds but they can control the artificial lighting (figure 5-16).

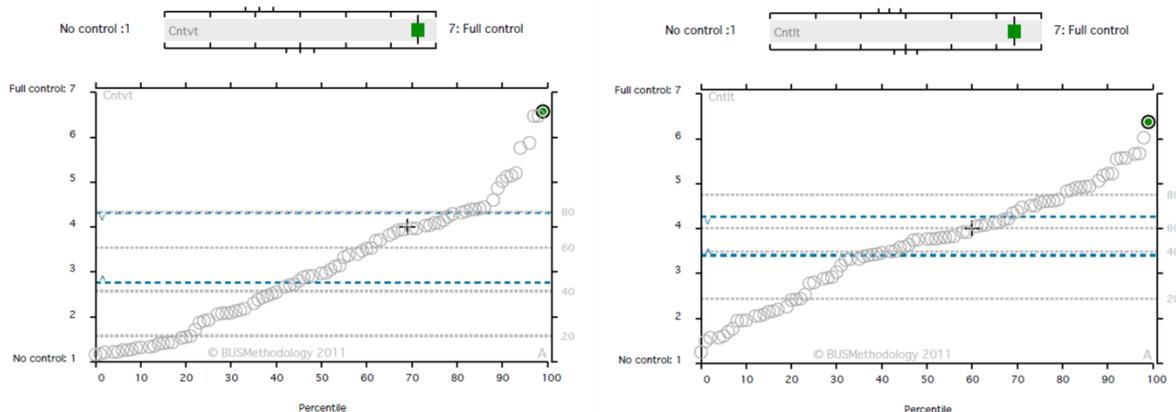


Figure 5-16. Control over ventilation (left) and over lighting (right).

Image given to visitors and occupant needs: For the staff, their perception of the image that the building gives the visitor scores 6.2 on average, with the student score of 5.74. For the needs category, the rating given by the staff is 5.78, which is well above the benchmark. Scores better than benchmark scores were also achieved for the space in the building (5.6), furniture (5.8), meeting rooms (6.33) and storage (5.4).

Perceived productivity and health: Productivity is generally better than the benchmark figure with averages of +11.25% for students and +17.5% for the staff. This places the ENERPOS building within the top 10% of the benchmark set. All the interviewed people have experienced an improvement in their productivity. As for the health, the results are rather high because they reach 4.22 for staff and 4.47 for students, which is the upper limit of the benchmark for staff and above the benchmark for students. The most recurrent comments concerning the health issue are dry eyes due to natural ventilation.

Journey to work: In determining the environmental performance of a building, a factor often overlooked is the method of transportation from home to the work place. Indeed, a building can be ecologically efficient but if the only way to reach it is by plane or helicopter, it loses all its environmental performances. It is therefore interesting to study this parameter. On that score, this building performs less well. The average travel time between home and work is 39 minutes. The majority of people surveyed (71%) stated that they come to work alone in their car, a rather discouraging result. This is also due to the lack of efficient public transportation facilities on the island that do not encourage people to leave their car at home.

User comments: The comments from users indicate they are generally satisfied with their workspace. Interesting requests have been submitted through this questionnaire, for example, the desire to have a bike park or a shower in the building. As construction work was in progress near the building during the survey, comments on this point were registered and also about the noise generated by the maintenance of the garden (principally the discomfort due to noise of the lawnmower). Of the 52+ comments from the students, only 8 concerned health and ventilation. The most frequent comments concerned the noise generated by other students during class breaks or when they move near their classrooms.

5.4.4. CONCLUSIONS OF THE POE CONDUCTED IN ENERPOS

This study shows that the people surveyed were satisfied overall with their work environment. The total score given by the building is 6 out of 7, which is a very high performance. This corresponds to the Good Practice rate. ENERPOS showed that a building can reduce its energy consumption significantly and thus its environmental impact while maintaining a good level of comfort for its users. Indeed, the study showed that this building is generally rated higher than others in the BUS benchmark set. This building serves as a suitable example for new projects in tropical climates. It demonstrates that even an academic building can achieve comfortable conditions for its occupants by enabling them to use passive methods (natural ventilation, daylight) rather than energy-consuming systems such as air conditioning.

5.5. LESSONS LEARNED FROM THE ENERPOS BUILDING

5.5.1. LESSONS LEARNED FROM THE BUILDING MANAGEMENT SYSTEM

The Building Management System (BMS) of ENERPOS is presented in Appendix A - . The building has been monitored since January 2010. An eighteen-month period was necessary after completion to achieve a proper monitoring system. Numerous technical issues emerged when the building was terminated and had to be solved so that the final result could live up to all original expectations.

Electrical wiring: The energy consumption of ENERPOS was to be measured by type of end-uses. But when the electrical wiring of the building was double checked after completion, it was noticed that the lights of the exterior walkways were wired to the energy metre measuring the interior lighting consumption. As a consequence, the lighting wiring was modified. It was also noticed that the energy supply for the BMS was wired to the energy metre measuring the consumption of ceiling fans. However, it was not possible to modify the wiring for the BMS and this is still the case currently. The power demand for the BMS has been estimated at 10 to 15 W and this value should be subtracted from the overall measurements of the ceiling fans' energy metre.

The accuracy of the energy metres: The Special Technical Terms of Reference of ENERPOS was not precise enough with regard to the specific requirements for the BMS. As a consequence, the energy metres that were installed during the construction work emitted a pulse every 10 kWh, for instance, at least two and a half days would have been necessary to emit one pulse for the energy use of the ceiling fans. Knowing that the monitored data are recorded every minute, this precision was not satisfactory. All energy metres were replaced with new energy metres communicating via the Modbus protocol with 10 pulses every kWh.

The COP of the air conditioning system: The COP of the air conditioning system was supposed to be measured through energy monitoring. However, because the air conditioning has not been used for more than 5 days in 3 years, there is no COP value available with the BMS.

The measuring time: During the design stage, the option of a data collection frequency of a minute was taken; however, after one year of measurements, it was noticed that such a short time step was not particularly useful to obtain satisfactory knowledge of the energy balance of the building. Moreover, the huge amount of data creates communication problems with the monitoring system and the database resulting in loss of data because the system had switched itself off. To operate correctly, the system should be checked almost every day and this is not viable for large spread applications. In order to simplify the data processing, data were gathered every 10 minutes; therefore, the measuring frequency has been increased from 1 to 10 minutes during the update of the BMS in January 2013.

5.5.2. LESSONS LEARNED BY END-USES

INTERIOR LIGHTING

Figure 5-17 gives the interior lighting power density for September 2010. We can note a peak between 5 and 6 a.m. which is outside of work hours. This is due to housekeeping that was done early in the morning. The housekeepers were lighting all the office and classroom lights for one hour. This

consumption is the highest of the day because the building was designed to use daylighting during work hours so that the artificial lighting would not be necessary.

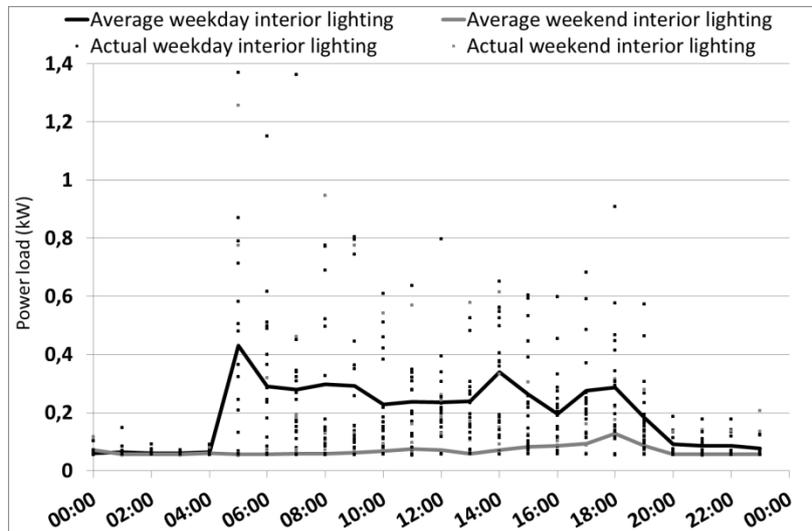


Figure 5-17. Interior lighting power density for September 2010.

The lighting consumption due to housekeeping was also noticed in other Net ZEBs. At the NREL Research Support Facility in Golden (Colorado), the same problem was noted, when the cleaning was taking place after 5 p.m. and the housekeeping staff lit all the offices when working (Pless et al., 2011). During the first months, they were not sensitized to the energy performance of the building and they did not turn off the lights when leaving a space. Fortunately, there is a two-hour time delay for the lighting, coupled with presence detectors, so the lighting switched itself off after two hours, but the consumption of the lighting was still higher than predicted during simulations. When the building manager noticed this fact, he asked the housekeeping staff to turn off the lights after the cleaning was over. The energy consumed for lighting after 5 p.m. in the following months decreased.

Another example is the Elithis Tower, a Net ZEB in Dijon, France, which has a window-to-wall ratio of 80%; therefore daylight contributed considerably to decrease the energy use of the building. The consumption due to housekeeping was anticipated and it was decided during the design that it would be carried out at lunch time to avoid the use of artificial lighting for cleaning.

PLUG LOADS

Results obtained from the monitoring system: figure 5-18 gives the power density of the plug loads of the building for March 2011. An inventory of equipment plugged into the electrical outlets of the 7 offices and the meeting room was completed in May 2011 and is provided in table a- 3.

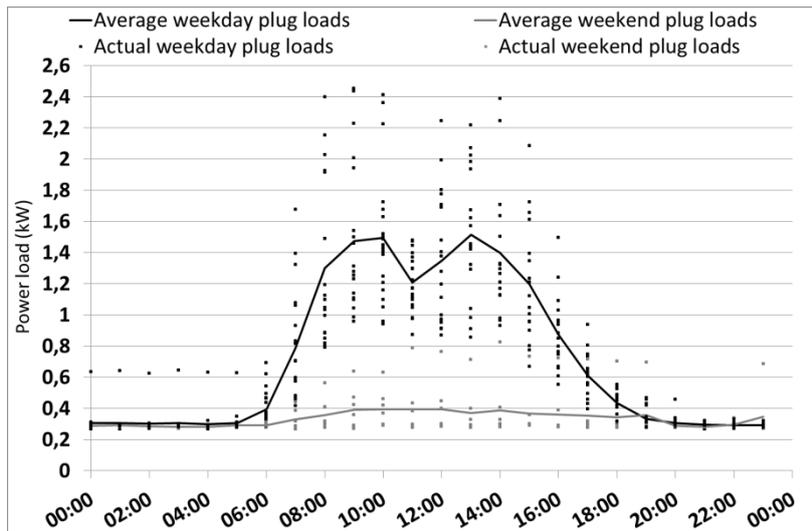


Figure 5-18. The power density for the plug loads for March 2011.

It is noteworthy that the power due to the plug loads during nights and weekends remain close to 0.3 kW. Measurements were run on the systems connected to the plug loads to know where this stand-by load came from.

Measurements carried out on the equipment used in the building: To have an accurate idea of the energy consumed by the plug loads of ENERPOS, a certain amount of measurements were launched on several appliances. Figure 5-19 provides a comparison of the loads of a desktop and a laptop computer. It gives the mean value of measurements over seven working days as well as the maximum value for both. When in use, the desktop has a mean load of about 60 W whereas the laptop's power is approximately 30 W. This load depends on the use of the computer and it varies greatly as can be seen from the curves representing the maximum load of both (approximately 100 W for the desktop and 60 W for the laptop). These values are lower than the ones that were used during the design to predict the energy consumption of the building (130 W for a desktop and 80 W for a laptop).

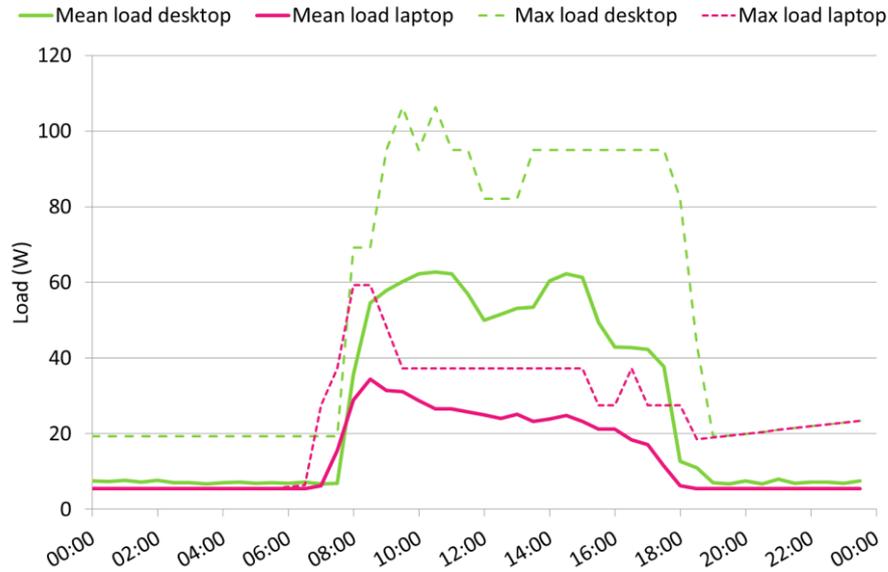


Figure 5-19. Mean and max load measurements for a desktop and a laptop computer for 7 days.

CEILING FANS

During the design, it was assumed that the ceiling fans would be used from November to April, 8 hours per day with a diversity factor of 0.3; the diversity factor takes into account the fact that all the ceiling fans are not used at the same time and not with their maximum power (Lenoir et al., 2011). The total load of the ceiling fans in the building is 3.8 kW. This gave an energy index during design of 1.6 kWh/m².y. A close examination of table 5-4 shows that the measured energy ratio for ceiling fans is also 1.6 kWh/m².y. The assumptions made about the operation of the ceiling fans during the design can be checked against the real data. Firstly, figure 5-20 gives the monthly energy consumption of the ceiling fans. This curve shows that the ceiling fans are indeed used from November until April. Figure 5-21 gives the average power load for ceiling fans during weekdays and weekends of March (the month that had the higher energy use for ceiling fans). It is to be noted that the ceiling fans are used from 8 a.m. until 5 p.m. (9 hours per day). That is the assumption that was made during the design, except that it was assumed users would turn off the ceiling fans during lunch break. Looking at the curve, it can be seen that the load decreases just a little at midday, meaning that users do not automatically turn off ceiling fans when they leave the room. Concerning the diversity factor, it is possible to assess that the value of 0.3 was a correct assumption, given that on average the power load of the ceiling fans is 1.2 kW when they are used, for a total load of 3.8 kW in the building. The value of 0.3 is therefore rather accurate.

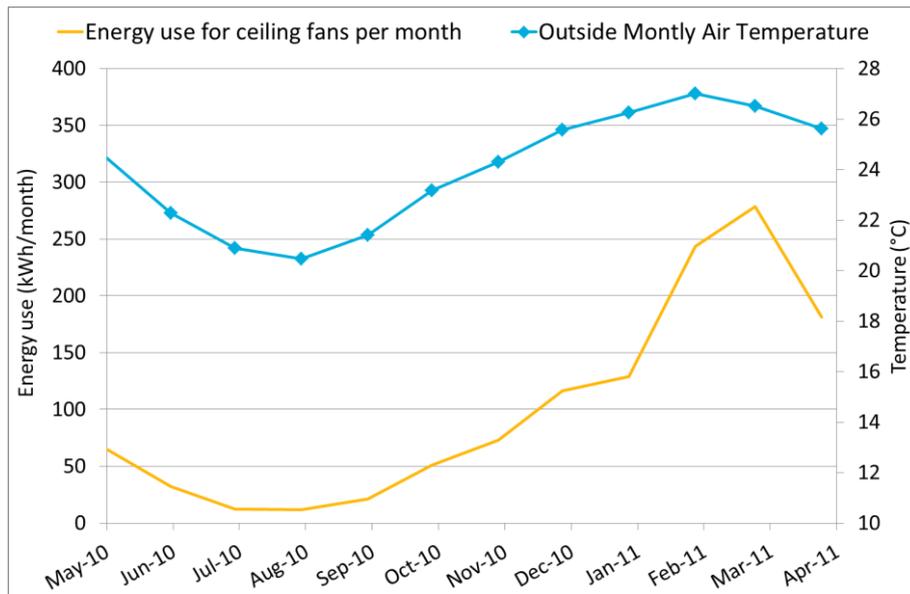


Figure 5-20. Monthly energy use for ceiling fans from May 2010 until April 2011 and mean outside monthly air temperature.

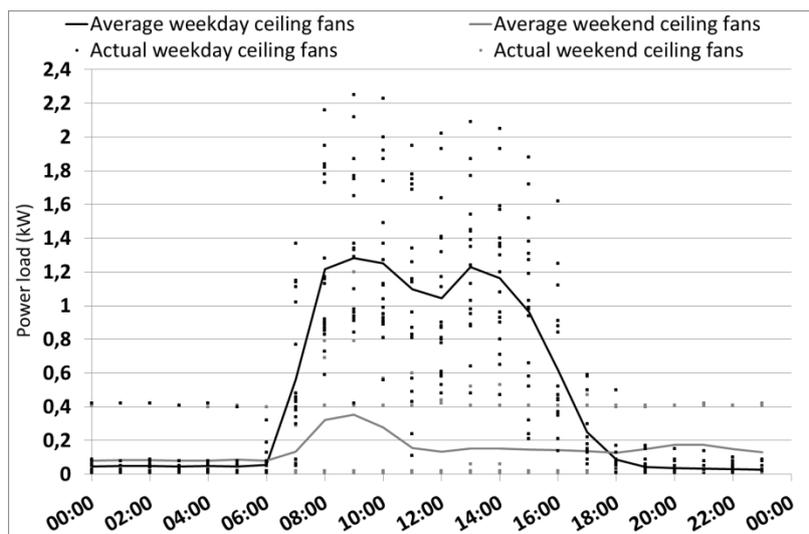


Figure 5-21. The power density of the ceiling fans for March 2011.

LIFT

The energy monitoring system was put into service in January 2010 and since this date it has been observed that the consumption of the lift accounted for approximately 13% of the overall energy use of the building (which represents a monthly energy index of 120 kWh/m²_{NFA}). All the inside lights were found to be constantly turned on even when the lift was closed and empty. Therefore, when the maintenance of the lift was carried out in May 2010, the service engineer was asked to turn on the standby mode of the lift. This measure led to a reduction of fifty per cent of the energy used by the lift and its monthly energy index dropped to 55 kWh/m²_{NFA}.

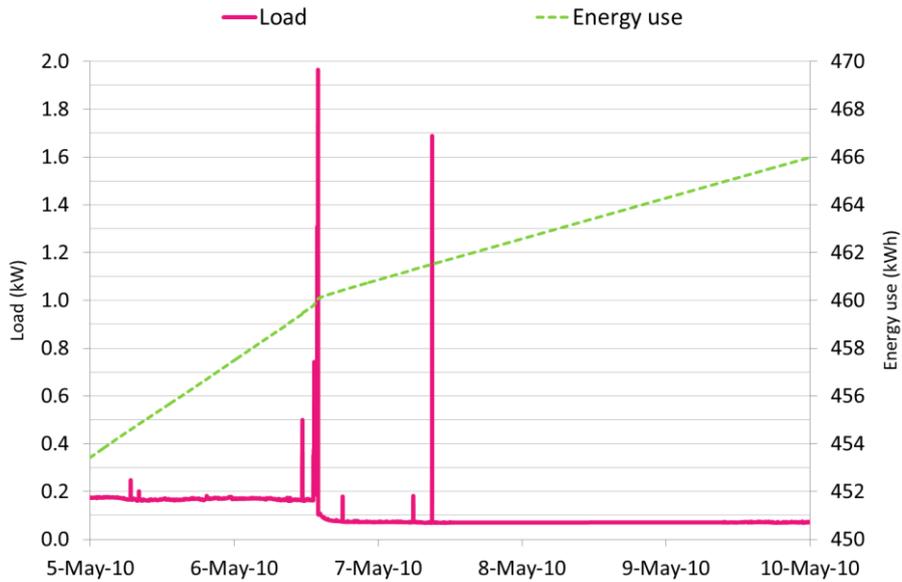


Figure 5-22. Load and energy used by the lift before and after the standby mode was set up.

Figure 5-22 depicts the load curve and the energy used by the lift for a few days in May 2010. The maintenance was carried out on May 6th 2010 and this is clearly visible on the load curve of the lift: its power switched from 170 W to 70 W. The change in the slope of the energy consumption is clearly visible after the intervention.

It can be seen that the different peaks (on the load curve), that seem to be caused by the use of the lift, do not reach the same height. A 200 W peak does not represent the use of the lift, this power seems to be too low. It can be explained by the fact that the one-minute time step for the measurements is too long to be able to measure the power of the lift when used.

The load curve of the lift also indicates the fact that it is actually used less than once a day (mainly by the cleaning staff). In this way, it is possible to calculate the annual energy use of the lift. Between May 2010 and April 2011, the measurement of the energy consumption of the lift is 623.3 kWh/y.

Taking into account only the power due to the standby mode, about 70 W, the total number hours of the year, i.e. 365 days × 24 hours = 8,760 hours, we find a consumption value of 613.3 kWh/y which is very close to the measured value.

It can therefore be concluded that the energy use of the lift is practically only due to the standby mode power of the equipment, and not due to its real use (less than 2% of the total energy consumption is due to the use of the lift).

AIR CONDITIONING

As observed during the three summer seasons, the air conditioning in offices was practically not used at all (less than 1 week/year). A thermal comfort study was carried out with surveys for the users of

the building and they responded they were feeling comfortable nearly all year long only with natural ventilation and ceiling fans (Lenoir et al., 2011).

Figure 5-6 shows that the overall consumption due to air conditioning represents 15% of the energy use of ENERPOS (2.2 kWh/m².y), of which the VRV represents 2.5% (20 kWh/month), the ATU represents 0% (it has not been turned on during the year); the ceiling cassette units represents 8% (68 kWh/month) and the split systems represent 8% (only the 700 W split system was on because only one technical room houses switchgear cubicles, the other technical room is empty).

Because air conditioning has only been used for two single days from May 2010 until April 2011, its consumption should be close to zero. Yet, the VRV group and the ceiling cassette units represent more than 10% of the overall energy use of the building. In fact, it was discovered that the small display screens installed in the offices and computer rooms have a power of 3 W each, which add up to 20 kWh/month. The consumption due to the ventilation (ceiling cassette units) has no satisfactory explanation. It seems that the Building Management System does not turn off the ventilation units even when the VRV group is not in operation.

The points mentioned in relation to air conditioning highlight the importance of a reliable monitoring system in a high performance building. Indeed, while air conditioning is not useful in ENERPOS, its energy use still represents about 10% of the overall consumption of the building. The only solution found to avoid this consumption was to switch off the circuits of the VRV group, ATU and ventilation on the general electrical panel.

BUILDING MANAGEMENT SYSTEM

The consumption due to the building management system has also been measured. Its power load fluctuates from 10 and 18 W with an average of 13.7 W. The energy index of the building management system is approximately 0.2 kWh/m².y (NFA). It represents less than 2% of the overall energy used by ENERPOS.

5.5.3. POSSIBLE IMPROVEMENTS IN ENERPOS

The first year of occupancy of a building is particularly critical as discomfort issues of the users can appear as well as problems related to energy consumption. The ENERPOS building is used as an example to demonstrate the improvements that can be achieved with the analysis of the monitoring results. The results presented in this paragraph correspond to the first year of occupancy of the building. It is possible with this analysis to improve the energy use of the building as well as occupant comfort. The improvements that were realized, that are planned, or that would be interesting to carry out are presented in this section.

CEILING FANS

As a result of measurements conducted of the performance of ceiling fans, it was proven that the centralised controls lead to a lower air speed in the classrooms than when the ceiling fans are controlled individually (in the offices). It would be interesting to modify the wiring of the ceiling fans in the classrooms in order to have individual control of each ceiling fan.

The ceiling fans remain on sometimes in empty classrooms and offices which represents an unnecessary over-consumption. For instance, in February 2012, this over-consumption was estimated at 41 kWh which represents 13% of the monthly energy used by ceiling fans in the building. It would be efficient to wire a two-hour timer (corresponding to the course duration) at least in the classrooms. This measure would have saved approximately 32 kWh in February 2012.

DAYLIGHTING

Another improvement could be made to the interior lighting switches of the classrooms. Daylighting measurements showed that three parallel areas can be defined: the daylighting is very efficient near the windows overlooking the exterior (above 500 Lux during the hours of occupancy), slightly weaker in the middle (below 300 Lux during a few hours per day) and even weaker on the side of the windows overlooking the other part of the building (below 300 Lux several hours per day). To light only the darker part (or parts) of the classrooms and thus to optimise the lighting consumption, three different circuits should be installed for the three rows of light fittings.

AIR CONDITIONING

In paragraph 5.5.2, the problem of the standby power consumption of the air conditioning system was raised. This over-consumption is estimated as 65 kWh/month. By switching off the circuits of the VRV group, ATU and ventilation on the general electrical panel, around 780 kWh/y can be saved, which represents approximately 10% of the overall energy used by the building.

IMPLEMENTATION OF ALARMS AND SAFEGUARDS

The way forward for this study would be to set up a series of alarms so that the building manager can notice an over-consumption of the building quickly and thus intervene rapidly. Maximum values by end-uses could be defined, taking the usage period and the occupancy of the building into account. Several values should be tested in order to have a reliable and relevant system.

5.5.4. CONSIDERATION OF THE ECONOMIC ASPECTS

Building developers focus most of the time on the initial investment costs but they do not think in terms of overall cost, i.e. the cost throughout the building lifespan.

In the case of ENERPOS, the building cost was 9% higher compared to a standard building. In terms of euros per square metres of gross floor area, ENERPOS has cost approximately 1650 €/m²_{GFA} whereas a standard building cost is approximately 1500 €/m²_{GFA}.

The operating cost of a standard building is 18.4 €/m².y. That includes the cost of the energy consumed, the power subscription to the French public utility (which is 80 €/kW.y) and the cost of maintaining HVAC systems, which is 6 €/m² at the University of Reunion Island. For ENERPOS, the operating cost only reaches 3.7 €/m².y. The roof of ENERPOS is rented at 1,300 €/y for 15 years by a private company that installed the PV cells. The payback period for the incremental investment made on ENERPOS building is estimated to be 9.7 years. Compared to the lifespan of the building, estimated at 50 years, this represents an attractive return on investment.

Compared to a standard building at the University, ENERPOS allows 64,000 kWh of electricity to be saved every year. If the PV production is included, the savings represent approximately 133,000 kWh per year. In terms of greenhouse gas emissions, this corresponds to 110 tonnes of CO₂ equivalent annually, or a car journey twelve times around the world.

Table 5-8. Calculation of the payback time of the ENERPOS building taking into account the incremental investment and operation costs.

	ENERPOS	Standard Building	Cost difference
Investment Costs	1650 €/m ² _{GFA}	1500 €/m ² _{GFA}	+150 €/m²_{GFA}
Operation Costs			
Consumption <i>0.1 €/kWh</i>	14 kWh/m ² _{NFA} .y	100 kWh/m ² _{NFA} .y	- 86 kWh/m ² .y -8.6 €/m ² .y
Power subscription <i>80 €/kW.y</i>	0.3 W/m ²	30 W/m ²	26 W/m ² - 2 €/m ² .y
Maintenance of HVAC systems <i>Data provided by the University</i>	2.0 €/m ²	6.0 €/m ²	-4.0 €/m ² .y
Total Operation Costs	3.7 €/m ² .y	18.4 €/m ² .y	-14.7 €/m².y
PV roof rental at ENERPOS	1300 €/y <i>(for 15 years)</i>	∅	+1.8 €/m².y
Payback time			9.7 years

The conclusion of this brief analysis is that it is worth investing in buildings such as ENERPOS for both economic and environmental reasons. The payback time of the incremental investment is particularly interesting compared to the lifetime of the building.

In the framework of the IEA Task 40, four levels of monitoring have been defined. The example of ENERPOS has shown the type of analysis that was possible to complete for each level of monitoring.

As a conclusion, the ENERPOS building provides living proof that with the current technologies and an extra investment cost of 9%, it is possible for a building to use seven times less energy than a standard building and produce seven times its own consumption. But a Net ZEB should not only have a very low energy use, it must also be comfortable for its occupants. To assess the comfort level of ENERPOS, a post-occupancy evaluation was conducted on the users of the building, including the staff working in the administration zone and students that use the classrooms. The users were satisfied overall with their work environment. ENERPOS has thus proven that a building can reduce its energy consumption and its environmental impact significantly while maintaining an acceptable level of comfort for its users.

In general, the performances of the building far exceeded the expectations during the design. But some improvements are still possible to further decrease the energy use of the building. Indeed most of these improvements depend largely on the building occupants. The success of the process is to inculcate active behaviour of people in passive buildings instead of passive behaviour of people in active buildings. To achieve this, people need to be educated and ready to make behavioural changes to achieve greater energy savings and environmental benefits.



CONCLUSION AND PERSPECTIVES

Reunion Island is an experimental laboratory for the Indian Ocean region as well as all intertropical zones with similar climate. The economic power of the island offers the opportunity to consider ambitious research programmes, particularly within the field of energy management and conservation. Those have to be part of a sustainable development impetus that can suit both developed and developing countries. The research presented in this PhD thesis has been carried with this perspective in mind.

The aim of this thesis was to propose a suitable methodology for the design and operation of net zero energy buildings in tropical climates. Although energy efficiency and conservation are essential when dealing with net zero energy buildings, we chose to focus on the challenges associated with the users of passive buildings. This choice has been motivated by the fact that a passive building acts as a filter between the outside conditions imposed by the weather and the indoor conditions that need to be comfortable for the occupants. As long as the building offers favourable thermal and visual comfort, energy-consuming systems such as air conditioning or artificial lighting are not required. The study of occupant comfort is therefore essential when it comes to the design of such buildings, and tools and methods to assess comfort depending on the indoor conditions are needed. However, comfort remains a subjective concept that is distinctive for each individual and verification measures such as questioning the users about their sensations must be undertaken. It was with this objective in mind that different approaches to thermal and visual comfort are presented in chapter 2.

With regard to thermal comfort, the conventional static standards, for example the PMV, are not adapted to the tropical climate and especially to non-air-conditioned (or passive) buildings, where conditions are dynamic and follow the changes in the external environment. Instead of being affected by the conditions of the immediate environment, the occupant responds by adapting to this environment. This adaptation is expressed by feedback loops, such as behavioural responses, acclimatisation factors, or occupant expectations that are implemented in a situation of discomfort. Between the optimum thermal comfort conditions specified by static models and a situation described as uncomfortable, a significant opportunity for adaptation may be found. Having reviewed several approaches to thermal comfort, we finally agreed upon the comfort zones defined by Givoni. This choice was made because it is adapted to tropical climates and it takes into account the air speed

which allows the body to cool itself. The comfort zones of Givoni are already commonly used amongst the design offices of Reunion Island to investigate thermal comfort. In order to verify and improve the comfort zones for Reunion Island, a field study was conducted on the ENERPOS building in Reunion Island over three summer seasons. This survey constitutes the first field study of thermal comfort conditions in a net zero energy building in a tropical climate. The results were compared with the comfort zone proposed by Givoni for a naturally and mechanically ventilated building. It is important to be aware that even though this study was carried out on a particular sample (only one typology of building, a university building and thus with a young population composed mostly of students), interesting lessons can be drawn from the results. This reveals that the comfort zones defined by Givoni can be slightly extended in terms of high humidity levels but that the temperature should be kept below 30°C which is a critical limit for thermal comfort even when the building is naturally ventilated and when ceiling fans are available for the users. Suggesting this new comfort zone will enable those involved to further optimise the design of the envelope of passive buildings in Reunion Island.

An innovative methodology using simulations and taking the passive behaviour of the building into account, as opposed to the conventional approach with regard to the energy use, was proposed in this thesis to facilitate the optimisation of the design of passive buildings. A passive building in tropical conditions must fulfil two main principles: efficient natural cross ventilation and adequate solar protection. We chose to concentrate the study on the design of solar shading as this plays an extensive role in tropical climates and has a direct impact on the thermal and visual comfort of the building users. The outputs of the model were defined as the percentage of thermal comfort, in relation to the natural and mechanical ventilation comfort zone defined in chapter 3, and the daylight autonomy or the useful daylight index. Parametric studies on the type and dimensions of the solar shades have been carried out with regard to their impact on the percentage of thermal comfort and the availability of daylighting in the room. The methodology has been applied to a typical single-window office and a naturally cross ventilated classroom. The results showed that when solar shading is added, thermal comfort increases at the outset while having an impact on visual comfort which subsequently decreases. Once a certain length of solar shade is reached, the daylight availability drops off rapidly. It is therefore important to apply such a methodology in the design of future passive buildings in order to make appropriate compromises to limit the sources of thermal and visual discomfort.

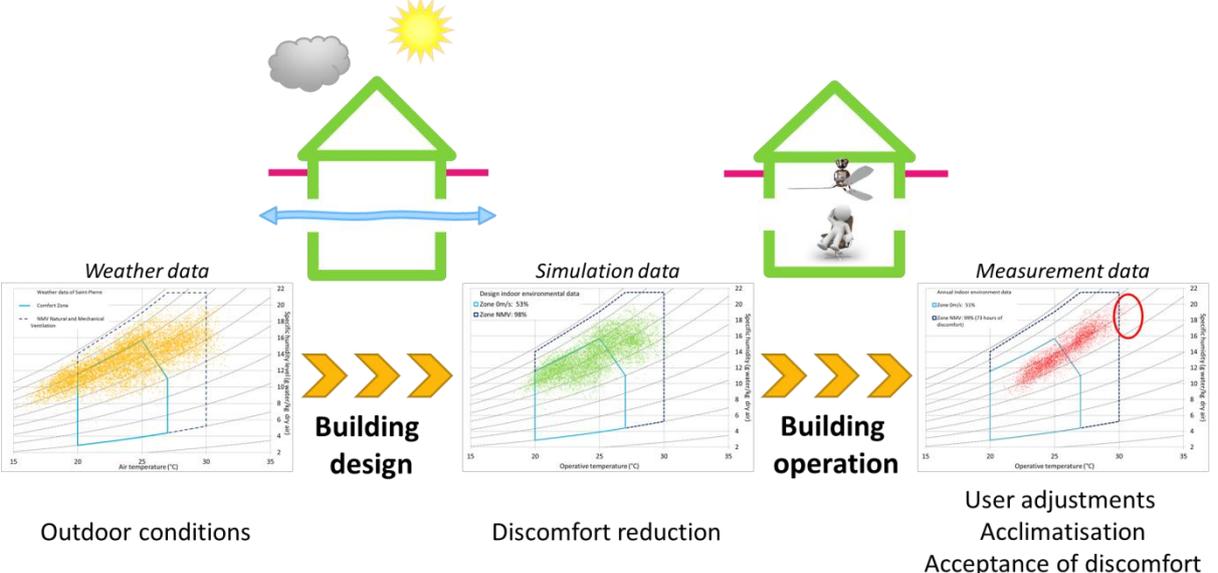
Although the design phase aims to optimise the building to limit both discomfort and energy consumption, the operation of the building remains the critical phase that is often neglected or overlooked by design teams. The last chapter of this thesis proposes an examination of the operation phase of the ENERPOS building, the case study of a net zero energy building in Reunion Island, from both energy and users' point of view. To date, little work has been done in this field and this thesis constitutes a contribution to an extensive assessment of the performance of a building. Within the framework of the IEA Task40/Annex 52, four levels of monitoring have been defined based on the database of the 30 Net ZEBs analysed during the project. Firstly, the results for each of the four levels are developed for the ENERPOS building with the degree of analysis that is possible to provide for each of them. Secondly, in order to obtain feedback on the building from the users, a post-occupancy evaluation was carried out. The aim was to determine whether the occupants of ENERPOS recognised themselves as being comfortable and to identify modifications that will enhance comfort. This study showed that the people surveyed were in general satisfied with their work environment. ENERPOS therefore proves that a building can significantly reduce its energy consumption – approximately 7

times less than a standard university building in Reunion Island – and thus its environmental impact while maintaining an acceptable level of comfort for its users.

The example of ENERPOS also provides an opportunity to question the definition of a Net ZEB in a tropical climate. According to the generally accepted definition, a Net ZEB is a low-energy building that balances its low-energy consumption using on-site renewable energy on an annual basis. However, in tropical climates, the energy consumption and production are usually synchronized. The balancing period can be reduced to one week or even to one day. It has been proven that ENERPOS balances its own energy use on a daily basis.

The general comfort approach that we are putting forward in this PhD thesis can be summarised as presented in the figure shown below. First and foremost, the climate of the location and the comfort conditions of the building type must be studied. Ideally, the envelope of the building is designed to provide comfortable indoor conditions all-year-round, whatever the outdoor weather conditions may be. In practice, this target is not always achievable because, on the one hand, at certain times of the year, the weather conditions are too remote from the possible comfort conditions, and, on the other hand, comfort is a very personal experience that is unique to each individual. During the design of the building, the aim is thus to reduce the sources of discomfort as far as possible by optimising the passive behaviour of the building. Then, during the operation phase, users have to be able to make adjustments to reach their own comfort conditions. Finally, the users may acclimatise to their environment or accept that discomfort can occur at certain times of the year.

Whatever the intended objectives in terms of energy efficiency, it is fundamental to remember that the users must be at the very heart of the process during both the design and the operation of the building. A sustainable building should work with the users, and not against them.



Following this research, other thermal comfort surveys could be conducted in other types of building, in other tropical areas and involving individuals of different ages than those covered in this thesis. The study of thermal comfort remains fundamental when designing passive buildings, particularly in tropical climates. In our work, visual comfort was approached by the availability of interior daylighting. However, further studies should be carried out on this topic, especially on the glare effect and on the user behaviour with regard to electrical lighting depending on daylight conditions.

Concerning the use of simulation in building design, the trend is moving towards co-simulation platforms integrating all aspects of a building such as thermal design, airflow, daylight, acoustics, energy, economic aspects, life cycle analysis along with others. During the operation of the building, the model would integrate indoor and outdoor measurements as well as weather forecasting, to control the equipment and the systems in real time. In this context, the optimisation should be carried out not only with regard to energy use but through the application of a multi-physics approach.

In terms of general perspectives, questions can be raised concerning the scale of the net zero concept. At the energy level, the building itself cannot be considered the correct scale and the approach should be extended to the neighbourhood scale. For instance, ENERPOS produces approximately 7 times its own energy use with the BIPV roofs, which is not useful in itself, except to ensure that the building is net zero on a daily basis. The amount of surplus energy that the building exports must be managed to ensure that the grid remains stable. One needs to consider this aspect at a neighbourhood scale with different building typologies that use energy at different times of the day. Several buildings should be able to interact with each other in terms of energy consumption, production and storage systems, like a smart grid. Moreover, in terms of passive design, the building shape, the orientation and the surroundings need to correspond to the use of natural ventilation. The post-occupancy evaluation conducted on ENERPOS showed that thermal comfort achieved thanks to natural ventilation can lead to acoustic discomfort or problems related to air pollution and dust in inappropriate surroundings. To reduce these risks and to be able to design naturally ventilated buildings, the environment must be adapted and this reflection has to be extended to the neighbourhood scale by limiting for instance the traffic in the vicinity of the buildings.

The scales of reflection can be brought even further to those of the territory in the case of Reunion Island. To achieve energy self-sufficiency by 2030, a determined effort must be undertaken in order to reduce the overall energy demand of the island. As it has been illustrated in the energy policy pyramid, the priority must be given to the design and the energy efficiency of buildings with the aim of reducing the energy use. Therefore renewable energy systems should only be incorporated afterwards as an additional enhancing feature.

Appendix

A

CASE STUDY: THE ENERPOS BUILDING

The ENERPOS building is the first zero energy building of the French overseas departments. On a wider scale, it is the single educational Net ZEB that has been listed for tropical climates within the framework of the IEA SHC Task 40 / ECBCS Annex 52 "Towards Net Zero Solar Energy Buildings" (IEA, 2008).

The building was inaugurated in January 2009 and is located in the University Institute of Technology (IUT) of Saint-Pierre (in the south of the island). The two-storey building is split into two parallel blocks separated by a green patio. The blocks are composed of an administration zone on the ground floor (seven offices and a meeting room), two computer rooms and five classrooms for a net floor area of 681m².

Table A- 1. Building team of the ENERPOS building.

Building owner / Representative	University of Reunion Island
Architect	Thierry Faessel-Boehe
General Contractor	Léon Grosse
Mechanical, Electrical Engineer	INSET
Energy Modeler	PIMENT Laboratory and Imageen
Lighting Design	Imageen
Structural Engineer	RTI
Environmental Consultant	TRIBU Paris



Technical data:
 Net Floor Area: 739 m²
 Gross Floor Area: 1,425 m²
 Conditioned Area: 246 m² (33% of the NFA)
 2 buildings – 2 floors
 PV: 365m² - 50 kWp
 Construction completion: July 2008
 Cost: 3,200€/m²_{NFA} – 1,660€/m²_{GFA}

Figure A- 1. Picture of the south facade and west gables of ENERPOS (picture credits: Jerome Balleydier).

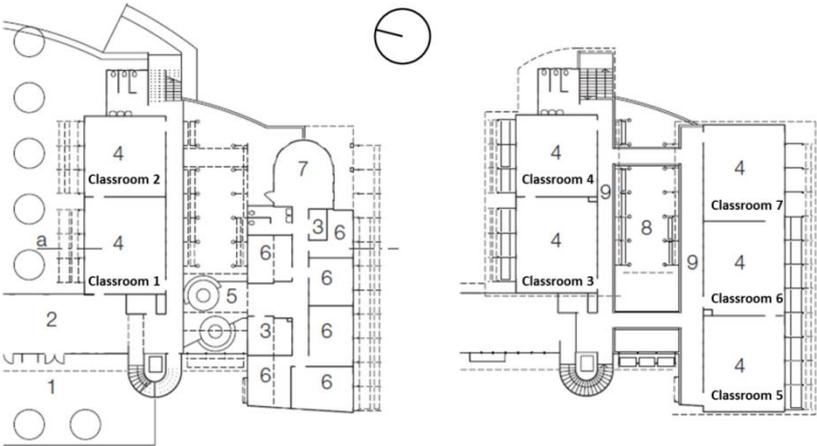


Figure A- 2. Plan view of ENERPOS. 1. Antespace. 2. Foyer. 3. Technical room. 4. Classrooms (classrooms 2 and 4 are computer rooms, all others are tutorial rooms). 5. Planted Patio (above the car park). 6. Offices. 7. Meeting room. 8. Void over patio. 9. Outdoor walkways.

A.1. PASSIVE DESIGN

A.1.1. ORIENTATION AND SURROUNDINGS PASSIVE DESIGN

The main facades are north and south oriented to avail of the cooling breezes during summer and to reduce the solar energy gained by the building on the western and eastern façades.

The building is surrounded by a minimum 3 metre band of endemic plants to prevent the air from heating up before entering the building. The car park is located under the building to avoid the excess heat that occurs from having pavement around the building, and to increase the soil permeability to prevent flooring after heavy tropical storms.

A.1.2. NATURAL VENTILATION AND CEILING FANS

The building has been designed with priority given to passive components/technologies. The building is naturally crossed-ventilated with a window to wall ratio (WWR) of 30% by using glass louvres, which have the advantage of regulating the airflow while also providing protection against cyclones and break-ins. In the administration zone, natural ventilation was not possible because of the central corridor and thus indoor frosted louvres were installed to enhance the airflow, providing an interior WWR of 30% (figure a- 3).

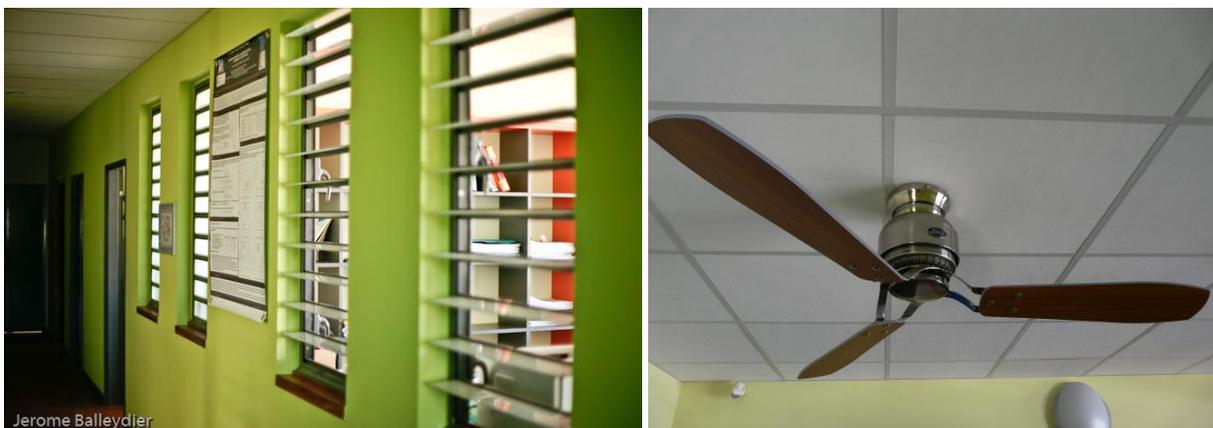


Figure A- 3. Left: Picture of the indoor louvres of the administration zone. Right: High performance ceiling fan. Picture credits: Jerome Balleydier.

Large ceiling fans are installed in all spaces, including those with air conditioning. The use of ceiling fans guarantees additional air movement during windless days and allows a transitional period before using active air conditioning systems (figure a- 3).

A.1.3. SOLAR SHADING AND DAYLIGHTING

The main facades are solar protected with fixed shading (figure a- 1). The solar shading has been designed on the basis of 3D simulations and optimised to find a compromise between thermal efficiency and daylighting. With regard to daylighting, because of the high window-to-wall ratio for natural cross-ventilation, most of the spaces have a UDI (Useful Daylight Index) of at least 90%. Two classrooms were not equipped with electric lighting appliances while simulations have demonstrated that during the working hours (8 a.m.-5 p.m.), the UDI was 100%.

A.1.4. MATERIALS

With regard to the envelope, the walls are made of concrete; the roofing is insulated with a 10 cm-layer of polystyrene and a ventilated BIPV (Building Integrated Photovoltaic) over-roof; the solar shading systems are made of wooden strips; the east and west gables are insulated with mineral wool and a wooden cladding. The paint used is completely organic and the wooden components have not undergone any specific treatment. No insulation is required on the main facades as they are very efficient in terms of S-value due to the solar shading.

Table A- 2. Description of the envelope of ENERPOS.

Roof	BIPV over-roof + 10 cm of polystyrene + 20 cm concrete Overall R-value: 3.4 / Solar factor: 0.0003
Walls	East and West: 18 cm concrete + 8 cm mineral wool or 18 cm concrete + ventilated air gap + wooden siding North and South: 18 cm concrete + solar shading Overall R-value: East and West: 1.8 / Solar factor: 0.02 North and South: 0.1 / Solar factor: 0.03 Glazing percentage: 30%
Windows	U-value: 1.4 Solar Heat Gain Coefficient (SHGC): North 0.10 / South 0.15 Visual Transmittance: 0.4
Orientation	East/West (14°NE)

A.1.5. ERGONOMICS

A particular effort has been made for the indoor design of all the spaces, ranging from the choice of wall colours to the choice of chairs. The building team aimed to prove that a comfortable working space can be designed without extra costs and that a Net ZEB can be comfortable. The ergonomics of the offices have been studied to achieve the maximum level of comfort for the occupants. The desks are positioned perpendicularly to the windows leaving a 50 cm gap to avoid the glare effect and direct solar radiation on desks. The backs of the chairs are made from breathable fabric to refresh the users' backs. To avoid using white, which is common in educational buildings, all the walls were painted with green organic colours.

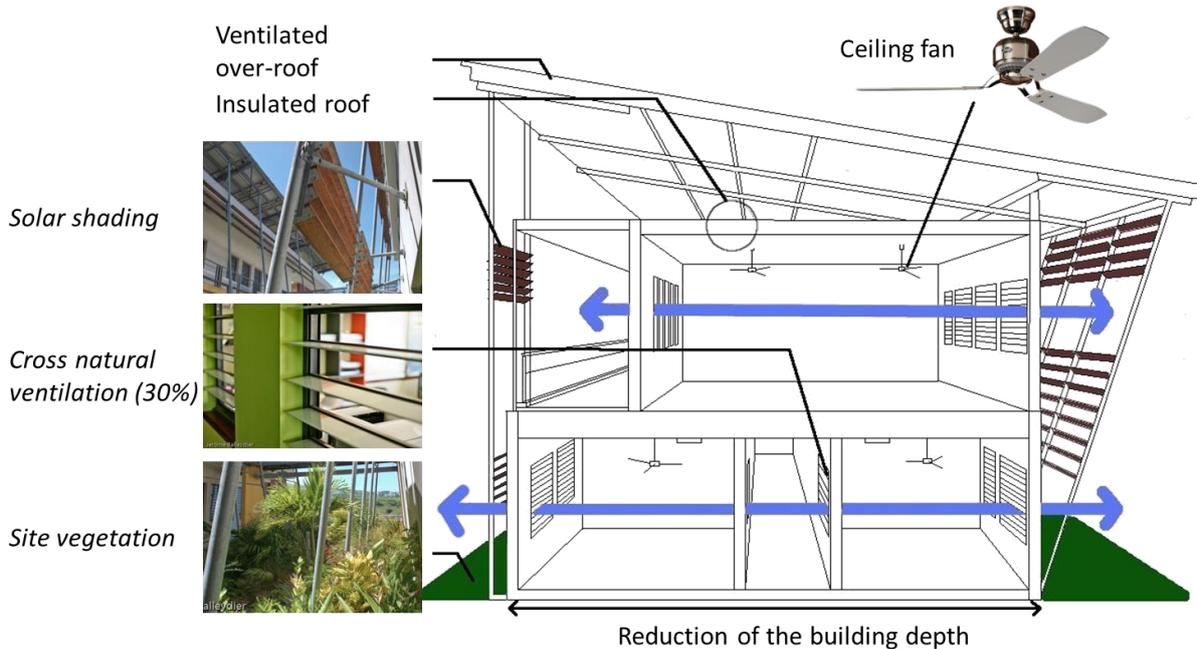


Figure A- 4. Main features of the bioclimatic design of the ENERPOS building.

A.2. ENERGY EFFICIENCY

The building saves energy mostly because of its bioclimatic and passive design. Energy management strategies are used to decrease the total consumption of the active systems.

A.2.1. ARTIFICIAL LIGHTING

The installed electric density of artificial lighting is lower than in a standard building (7 W/m^2 in the classrooms and 3.7 W/m^2 in the offices). The classrooms were designed on the basis of 250 Lux on the work plane. Timers in the classrooms turn the lights off automatically after two hours. For the offices, low energy T-5 luminaires provide indirect ambient lighting (100 Lux), while LED desk lamps provide additional lighting (300 Lux) as required.

A.2.2. CEILING FANS

Ceiling fans are used in conjunction with the natural ventilation strategy to create air movement on the skin of the occupants, thus increasing their comfort. A total of 55 ceiling fans with a 132 cm blade diameter is installed in the offices and classrooms. Ceiling fans are controlled individually (offices) or in groups of two or four (classrooms) from wall-mounted switches and have three speed levels. The maximum power used for one ceiling fan is 70 W which represents 7 W/m^2 (on the assumption of one ceiling fan per 10 m^2). The power density is approximately one-tenth of that of air conditioning.

A.2.3. AIR CONDITIONING SYSTEM

A variable refrigerant flow (VRF) air conditioning system has been installed to cool the offices and the computer rooms. The air conditioning system is composed of several appliances:

- a VRV (Variable Refrigerant Volume) system; its cooling capacity is 25.3 kW_(cooling) and the Energy Efficiency Ratio is 4.8 (data given by the manufacturer Daikin);
- an Air Treatment Unit (ATU);
- twelve ceiling cassette air conditioning units (1 per office and 2 per computer room and meeting room);
- two split systems to cool the technical rooms (one of 1,780 W and the second one of 700 W).

The air-conditioned area of the building is 246 m² which corresponds to 36% of the net floor area. The cooling capacity of ENERPOS is 102 W_c/m². Usually, 90% of the area of the buildings at the University of Reunion Island is air-conditioned with a cooling capacity of 150 W_c/m².

A standard university building is usually air conditioned during 9 months. Designers reduced the predicted cooling period for the computing rooms to six weeks by using natural ventilation and ceiling fans. During the design phase, a dynamic thermal model of the building was undertaken in the DesignBuilder simulation tool. Using Givoni's comfort diagram on a psychometric chart, it was possible to predict the different operational periods for natural ventilation, ceiling fans or air conditioning (Garde et al., 2011). The offices were to be air-conditioned for 1.5 months and the computer rooms for 3 months (15 days in December and from the start of February to mid-April which represents 42 working days).

The ceiling fans have a dual purpose; they allow the air conditioning period to be drastically reduced, and when the air conditioning is used, the set temperature can be raised. In standard buildings, the maximum set temperature is 26°C as it is the maximum comfort temperature. But with an air velocity on the skin of 1 m/s (provided by a ceiling fan), the maximum comfort temperature rises to 30°C. Energy savings from air conditioning are about 10% per degree on the set point temperature. We can therefore achieve 30% to 40% of energy savings with regard to the consumption of air conditioning.

A.2.4. COMPUTER NETWORK AND PLUG LOADS

The use of laptops and nettops which consume much less energy than desktop computers is encouraged in the offices. The computing rooms are only equipped with screens, mice and keyboards. All central units are located in an air-conditioned technical room. The thermal loads from the computers are thus kept outside the computing rooms.

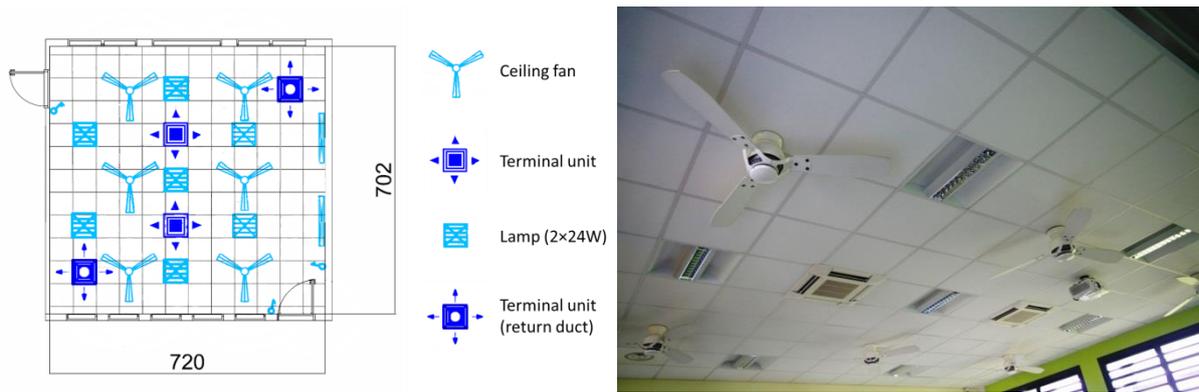


Figure A- 6. Layout of the systems on the ceiling of a computing room

A.2.6. BUILDING MANAGEMENT SYSTEM AND INDIVIDUAL CONTROLS

A building management system (BMS) controls the air conditioning system (operating period, set point temperature); the schedules of exterior lighting and energy consumption by type of end-uses (lighting, ventilation, plug loads, air conditioning, and elevator) to target the energy management actions on most energy consuming items.

In the offices the use of ceiling fans and lighting is left to the discretion of the occupants with individual controls. In the classrooms, the controls are grouped for the ceiling fans. Timers turn off the lighting after two hours.

A.3. INTEGRATION OF RENEWABLE ENERGY TECHNOLOGY

A.3.1. ROOFTOP BIPV SYSTEM

The very low consumption of the building is balanced by 365 m² of building integrated photovoltaic (BIPV) roofs. The PV panels serve as over-roofs, with half oriented north and half oriented south to allow for an architectural homogeneity of the building (figure a- 7). The slope of the PV cells is 9° for both roofs. Besides electricity production, the PV panels provide a ventilated double roof, which creates solar shading of the terrace roof of the building. Because of the PV layer, the solar factor (the percentage of solar heat that penetrates the roof to the building's interior) of the roof is 0.003 whereas the PERENE requirement is 0.02.

The underlying philosophy of ENERPOS is to balance the final energy consumption of all its uses with its PV production and to reduce the extent of time required to reach the energy balance.



Figure A- 7. BIPV roof on ENERPOS. 365 m² of PV panels to balance the low consumption of the building.
Picture credits: Jerome Balleydier.

A.3.2. TECHNICAL DATA

The PV panels are polycrystalline cells. The installation is composed of 14 inverters (3,300 W). Table A-4 gives the main characteristics of the two fields as well as the expected PV production that was calculated during the design with the software PV-syst.

Table A- 4. Characteristics of the BIPV roofs.

	South field	North field	Total
Area	219 m ²	146 m ²	365 m ²
Modules	144 modules TE2000-210 Wp (field 8×18)	96 modules TE2000-210 Wp (field 6×16)	240 modules
Inverters	8 inverters 3300 W	6 inverters 3300 W	14 inverters 3300 W
Peak power	30,240 Wp	20,160 Wp	50,400 kWp
Azimuth	166° SW	-14° NE	
Tilt	9°	9°	
Productivity	1298 kWh/kWp.y	1578 kWh/kWp.y	
Yield	82%	99.7%	
Expected production (PV-syst simulation)	44,612 kWh/y	32,391 kWh/y	77,003 kWh/y

The roof is rented by the university to an independent company who made the investment in the PV panels. They have their own monitoring system from which data were obtained for analysis.

A.4. MONITORING SYSTEM

A.4.1. ENERGY AND POWER MEASUREMENTS

The building is closely monitored with data collected every minute, thanks to the building management system. This allows for better control of electricity consumption, rapid identification of excessive consumption and improved understanding of the electrical consumption characteristics of the building. Energy metres measure the consumption of electricity by end-use to identify the most energy-consuming items and to correct them, if necessary. Portable units measuring environmental conditions have been deployed to provide short-term assessment of the indoor environment.

The monitoring system of the building for energy and power is described in figure a- 8 and includes:

- energy and power metres (10 pulses/kWh) by end-uses – 15 metres: interior lighting, exterior lighting, ceiling fans, air conditioning terminal units, split systems (for the two technical rooms), VRV group, air treatment unit, plug loads and lift;
- presence detectors in all classrooms and offices (15) to measure the occupancy rate;

The data are collected on a data logger every minute and are then transferred into a php database accessible from the Internet.

A.4.2. THERMAL COMFORT METROLOGY

The monitoring system also includes thermal comfort features:

- temperature and humidity sensors in all classrooms and offices (15);
- weather station on site – outside temperature, humidity, global, direct and diffuse solar radiation, wind speed and direction, pluviometry;
- a portable comfort measuring device: inside air temperature, black globe temperature, air velocity, humidity, illuminance and a data recorder. This unit was used in particular during the thermal comfort surveys that are presented in chapter 3 and in (Lenoir et al., 2011).

The overall monitoring system cost € 72,425 which represents 3% of the overall cost of the building construction. This price includes the fixed instrumentation (energy metres, temperature and humidity sensors, the wiring and the commissioning) as well as the portable comfort measuring device.

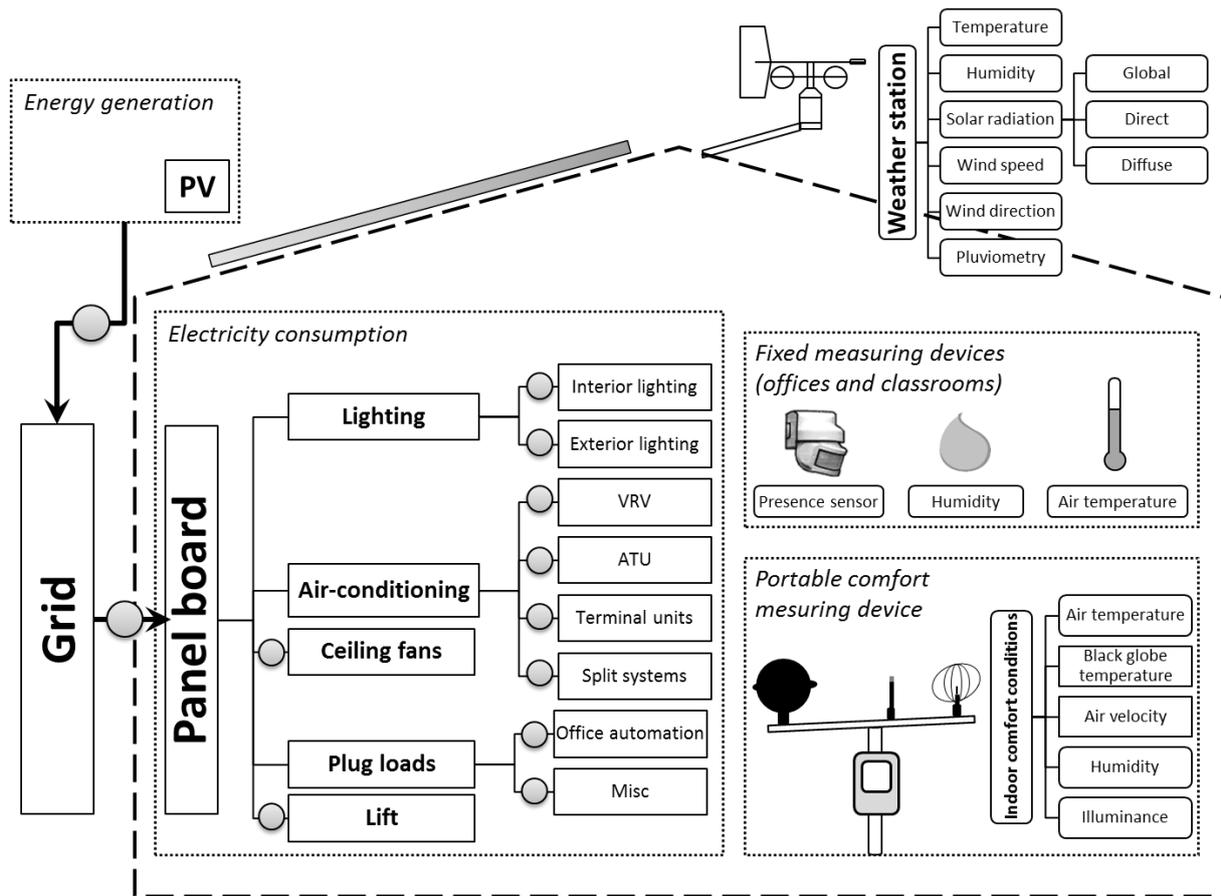
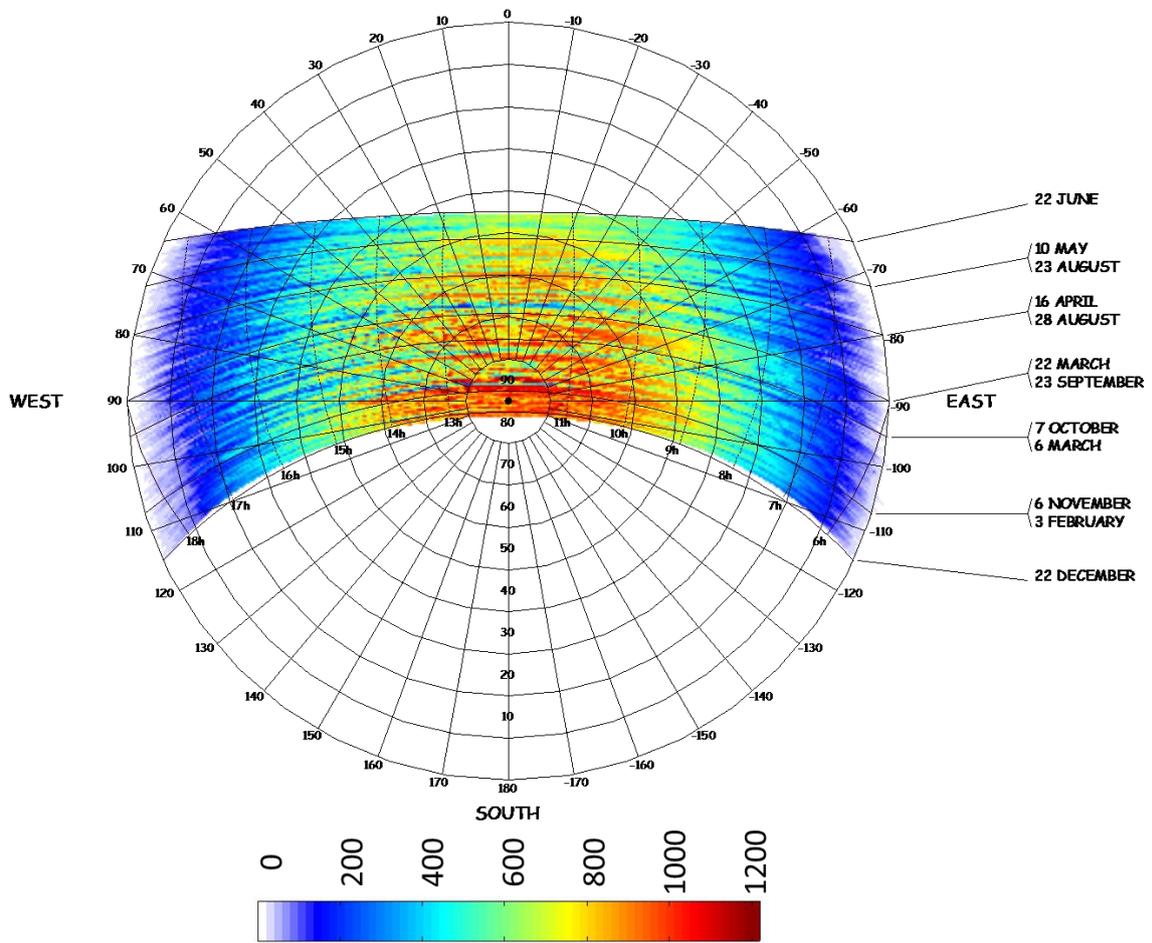


Figure A- 8. Diagram of the monitoring system of ENERPOS.

Appendix

B

SOLAR DIAGRAM OF REUNION ISLAND



Measured global horizontal solar irradiance in Saint-Pierre (W/m^2)

Figure B- 1. Solar diagram of Reunion Island with the measured global horizontal solar irradiance in Saint-Pierre. Data processed by Emeric Tapachès.

Appendix

C

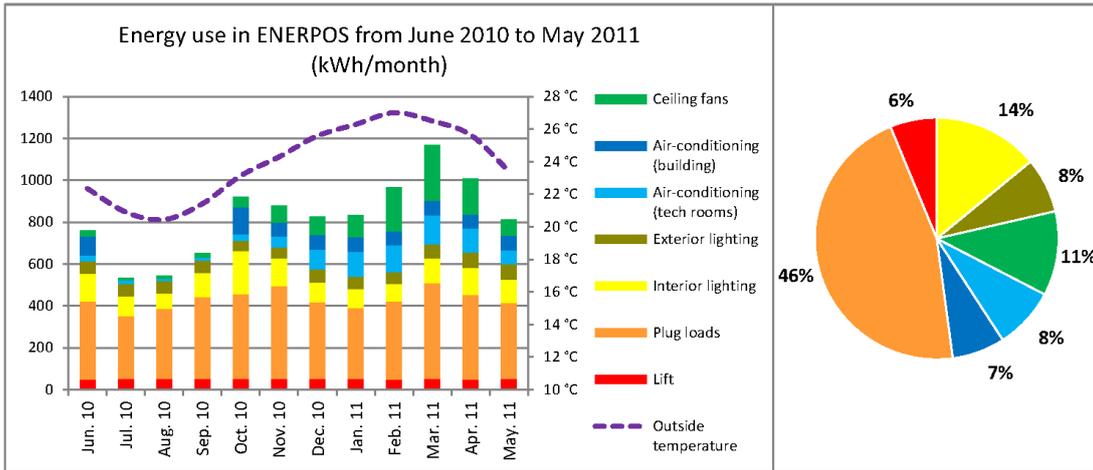
ANNUAL TRACKING SHEETS OF
THE ENERPOS BUILDING

Annual Energy Tracking Sheet of ENERPOS

YEAR 1 : June 2010 to May 2011

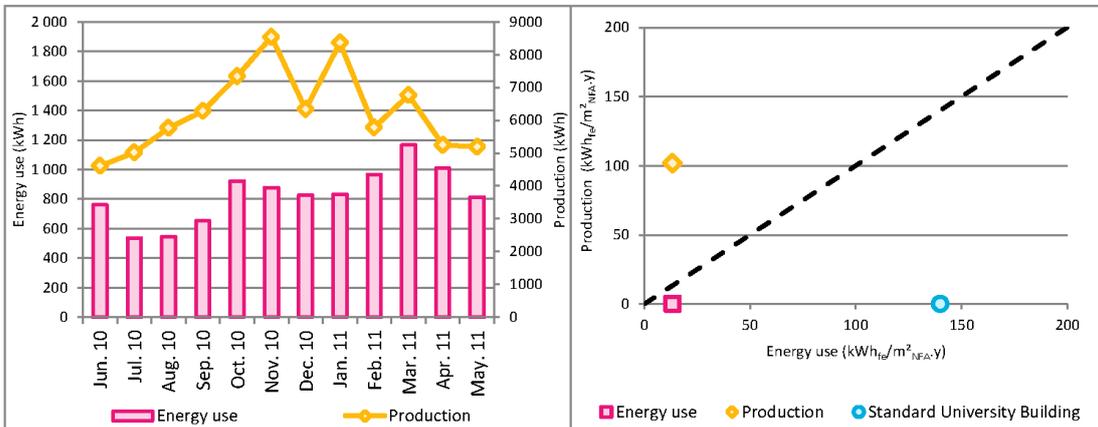
Energy use	
Annual energy use	9 908 kWh
Energy index	13.4 kWh/m ² _{NFA}

Production	
Annual production	75 213 kWh
Energy index	101.8 kWh/m ² _{NFA}
Productivity	1 607 kWh/kWc



	Jun. 10	Jul. 10	Aug. 10	Sep. 10	Oct. 10	Nov. 10	Dec. 10	Jan. 11	Feb. 11	Mar. 11	Apr. 11	May. 11
Ratio (kWh/m ² _{NFA})	1.0	0.7	0.7	0.9	1.2	1.2	1.1	1.1	1.3	1.6	1.4	1.1

	Int. Lighting	Ext. Lighting	Ceiling Fans	Air-conditioning	Plug loads	Lift
Energy use	1388 kWh/y	729 kWh/y	1119 kWh/y	1509 kWh/y	4548 kWh/y	615 kWh/y



Maximum load of the building	10.3	W/m ² _{NFA}
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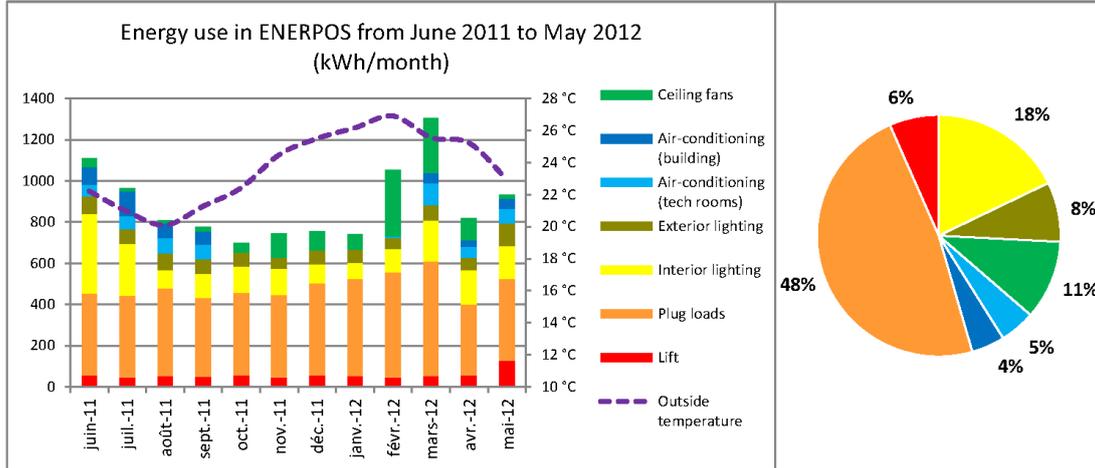
Figure C- 1. Annual energy tracking sheet from June 2010 to May 2011.

Annual Energy Tracking Sheet of ENERPOS

YEAR 2 : June 2011 to May 2012

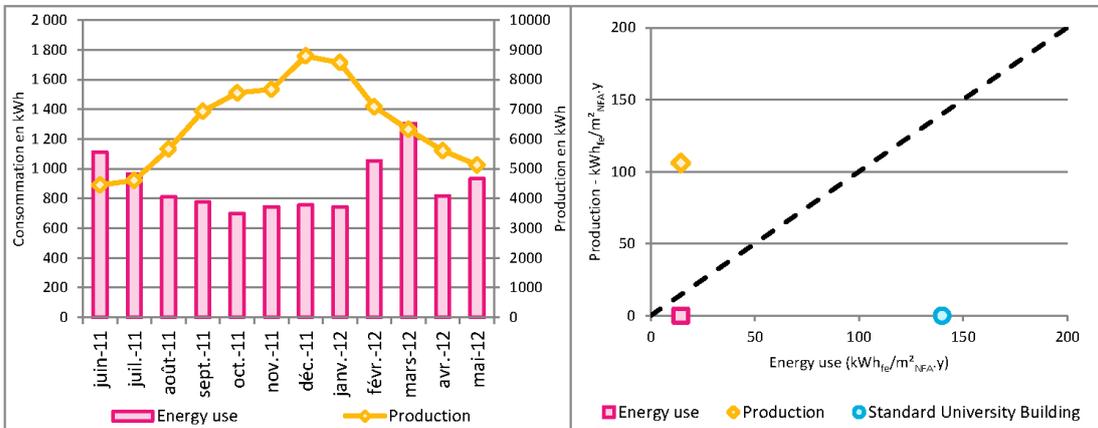
Energy use	
Annual energy use	10 712 kWh
Energy index	14.5 kWh/m ² _{NFA}

Production	
Annual production	78 333 kWh
Energy index	106.0 kWh/m ² _{NFA}
Productivity	1 674 kWh/kWc



	Jun. 11	Jul. 11	Aug. 11	Sep. 11	Oct. 11	Nov. 11	Dec. 11	Jan. 12	Feb. 12	Mar. 12	Apr. 12	May. 12
Ratio (kWh/m ² _{NFA})	1.5	1.3	1.1	1.0	0.9	1.0	1.0	1.0	1.4	1.8	1.1	1.3

	Int. Lighting	Ext. Lighting	Ceiling Fans	Air-conditioning	Plug loads	Lift
Energy use	1909 kWh/y	856 kWh/y	1134 kWh/y	980 kWh/y	5129 kWh/y	704 kWh/y



Maximum load of the building	9.8	W/m ² _{NFA}
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Figure C- 2. Annual energy tracking sheet from June 2011 to May 2012.

Appendix

D

COMPLEMENTARY STUDIES ON ENERPOS

D.1. IMPORTANCE OF THE LOCATION OF SENSORS

This paragraph aims to compare data of temperature and humidity recorded by the Building Management System (BMS) of ENERPOS with other types of sensors and other locations in the room.

D.1.1. OBJECTIVES

All the rooms of ENERPOS are equipped with temperature and humidity sensors that are generally located at the entrance of the room against the wall next to the door. The objective of this section is to draw comparison between measurements by the sensors of the BMS of ENERPOS and other types of thermo-hygrometer sensors located on the wall, close to the BMS sensors or in the centre of the room. The first aim is to show the differences between the measurements of the BMS sensor and that of a sensor placed at the same location so that the possible uncertainties of the data provided by the sensors of the BMS of ENERPOS can be noticed. The second aim is to examine the differences between the measurements given by the BMS sensor and those provided by another sensor located in the centre of the room to question the choice of the location of the BMS sensor in the room.

The methodology includes different measurements in classrooms and offices using three types of sensors:

- Type "BMS ENERPOS"
- Type "Testo 175"
- Type "Portable comfort measuring device" or "comfort totem"

D.1.2. RESULTS AND ANALYSIS

In the offices, the measurements between the BMS sensors (against the wall) were compared with a "Testo 175" sensor placed close to the BMS sensor and a "Testo 175" sensor located in the centre of the room. The differences are of the order of 3°C and 5 to 10% of RH between the BMS sensor and the "Testo 175" located close to it. But the differences are similar between the sensor placed against the wall and the one at the centre of the room.

Dates of the measurements	December 11 th -12 th 2009
Room	Office 5
Types of sensors	- "ENERPOS" sensor - "Testo 175" wall - "Testo 175" centre

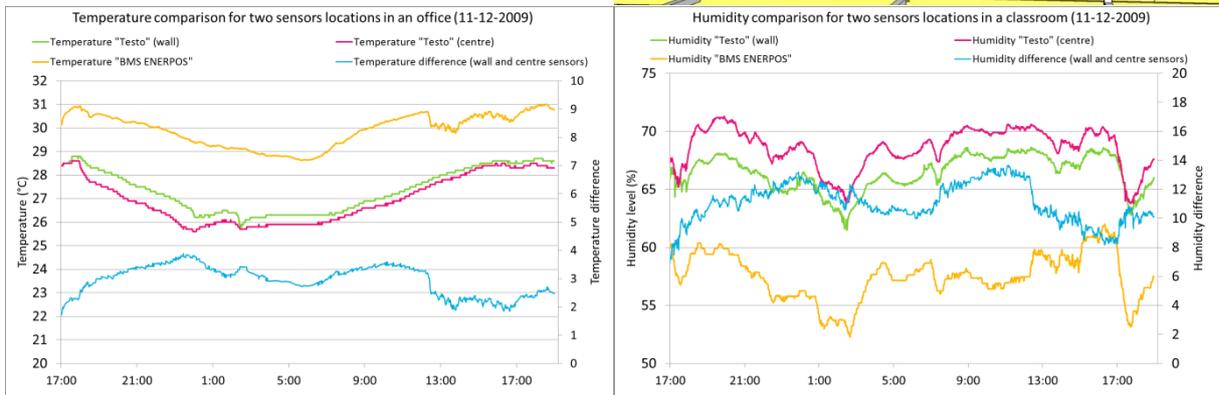
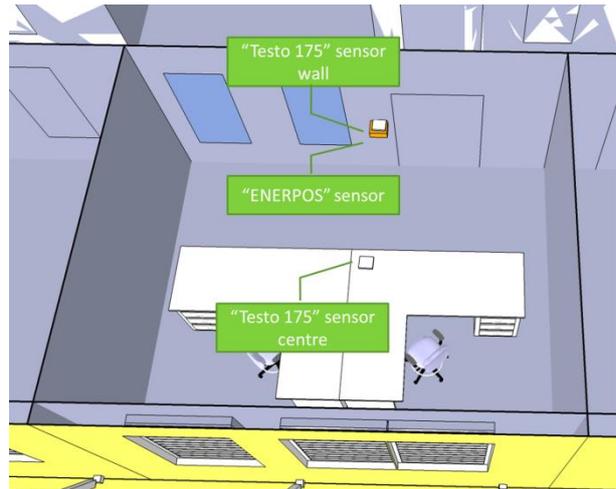


Figure D- 1. Temperature and humidity comparisons for two sensors locations in an office of the ENERPOS building.

In the classroom, the study compares the temperature and humidity given by the ENERPOS BMS sensor (against the wall) and the comfort totem placed at the centre of the room (height: 80 cm). On day 1 (January 20th), the louvres are closed. In this case, the temperature difference between both sensors remains lower than 1°C. As for the humidity level, the difference fluctuates between 2% and 10%. On day 2 (January 21th), all louvres are open. The temperature difference is approximately 0.5°C during the day, but increases at night, reaching 2°C. The humidity level difference remains close to 4%.

Dates of the measurements	January 20 th - 21 th 2010
Room	Classroom 2
Types of sensors	- "ENERPOS" sensor - "Comfort totem"

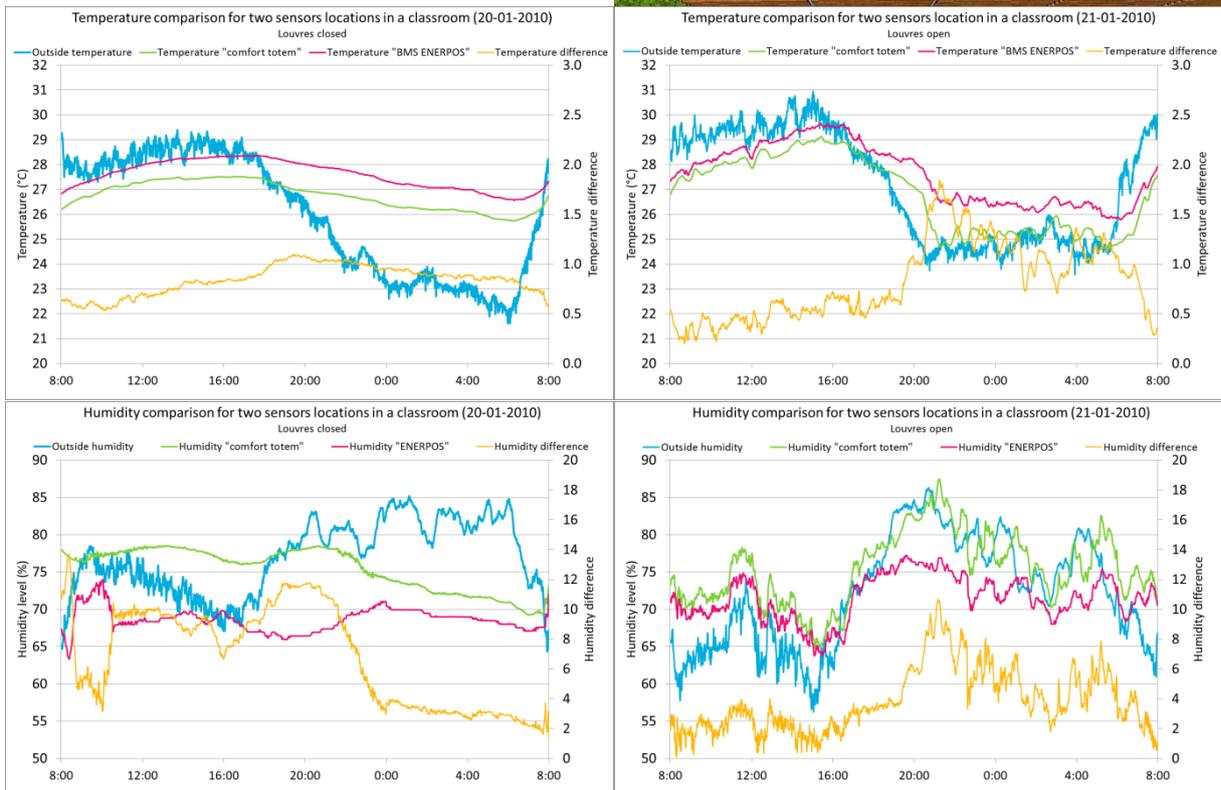
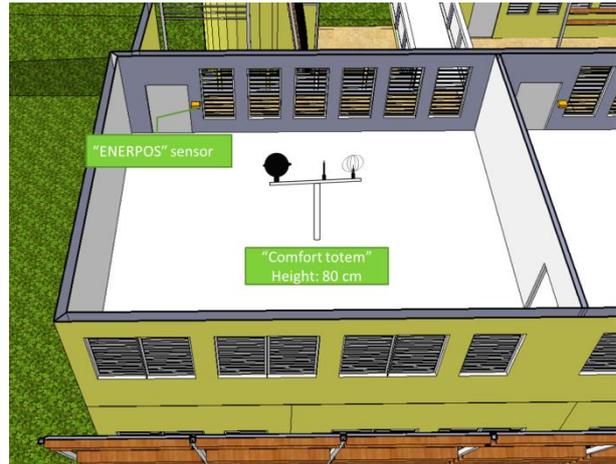


Figure D- 2. Temperature and humidity comparisons for two locations of the sensors in a classroom of the ENERPOS building. Day 1 (January 20th): Louvres closed. Day 2 (January 21th): Louvres open.

The measurements that are presented show large discrepancies between the ENERPOS BMS sensors and the Testo 175 or the comfort totem sensors (of the order of 2°C and 5 to 10% RH). The location of the BMS sensors placed against the wall is questionable in the view of the gradient of both temperature and humidity between the centre of the room, where the occupants are likely to sit, and close to the walls, where the BMS sensors are located.

D.2. OCCUPANCY OF THE BUILDING

The importance of the people factor in building performance seems obvious. A building is composed of several types of equipment whose use depends on the occupancy of the building as well as the behaviour of its users (Mahdavi, 2011). The occupants operate control devices such as windows, shades, lights, air conditioning and fans to achieve the best indoor environmental conditions. These control actions obviously have a significant impact on the building performances. This is especially true for a passive building like ENERPOS because for the users to reach comfort, they will always have a choice between using a non-consumer passive system e.g. opening the louvres to ventilate the building, not turning on the light when not required, and an energy-active system e.g. turning on the ceiling fans without opening the louvres, using the air conditioning or the artificial lighting.

The energy consumption should obviously be viewed in relation to the occupancy rate of the building. With the presence detectors located in all offices and classrooms, it is possible to have a satisfactory overview of the occupancy rate of ENERPOS. The information given by the presence sensors is not fully accurate because it is only possible to say whether the office or the classroom was occupied or not, but no information is given on the number of people inside. The sensors will trigger with the movement of occupants, and it may happen that an office is occupied but the sensor does not trigger if its occupant is not mobile enough to be spotted. So the occupancy parameter is quite different to the monitored one.

D.2.1. OFFICES

Since August 2010, the offices of the building are nearly fully occupied with 2 secretaries, 4 to 6 PhD and master students and 5 professors (for a total of 7 offices and 14 desks). The occupancy hours are the usual office hours for the secretaries (8 a.m. - 5 p.m.), the professors have similar hours of work but they are not in their offices all day long and not every day. As for the PhD and master students, they are in their offices generally from 7 or 8 a.m. to 6 or 7 p.m. and even sometimes later.

Figure D- 3 represents the average data of occupancy (from the presence detectors) for the 7 offices of ENERPOS as well as the meeting room. A 100% of occupancy corresponds to a fully occupied office from Monday to Friday all year long (that percentage does not take into account school holidays). The two most occupied offices are the ones used by the PhD and master students throughout the year, whereas the other offices are not used during school holidays.

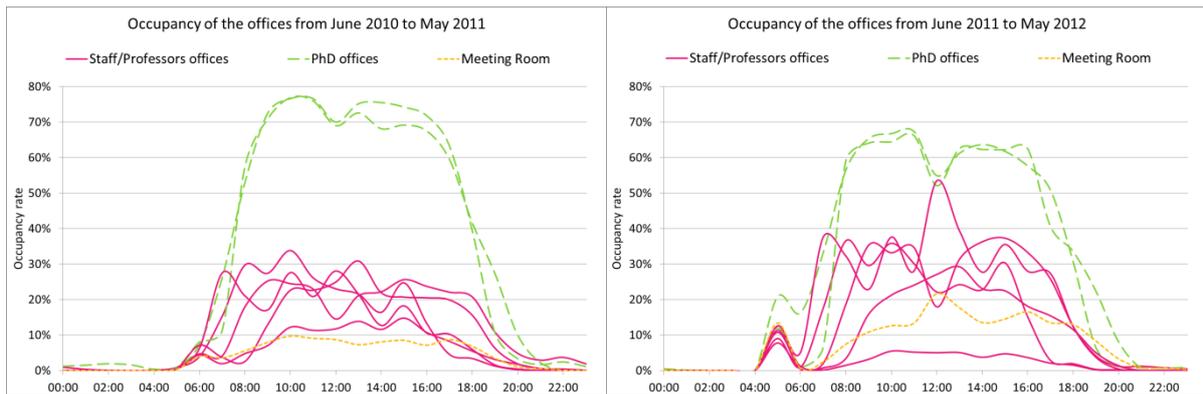


Figure D- 3. Mean work day occupancy of offices in ENERPOS from June 2010 to May 2011 and from June 2011 to May 2012.

Two patterns of use of the offices are noticeable from figure d- 3. The two offices occupied by PhD students are used approximately 75% and 65% of the time during the weekdays from 8 a.m. to 6 p.m. throughout the year. Even the lunch break is noticeable in this pattern. The five other offices that are occupied by members of the staff and teachers are used 20% to 35% of the time during the weekdays from 6-7 a.m. to 5-6 p.m. Those offices were used more from June 2011 to May 2012 than the previous year. There is not an obvious pattern in this case, because the professors often drop by outside of class hours. The meeting room is used approximately 10 to 15% of the time. The small peak at 5 a.m., visible from June 2011 to May 2012, corresponds to the cleaning of the building, which was moved to an early morning slot that particular year.

D.2.1. CLASSROOMS

Concerning the occupancy of the classrooms, this varies a lot during the year. ENERPOS is indeed a university building that houses several courses of study in which adult continuing education features. The students of those courses occupy the building during specific periods of time that do not necessarily correspond to usual university periods. There are months during which the building is not very occupied and other times when all classrooms are used.

The presence detectors placed in every classroom give interesting results on the occupancy of the classrooms during the year. The presence detector of classroom 2 is defective and no results were recorded for this classroom.

Table D- 1. Hours of occupancy of the classrooms for two years.

Classroom	Classroom 1	Computer Room 1	Computer Room 2	Classroom 3	Classroom 4	Classroom 5
<i>June 2010 to May 2011</i>						
Number of hours of use	1052	547	491	194	653	719
Occupancy rate	92%	48%	43%	17%	57%	63%
<i>June 2011 to May 2012</i>						
Number of hours of use	661	545	664	741	777	726
Occupancy rate	57%	47%	58%	64%	68%	63%

As defined by the French Ministry of National Education for university buildings, an occupancy rate of 100% corresponds to 1,150 hours of occupancy per year for a given classroom.

The average occupancy rate of all the classrooms of the University of Reunion Island was 60% for the academic year 2009-2010. As for the classrooms of the University Institute of Technology (where the ENERPOS building is located) this rate was approximately 45%. As for ENERPOS, the average occupancy rate (based on 6 classrooms) is 53% from June 2010 to May 2011 and 60% from June 2011 to May 2012. The ENERPOS building has an occupancy rate that is comparable to the other buildings of the university. Its energy use can be compared with that of other buildings of the University of Reunion Island.

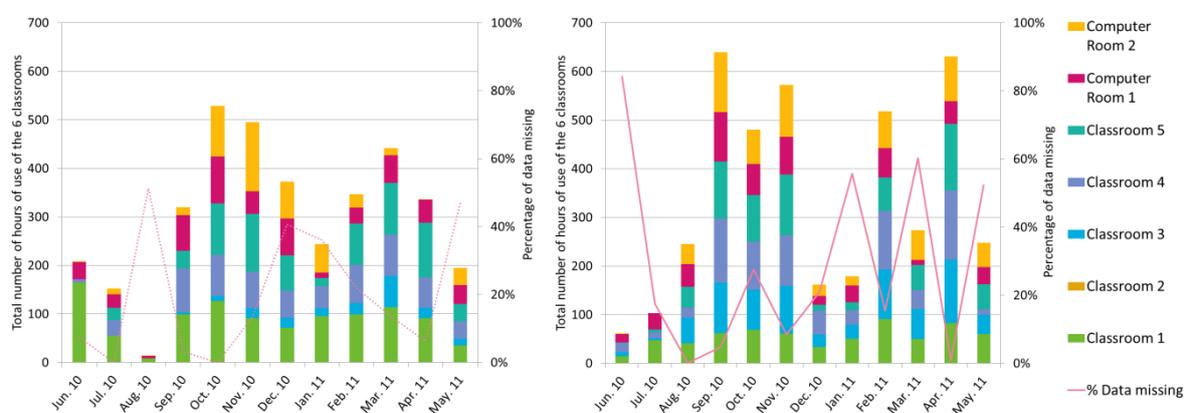


Figure D- 4. Number of hours of occupancy of the classrooms and computer rooms per month from June 2010 to May 2011 and from June 2011 to May 2012.

Figure D- 4 represents the number of hours of occupancy of the classrooms of the building between June 2010 and May 2012. The dotted line represents the percentage of missing data over the month. Indeed, the monitoring system is very unstable and if not checked very often, it crashes and data are lost. It should be noted that the data for the last two weeks of August 2010 were not recorded because of a problem of communication within the monitoring system (50% of missing data for August 2010). In Reunion Island, the school year starts mid-August so the classrooms were occupied for the last two

weeks of August 2010, but because the data are missing, the classrooms seem as if they were not occupied during August. The same problem occurred for the last ten days of May 2011, so the occupancy rate should be a little higher than the one given by the curve. In March 2012, the classrooms were much more occupied than what was recorded by the presence detectors because 60% of the data for this month are missing.

In conclusion, the data recorded by the presence detectors give useful information about the occupancy rate of the building through the year. The energy consumption has to be weighed against the occupancy rate of the building. The energy index from June 2011 to May 2012 (14.5 kWh/m².y) is slightly higher than that from June 2010 to May 2011 (13.4 kWh/m².y) and the occupancy rate of ENERPOS follows the same pattern.

Appendix

E

THERMAL COMFORT SURVEY CONDUCTED IN ENERPOS

Informations personnelles

5. Combien de jours par semaine passez-vous dans le bâtiment ENERPOS.....
6. Depuis combien de temps vivez-vous à la Réunion ?
7. A quelle altitude habitez-vous ?(approximativement).....

8. Quelle était votre activité avant votre arrivée dans cette salle ?

	Sommeil	Suivi d'un cours	Restauration	Sport	Conduite	Marche
Il y a 30 min						
Il y a 10 min						

9. Autres activités (précisez) ?.....

Quelle est votre tenue vestimentaire ?

Haut: plusieurs réponses possibles, indiquez aussi le nombre	<input type="checkbox"/> Manches courtes	<input type="checkbox"/> Manches longues	<input type="checkbox"/> Débardeur
Bas	<input type="checkbox"/> Jupe courte/short	<input type="checkbox"/> Jupe longue	<input type="checkbox"/> Pantallon
	<input type="checkbox"/> Collants		<input type="checkbox"/> Chaussettes
Chaussures	<input type="checkbox"/> Fermées		<input type="checkbox"/> Ouvertes
Autres (pull, veste, foulard, chapeu...)			

Début du cours

10. En ce moment vous avez ?
 Froid Légèrement froid Ni chaud, ni froid Légèrement chaud Chaud Très chaud Extrêmement chaud
11. Vous trouvez cette ambiance ?
 Confortable Légèrement inconfortable Inconfortable Très inconfortable Extrêmement inconfortable
12. Vous préféreriez avoir :
 Beaucoup plus froid Plus froid Un peu plus froid Aucun changement Un peu plus chaud Plus chaud Beaucoup plus chaud
13. Au sujet des mouvements d'air, vous les trouvez :
 Confortables Légèrement inconfortables Inconfortable Très inconfortables Extrêmement inconfortables
14. Vous auriez préféré :
 Moins de mouvements Un peu moins de mouvements Aucun changement Un peu plus de mouvements Beaucoup plus de mouvements

Avant la pause

15. En ce moment vous avez ?
 Froid Légèrement froid Ni chaud, ni froid Légèrement chaud Chaud Très chaud Extrêmement chaud
16. Au sujet des mouvements d'air, vous les trouvez :
 Confortables Légèrement inconfortables Inconfortables Très inconfortables Extrêmement inconfortables
17. Vous avez trouvé l'air :
 Très sec Sec Ni sec, ni humide Légèrement humide Humide Très humide Extrêmement humide

18. Vous avez trouvé cet environnement :
 Confortable Légèrement inconfortable Inconfortable Très inconfortable Extrêmement inconfortable
19. Vous auriez préféré que l'air soit :
 Beaucoup plus sec Un peu plus sec Sans changement Un peu plus humide Beaucoup plus humide

Après la pause

20. Pendant la pause vous étiez :
 Assis à l'intérieur Debout à l'intérieur Assis dehors Debout dehors Debout / assis au soleil
21. Si vous êtes sorti durant cette pause, à la reprise, vous avez trouvé l'ambiance :
 Plus froide Un peu plus froide Semblable Un peu plus chaude Plus chaude

Fin du cours

22. Avez-vous mis ou ôté un vêtement durant le cours? Le(s)quel(s)? (Précisez mis ou ôté)

23. Etes-vous intervenu durant le cours sur les équipements suivants?

	Non	Oui, une fois	Oui, plusieurs fois	Impact significatif
Ventilateur				
Jalousies				
Porte				

24. Si oui, précisez pour chaque intervention l'impact le plus significatif engendré:

25. D'autres personnes sont elles intervenues? Oui Non

26. Si oui, quelles actions ont été menées et quels effets ont été engendrés?

27. En ce moment vous avez ?
 Froid Légèrement Ni chaud, ni froid Légèrement chaud Chaud Très chaud Extrêmement chaud
28. Au sujet des mouvements d'air, vous les avez trouvés :
 Confortables Légèrement inconfortables Inconfortables Très inconfortables Extrêmement inconfortables
29. Vous avez trouvé l'air :
 Très sec Sec Ni sec, ni humide Légèrement humide Humide Très humide Extrêmement humide
30. Vous avez trouvé cet environnement :
 Confortable Légèrement inconfortable Inconfortable Très inconfortable Extrêmement inconfortable
31. Vous auriez préféré que l'air soit :
 Beaucoup plus sec Un peu plus sec Sans changement Un peu plus humide Beaucoup plus humide
33. Selon vos préférences personnelles, vous avez trouvé cet environnement thermique:
 Confortable Légèrement confortable Inconfortable Très inconfortable Extrêmement inconfortable
34. Vous avez trouvé la salle :
 Bien éclairée Légèrement sombre Sombre Très sombre
35. Avez-vous été ébloui(e) durant le cours? Oui Non
36. Si oui, quelle était la cause de cet éblouissement?.....

Remarques

37. Dans cette salle et plus généralement dans le bâtiment, y a-t-il des éléments que vous trouvez particulièrement agréables ou désagréables (acoustique, éclairage, thermique, architecture ...)? Lesquels et pourquoi ? Suggèreriez-vous des solutions d'amélioration ?

38. Commentaires libres, remarques, observations, etc...



REFERENCES

- Akimoto, T., Tanabe, S.-i., et al., 2010. Thermal comfort and productivity - Evaluation of workplace environment in a task conditioned office. *Building and Environment* **45**(1): 45-50.
- Arens, E., Turner, S., et al., 2009. Moving air for comfort. *ASHRAE Journal* **51**(5): 18-28.
- ARER, 2011. Bilan énergétique de l'île de La Réunion 2010. OER - Observatoire Energie Réunion, from http://www.arer.org/IMG/pdf/BER_Technique_2010.pdf.
- ARER, 2012. Bilan énergétique île de La Réunion 2011. OER - Observatoire Energie Réunion, from http://www.arer.org/IMG/pdf/BER_Technique_2011.pdf.
- ASHRAE, 2003. Thermal Environmental Conditions for Human Occupancy. **Standard 55P**.
- Athienitis, A., Torcellini, P., et al., 2010. Design, Optimization and Modelling Issues of Net-Zero Energy Solar Buildings. In *Eurosun Conference*, Graz, Austria.
- Baird, G., 2009. Incorporating User Performance Criteria into Building Sustainability Rating Tools (BSRTs) for Buildings in Operation. *Sustainability* **1**: 1069-1086.
- Baird, G. and Field, C., 2013. Thermal comfort conditions in sustainable buildings – Results of a worldwide survey of users' perceptions. *Renewable Energy* **49**(0): 44-47.
- Bay, J.-H. and Ong, B. L., 2006. Tropical Sustainable Architecture - Social and Environmental Dimensions. *Elsevier Ltd*, ISBN: 978-0-75-066797-5.
- Beattie, P., 2010 The World's Tropical Zone – Rich Beauty, Rare Opportunity. *The Burrill Report*. March, 5th.
- Beck, W., Dolmans, D., et al., 2010. Solar Shading. How to integrate solar shading in sustainable buildings. *REHVA Guidebook*, ISBN: 978-2-930521-02-2.
- Bies, D. A. and Hansen, C. H., 2009. Engineering Noise Control: Theory and Practice. *Spon Press, UK*. ISBN: 978-0-415-48706-1.
- Bøhm, B. and Danig, P. O., 2004. Monitoring the energy consumption in a district heated apartment building in Copenhagen, with specific interest in the thermodynamic performance. *Energy and Buildings* **36**(3): 229-236.
- Bouden, C. and Ghrab, N., 2001. Thermal Comfort in Tunisia: Results of a one year survey. In *Moving Thermal Comfort Standards into the 21st Century Conference*, Windsor, UK.
- Boyer, H., Chabriat, J. P., et al., 1996. Thermal building simulation and computer generation of nodal models. *Building and Environment* **31**(3): 207-214.
- Cantin, R., Moujalled, B., et al., 2005. Complexité du confort thermique dans les bâtiments. In *6ème Congrès Européen de Science des Systèmes*, Paris, France.
- Chahwane, L., 2011. Valorisation de l'inertie thermique pour la performance énergétique des bâtiments. *PhD Thesis*, Université de Grenoble.

- Cole, R. J., 2003. *Green Buildings - Reconciling Technological Change and Occupant Expectations*. Blackwell, Oxford, UK.
- Cory, S., Lenoir, A., et al., 2011. Formulating a building climate classification method. In *Building Simulation - 12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- Crawley, D., Lawrie, L., et al., 2001. EnergyPlus: creating a new-generation building energy simulation program. *Energy and Buildings* **33**(4): 319-331.
- Crawley, D. B., Lawrie, L. K., et al., 2000. EnergyPlus: Energy Simulation Program. *ASHRAE Journal* **42**(4): 49-56.
- Danny S, P., 2009. Very low energy homes in the United States: Perspectives on performance from measured data. *Energy and Buildings* **41**(5): 512-520.
- David, M., Donn, M., et al., 2011. Assessment of the thermal and visual efficiency of solar shades. *Building and Environment* **46**(7): 1489-1496.
- de Dear, R. J., 1998. A global database of thermal comfort field experiments. *ASHRAE Transactions* **104**(1b): 1141-1152.
- de Dear, R. J. and Brager, G. S., 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. *Energy and Buildings* **34**(6): 549-561.
- Deuble, M. and Dear, R. d., 2010. Green Occupants for Green Buildings: The Missing Link? In *Adapting to Change: New Thinking on Comfort Conference*, Windsor, UK.
- Deval, J.-C., 1984. Le confort thermique en climat tempéré. *Revue de Physique Appliquée* **19**: 513-531.
- DOE, 2008. Building Technologies Program. U. D. o. Energy, *Planned Program Activities for 2008-2012*.
- Dubois, M.-C., 1997. Solar Shading and Building Energy Use, A Literature Review, Part 1. *Department of Building Science, Lund University, Sweden*, Report TABK--97/3049. from http://www.ebd.lth.se/fileadmin/energi_byggnadsdesign/images/Publikationer/Inlag3049-1.pdf.
- Ealiwa, M. A., Taki, A. H., et al., 2001. An investigation into thermal comfort in the summer season of Ghadames, Libya. *Building and Environment* **36**(2): 231-237.
- Ellis, P. G., Torcellini, P. A., et al., 2008. Energy Design Plugin: An EnergyPlus Plugin for SketchUp. In *SimBuild Conference, IBPSA-USA*, Berkeley, California, USA.
- EPBD, 2010. Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast), *Official Journal of the European Union*.
- Fairey, P. W., 1981. Passive Cooling and Human Comfort. *Florida Solar Energy Center*, Report FSEC-DN-5-81. from <http://www.fsec.ucf.edu/en/publications/pdf/FSEC-DN-5-81.pdf>.
- Fanger, P. O., 1970. Thermal Comfort *Danish Technical Press, Copenhagen*.
- Field, C. D. and Digerness, J., 2008. Acoustic Design Criteria for Naturally Ventilated Buildings. In *Acoustics'08 Conference*, Paris, France.
- Franco, M., Baird, G., et al., 2011. Environmental design and performance of the ENERPOS building, Reunion Island, France. In *ANZASCA Conference*, Sydney, Australia.
- Galasiu, A. D. and Veitch, J. A., 2006. Occupant preferences and satisfaction with the luminous environment and control systems in daylight offices: a literature review. *Energy and Buildings* **38**(7): 728-742.
- Garde, F., Bastide, A., et al., 2006. The construction of a Zero Energy Building in Reunion Island. Presentation of a new approach to the design studies. In *International Mechanical Engineering Congress and Exposition, ASME*, Chicago, Illinois, USA.
- Garde, F., Bastide, A., et al., 2007. ENERPOS: A French Research Program for Developing New Methods for the Design of Zero Energy Buildings in Hot Climates. In *CESB Conference*, Prague, Czech Republic.
- Garde, F., David, M., et al., 2005. Elaboration of Thermal Standard for French Tropical Islands: Presentation of the PERENE Project. In *REHVA World Congress CLIMA*.
- Garde, F., Lenoir, A., et al., 2010. Building design and energy performance of buildings in the French island of La Reunion. Feedback and updating of the PERENE project. In *REHVA World Congress CLIMA*, Antalya, Turkey.

- Garde, F., Lenoir, A., et al., 2011. Towards Net Zero Energy Buildings in Hot Climate. Part I: New Tools and Methods. *ASHRAE Transactions* **117**(1).
- Ghiaus, C. and Allard, F., 2005. Natural ventilation in the urban environment: assessment and design. *Earthscan*, ISBN: 9781844071296.
- Givoni, B., 1976. Man, climate and architecture. *Applied Science Publishers L.T.D.*,
- Givoni, B., 1998. Climate Considerations in Building and Urban Design. *John Wiley & Sons, USA*.
- Haldi, F. and Robinson, D., 2010. Adaptive actions on shading devices in response to local visual stimuli. *Journal of Building Performance Simulation* **3**(2): 135-153.
- Henry, M. C., 2007. The Heritage Building Envelope as a Passive and Active Climate Moderator: Opportunities and Issues in Reducing Dependency on Air-Conditioning. In *Expert's Roundtable on Sustainable Climate Management Strategies*, Tenerife, Spain.
- Heschong, L., 2002. Daylighting and Human Performance. *ASHRAE Journal*: 65-67.
- Hoes, P., Hensen, J. L. M., et al., 2009. User behavior in whole building simulation. *Energy and Buildings* **41**(3): 295-302.
- Humphreys, M. A., 1976. Field studies for thermal comfort: compared and applied. *Building Services Engineer* **44**: 5-27.
- Humphreys, M. A. and Hancock, M., 2007. Do people like to feel 'neutral'? Exploring the variation of the desired thermal sensation on the ASHRAE scale. *Energy and Buildings* **39**(7): 867-874.
- Humphreys, M. A. and Nicol, J. F., 2002. The validity of ISO-PMV for predicting comfort votes in every-day thermal environments. *Energy and Buildings* **34**(6): 667-684.
- Hussein, I., Hazrin, M., et al., 2009. Field Study on Thermal Comfort in Malaysia. *European Journal of Scientific Research* **37**(1): 127-145.
- Hwang, R.-L., Lin, T.-P., et al., 2006. Field experiments on thermal comfort in campus classrooms in Taiwan. *Energy and Buildings* **38**(1): 53-62.
- IEA, 2008. International Energy Agency SHC Task 40 / ECBCS Annex 52 - Towards Net Zero Energy Solar Buildings. from <http://www.iea-shc.org/task40/>.
- ISO, 1986. Thermal environments - Instruments and methods for measuring physical quantities. **7726**.
- ISO, 1994. Moderate thermal environments - Determination of the PMV and PPD indices and specification of the conditions for thermal comfort. **7730**.
- ISO, 1995. Assessment of the influence of the thermal environment using subjective judgement scales. *Ergonomics of the thermal environment*. **10551**.
- Jakubiec, A. J. and Reinhart, C. F., 2011. DIVA 2.0: Integrating Daylight and Thermal Simulations using Rhinoceros 3D, Daysim and EnergyPlus. In *Building Simulation - 12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- Jakubiec, J. A. and Reinhart, C. F., 2011. DIVA 2.0: Integrating Daylight and Thermal Simulations using Rhinoceros 3D, Daysim and EnergyPlus. In *Building Simulation - 12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- Jones, A. P., 1999. Indoor air quality and health. *Atmospheric Environment* **33**(28): 4535-4564.
- Jones, B. W., 2002. Capabilities and limitations of thermal models for use in thermal comfort standards. *Energy and Buildings* **34**(6): 653-659.
- Kleiven, T., 2003. Natural Ventilation in Buildings - Architectural concepts, consequences and possibilities. *PhD Thesis*, Norwegian University of Science and Technology.
- Kwok, A. G. and Chun, C., 2003. Thermal comfort in Japanese schools. *Solar Energy* **74**(3): 245-252.
- Kwok, A. G. and Rajkovich, N. B., 2010. Addressing climate change in comfort standards. *Building and Environment* **45**(1): 18-22.
- Laar, M. and Grimme, F. W., 2002. Sustainable Buildings in the Tropics. In *RIO 02 - World Climate & Energy Event*, Rio de Janeiro, Brazil.
- Laouadi, A., Reinhart, C. F., et al., 2007. The Daylight Coefficient Method and Complex Fenestration. In *Building Simulation Conference*, Beijing, China, IBPSA.
- Lavoye, F. and Thellier, F., 2008. Le confort thermique dans les bâtiments. Report.
- Leaman, A. J. and Bordass, W. T., 1997. Productivity in Buildings: the Killer Variables. In *Workplace Comfort Forum*, London, UK.

- Lee, E. S., DiBartolomeo, D. L., et al., 1998. Thermal and daylighting performance of an automated venetian blind and lighting system in a full-scale private office. *Energy and Buildings* **29**(1): 47-63.
- Lenoir, A., Baird, G., et al., 2012. Post-occupancy evaluation and experimental feedback of a net zero-energy building in a tropical climate. *Architectural Science Review*: 1-13.
- Lenoir, A., Cory, S., et al., 2012. Users' behaviour and energy performances of Net Zero Energy Buildings. *EcoLibrium*: 42-29.
- Lenoir, A., Garde, F., et al., 2009. Presentation of the Experimental Feedback of a French Net Zero Energy Building under Tropical Climate. In *ISES Solar World Congress*, Johannesburg, South Africa.
- Lenoir, A., Garde, F., et al., 2011. Towards Net Zero Energy Buildings in Hot Climates. Part II: Experimental Feedback. *ASHRAE Transactions* **117**(1).
- Lenoir, A., Garde, F., et al., 2010. Net zero energy buildings in France: from design studies to energy monitoring. A state of the art review. In *Eurosun Conference*, Graz, Austria.
- Lenoir, A., Garde, F., et al., 2011. Zero Energy Buildings in France: Overview and Feedback. *ASHRAE Transactions* **117**(2): 817-829.
- Levine, M., Urge-Vorsatz, D., et al., 2007. Residential and Commercial Buildings. *Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, USA Report.
- Lindelöf, D. and Morel, N., 2007. Bayesian estimation of visual discomfort. *Building Research & Information* **36**(1): 83-96.
- Mahdavi, A., 2011. The Human Dimension of Building Performance Simulation. In *Building Simulation - 12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- Mahdavi, A., Kabir, E., et al., 2006. User Interactions with Environmental Control Systems in Buildings. In *PLEA2006 - the 23rd Conference on Passive and Low Energy Architecture*, Geneva, Switzerland.
- Marszal, A. J., Heiselberg, P., et al., 2011. Zero Energy Building – A review of definitions and calculation methodologies. *Energy and Buildings* **43**(4): 971-979.
- Martin, M., Garde, F., et al., 2008. Combinaison of daylighting and solar shading performances for buildings in tropical climates. In *Eurosun Conference*, Lisbon, Portugal.
- Masoso, O. T. and Grobler, L. J., 2010. The dark side of occupants' behaviour on building energy use. *Energy and Buildings* **42**(2): 173-177.
- Matthews, J. and Nicol, F., 1995. Thermal Comfort of Factory Workers in Northern India. Standards for Thermal Comfort - Indoor air temperature standards for the 21st century. F. Nicol, M. Humphreys, O. Sykes and S. Roaf. London, UK, *E&FN Spon*.
- McCartney, K. J. and Nicol, J. F., 2001. Developing an Adaptive Control Algorithm for Europe: Results of the SCATs Project. In *Moving thermal comfort standards into the 21st Century Conference*, Windsor, UK, Oxford Brookes University.
- Mills, E., Bourassa, N., et al., 2005. The Cost-Effectiveness of Commissioning New and Existing Commercial Buildings: Lessons from 224 Buildings. In *National Conference on Building Commissioning*, New York, NY, USA.
- Mills, E., Friedman, H., et al., 2004. The Cost-Effectiveness of Commercial Buildings Commissioning: A Meta-Analysis of Existing Buildings and New Construction in the United States. *Lawrence Berkeley National Laboratory*, Report Retrieved 56637, from <http://eetd.lbl.gov/emills/PUBS/Cx-Costs-Benefits.html>.
- Musall, E., Weiss, T., et al., 2010. Net Zero Energy Solar Buildings: An Overview and Analysis on Worldwide Buildings Projects. In *Eurosun Conference*, Graz, Austria.
- Nabil, A. and Mardaljevic, J., 2006. Useful daylight illuminances: A replacement for daylight factors. *Energy and Buildings* **38**(7): 905-913.

- Napolitano, A. and Lollini, R., 2011. Measurement and Verification protocol for Net Zero Energy Buildings. *Subtask A - IEA Task 40 / Annex 52*, Report.
- Nicol, J. F., 1993. Thermal Comfort - A Handbook for Field Studies Towards an Adaptive Model. *University of East London, London*.
- Nicol, J. F., 2004. Adaptive thermal comfort standards in the hot-humid tropics. *Energy and Buildings* **36**(7): 628-637.
- Nicol, J. F., 2007. SCATs and other projects of the Thermal Comfort Unit at Oxford Brookes 1993-2007. *NCEUB Meeting, University College London, London, UK*.
- Nicol, J. F. and Humphreys, M. A., 2002. Adaptive thermal comfort and sustainable thermal standards for buildings. *Energy and Buildings* **34**(6): 563-572.
- Nicol, J. F., Raja, I. A., et al., 1999. Climatic variations in comfortable temperatures: the Pakistan projects. *Energy and Buildings* **30**(3): 261-279.
- O'Brien, W., 2012. Occupant-Conscious NZEB Design. *8th IEA Task40/Annex52 Meeting, Barcelona, Spain*.
- Olgay, V., 1963. Design with climate: Bioclimatic Approach to Architectural Regionalism. *Princeton University Press, Princeton*. ISBN: 9780691079431.
- Oliveira Pano, M. J. N. and Gonçalves, H. J. P., 2011. Solar XXI building: Proof of concept or a concept to be proved? *Renewable Energy* **36**(10): 2703-2710.
- Ossen, D. R., Hamdan Ahmad, M., et al., 2005. Optimum overhang geometry for building energy saving in tropical climates. *Journal of Asian Architecture and Building Engineering* **4**(2): 563-570.
- Osterhaus, W. K. E., 2005. Discomfort glare assessment and prevention for daylight applications in office environments. *Solar Energy* **79**(2): 140-158.
- Peel, M. C., Finlayson, B. L., et al., 2007. Updated world map of the Köppen-Geiger climate classification. *Hydrology and Earth System Sciences* **11**: 1633-1644.
- Pless, S., Lobato, C., et al., 2011. NREL's Research Support Facility: An Energy Performance Update. *U.S. Department of Energy, Golden, Colorado, USA*, Report, from http://www.nrel.gov/sustainable_nrel/pdfs/rsf_operations_10-2011.pdf.
- Price, L., Levine, M., et al., 2006. Sectoral Trends in Global Energy Use and Greenhouse Gas Emissions. *Lawrence Berkeley National Laboratory*, Report, from <http://ies.lbl.gov/iespubs/56144.pdf>.
- Raeissi, S. and Taheri, M., 1998. Optimum overhang dimensions for energy saving. *Building and Environment* **33**(5): 293-302.
- Raja, I. A., Nicol, J. F., et al., 2001. Thermal comfort: use of controls in naturally ventilated buildings. *Energy and Buildings* **33**(3): 235-244.
- Reinhart, C. F., 2002. Effects of Interior Design on the Daylight Availability in Open Plan Offices. In *ACE3 Summer Study on Energy Efficiency in Buildings*, Pacific Grove, USA.
- Reinhart, C. F. and Voss, K., 2003. Monitoring manual control of electric lighting and blinds. *Lighting Research and Technology* **35**(3): 243-260.
- Reinhart, C. F. and Wienold, J., 2011. The daylighting dashboard – A simulation-based design analysis for daylight spaces. *Building and Environment* **46**(2): 386-396.
- Saberi, O., Saneei, P., et al., 2006. Thermal Comfort in Architecture. In *WINDSOR 2006: Comfort and Energy Use in Buildings - Getting them right*, Cumberland Lodge, Windsor Great Park, UK.
- Salom, J., Widen, J., et al., 2011. Understanding Net Zero Buildings: Evaluation of load matching and grid interaction indicators. In *Building Simulation - 12th Conference of International Building Performance Simulation Association*, Sydney, Australia.
- Sartori, I., Napolitano, A., et al., 2010. Criteria for Definition of Net Zero Energy Buildings. In *Eurosun Conference*, Graz, Austria.
- Sartori, I., Napolitano, A., et al., 2012. Net zero energy buildings: A consistent definition framework. *Energy and Buildings* **48**(0): 220-232.
- Seppänen, O. and Fisk, W. J., 2002. Association of ventilation system type with SBS symptoms in office workers. *Indoor Air* **12**(2): 98-112.
- Soler, O., 1997. Atlas Climatique de La Réunion. *Météo France*, Report.

- Stellman, J. M., 1998. Encyclopedia of Occupational Health and Safety. J. M. Stellman. *International Labour Office, Geneva, Switzerland*. II: 46.12-46.14.
- Stephan, L., 2010. Modélisation de la ventilation naturelle pour l'optimisation du rafraîchissement passif des bâtiments. *PhD Thesis*, Université de Savoie.
- Tanabe, S.-i., Haneda, M., et al., 2007. Productivity, Energy, and Economics in Modern Offices. In *REHVA World Congress CLIMA WellBeing Indoors*, Helsinki, Finland.
- Thollander, P., Palm, J., et al., 2010. Categorizing Barriers to Energy Efficiency - an Interdisciplinary Perspective. *Energy Efficiency*. J. Palm, *In-Tech*.
- Torcellini, P., Ples, S., et al., 2006. Zero Energy Buildings: A Critical Look at the Definition. *ACEEE Summer Study, Pacific Grove, California, U.S.A.*
- Torcellini, P., Pless, S., et al., 2010. Main Street Net-Zero Energy Buildings: the Zero Energy Method in Concept and Practice. In *ASME 2010 4th International Conference on Energy Sustainability*, Phoenix, Arizona, USA.
- Tsiavanga, J., 2011. Etude de la conception bioclimatique en milieu tropical. *Master of "Espace Construction et Environnement"*, MBS thesis, University of Reunion Island.
- Tzempelikos, A. and Athienitis, A. K., 2007. The impact of shading design and control on building cooling and lighting demand. *Solar Energy* **81**(3): 369-382.
- Vieira, R., 2006. The Energy Policy Pyramid - A Hierarchical Tool For Decision Makers. In *Fifteenth Symposium on Improving Building Systems in Hot and Humid Climates*, Orlando, Florida, U.S.A.
- Vincent, D. and Pradalier, A., 1997. Impact sanitaire de la climatisation : qu'en est-il du syndrome des "bâtiments malsains" ? . *La revue de médecine interne* **18**: 460-469.
- Voss, K. and Musall, E., 2011. Net zero energy buildings. *Detail Green Books*, ISBN: 978-3-0346-0780-3.
- Voss, K., Sartori, I., et al., 2010. Load Matching and Grid Interaction of Net Zero Energy Buildings. In *Eurosun Conference*, Graz, Austria.
- Ward, G. J., 1994. The RADIANCE Lighting Simulation and Rendering System. In *'94 SIGGRACH Conference*.
- Webb, C. G., 1959. An Analysis of Some Observations of Thermal Comfort in an Equatorial Climate. *British Journal of Industrial Medicine* **16**(3): 297-310.
- Wetter, M., 2000 Design Optimization with GenOpt. *Building Energy Simulation User News* **Vol. 21 - September/October 2000**.
- Wetter, M., 2001. GenOpt - A Generic Optimization Program. In *Building Simulation, Seventh International IBPSA Conference*, Rio de Janeiro, Brazil.
- WHO, 1984. Indoor air quality research. Report on a WHO meeting. *World Health Organisation Regional Office for Europe, Stockholm, Sweden Report*, from http://whqlibdoc.who.int/euro/r&s/EURO_R&S_103.pdf.
- Wittkopf, S., Valliappan, S., et al., 2012. Analytical performance monitoring of a 142.5 MWp grid-connected rooftop BIPV system in Singapore. *Renewable Energy* **47**(0): 9-20.
- Zain, Z. M., Taib, M. N., et al., 2007. Hot and humid climate: prospect for thermal comfort in residential building. *Desalination* **209**(1-3): 261-268.
- Zhang, Y. and Barrett, P., 2012. Factors influencing occupants' blind-control behaviour in a naturally ventilated office building. *Building and Environment* **54**(0): 137-147.



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« C'est une question de discipline, me disait plus tard le petit prince. Quand on a terminé sa toilette du matin, il faut faire soigneusement la toilette de la planète. Il faut s'astreindre régulièrement à arracher les baobabs dès qu'on les distingue d'avec les rosiers auxquels ils ressemblent beaucoup quand ils sont très jeunes. C'est un travail très ennuyeux, mais très facile.

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J'ai connu une planète, habitée par un paresseux. Il avait négligé trois arbustes... »

